UNIVERSITY OF NAIROBI

ASSESSMENT OF THE PAST AND FUTURE METEOROLOGICAL DROUGHT CHARACTERISTICS IN THE EASTERN PROVINCE OF RWANDA UNDER A CHANGING CLIMATE

BY

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DECLARATION

I declare that this dissertation is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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DEDICATION

I dedicate this work to my Mother Seraphine MUKARUGAMBWA, Aunt Catherine RUTAGAMBWA, Brother Claude MUNYANTORE, friends and relatives.

ABSTRACT

The Eastern province of Rwanda faces frequent droughts in its low-lying areas, which may lead to severe negative effects on agriculture and livestock production during extreme climate conditions. This study aims at assessing the past and future drought characteristics in the Eastern Province of Rwanda under a changing climate.

The monthly gridded rainfall dataset known as ENACTS dataset for a period of 39 years (1981 to 2019) and monthly rainfall dataset from CORDEX-Africa-22 Domain for the period starting from 1981 – 2100 from the Earth System Grid Federation (ESGF) portal were used. The data were analyzed using Standardized Precipitation Index (SPI) in order to characterize the past drought over the Eastern Province of Rwanda based on the seven locations. Furthermore, the analysis of the temporal and spatial variability of rainfall amount, frequency and duration were carried out over the study region. Later, Future drought characteristics were analyzed based on the CORDEX-Africa-22 projection of the validated models on two Representative Concentration Pathways (RCPs) namely RCP2.6 and RCP8.5. Finally, a comparative study between the past and future drought was done in order to understand changes in frequency and severity of the drought over the Eastern Rwanda.

Based on the historical data, the results indicated that Nyagatare station faced 22 years out of 39 of no droughts from 1981 – 2019. Again, Nyagahanga and Nyamata did not experience droughts in 21 years out of the 39 years. Kawangire station in Kayonza district and Rwamagana experienced drier years than any other location, which are 22 out of 39 years based on 12 months-SPI. The most severe drought was recently experienced during the year of 2017 and it was drier across all the seven locations with mild to extreme droughts.

Based on Projected data, Nyarubuye followed by Kibungo Kazo will be the driest locations with only 8 and 9 years out of 26, respectively experiencing no drought while the rest of the years reported mild to extreme droughts under RCP2.6 from 2022-2047. Further, regarding the drought frequency from 2048 - 2073 over each location in the Eastern Province under RCP2.6, the study concludes that Kawangire and Rwamagana will experience drier seasons with only 14 years out of the 26 year-period exhibiting no droughts. Moreover, on the drought frequency from 2074 - 2099 under RCP2.6, Kibungo Kazo will only have 12 no drought years out of 26 years.

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AFR-22:	AFRICA-22
ANOVA:	Analysis of Variance
IPCC-AR4:	Fourth Assessment Report of the Intergovernmental Panel on Climate Change
BAMS:	Bulletin of American Meteorological Society
C2ES:	Center for Climate and Energy Solutions
CCLM5-0-15:	Climate model5-0-15
CDT:	Climate Data Tool
CMIP5:	Coupled Model Intercomparison Project Version 5
CMIP6:	Coupled Model Intercomparison Project Version 6
CDI:	Combined Drought Index.
CORDEX:	Coordinated Regional Downscaling Experiment
DJF:	December - February
DD:	Drought Duration
DF:	Drought Frequency
DMI:	Drought Monitoring Indicators
DS	Drought Severity
ECMWF-ERAINT:	European Centre for Medium-Range Weather Forecasts Re-Analysis Interim
ENSO:	El Niño–Southern Oscillation)
ENACTS:	Enhancing National Climate Services
ENS-OBS:	Ensemble Observations.
ESGF:	Earth System Grid Federation
FAO:	Food and Agriculture Organization
GDP:	Gross Domestic Product
GGCRS:	Green Growth and Climate Resilience Strategy
GCMs:	Global Climate Models
GWLs:	Global Warming Levels
ENS-RCMs:	Ensemble Mean of the Regional Climate Model
GWP CEE:	Global Water Partnership Central and Eastern Europe
ICPAC:	IGAD Climate Prediction and Applications Centre

ICTP-RegCM4-7: International Centre for Theoretical Physics-Regional Climate Model 4-7

IGAD: Intergovernmental Authority on Development

INDC: Intended Nationally Determined Contribution

IOD: Indian Ocean Dipole

ITCZ: Inter-Tropical Convergence Zone)

IPCC: Intergovernmental Panel on Climate Change

IRI: International Research Institute for Climate and Society

ITCZ: Inter-Tropical Convergence Zone

JJA: June – August.

MAM; March- May

MAE: Mean Absolute Error

ME: Mean Error

MIDIMAR: Ministry of Disaster Management and Refugee Affair of Rwanda

MINIRENA: The Ministry of National Resources of Rwanda

MOHC-HadGEM2-ES: Met Office Hadley Centre-Hadley Centre Global Environment Model version 2-Earth system

MPI-M-MPI-ESM-LR: Max-Planck-Institut für Meteorologie Earth System Model

NCC-NorESM1-M: The Norwegian Climate Center's Earth System Model,

NDVI: Normalized Difference Vegetation Index

NIR: Near-Infrared radiation

NISR: National Institute of Statistics of Rwanda

NMHS: National Meteorological and Hydrological Services

NDVI: Normalized-Difference vegetation index

PDSI: Palmer Drought Severity Index

PET: Potential Evapotranspiration

PCA: Principal Component Analysis

RCP: Representative Concentration Pathway

RegCM-ENSEMBLE: Regional Climate Model- ENSEMBLE

REMA: Rwanda Environment Management Authority

REMO: Report on State of Environment

RMSE: Root Mean Squared Error

SOND:	September, October, November and December
SON:	September, October, November
SPEI:	Standardized Precipitation Evapotranspiration Index
SPI:	Standardized Precipitation Index
SSTs:	Sea Surface Temperatures
SDSM:	Statistical Downscaling Model
SSAF:	Sub-Saharan Africa
TRMM:	Tropical Rainfall Measuring Mission
UNFCCC:	United Nations Framework Convention on Climate Change
UNISDR:	United Nations International Strategy for Disaster Reduction
US:	United States
USA:	United States of America
WMO:	World Meteorological Organization
WWAP:	World Water Assessment Program

CHAPTER ONE: INTRODUCTION

The chapter highlights the study background, problem statement, research questions, objectives, justification, as well as the area of study.

1.1 Background

The presence of extreme weather events such as drought provides significant concerns worldwide. Drought monitoring and assessment have been viewed as essential strategies for drought management. Drought might not be seen as a purely "natural hazard" because human beings have altered drought characteristics. In the past, drought have been observed over Rwanda with severe effects on food security and pastoral activities. According to Mikova *et al*, 2015 Rwanda has experienced drought from 1902/1903 with return period of more than 10 years which has reduced to 3 years return period in 2008. This is an indicator of an increasing frequency of drought over the country.

In Rwanda, a study done by Aminadab (2018) assessed the drought characteristics over Rwanda using Combined Drought Index (CDI), the study showed that the drought was higher in Eastern Province for both temporal and spatial. However, drought had a long duration at Nyagatare. Further, the study indicated that the first two years of the period understudied presented mild to moderate drought signs in most parts of the country. From that study, it is evident that the long drought duration is anticipated to be in the western province for both RCP4.5 and RCP8.5. Drought characteristics under RCP8.5 were established as the most severe as opposed to that of RCP4.5. The study suggested that drought is anticipated to begin early part of the period under study in Southern and Western parts of Rwanda.

Based on the aforementioned studies, it is clear that most of the research that has been carried out in the past has shown that past and future drought characteristics due to climatic change have a significant influence on environments that subsequently affect the entire ecosystems. Studies from various authors have all concluded that indeed climate change has resulted in increased drought globally. Consequently, there is a need for present studies that can provide recommendations to minimize the impacts thereby improving the drought resilience in Rwanda. The current study, therefore, joins the debate by assessing the past and future drought characteristics in the eastern province of Rwanda under a changing climate.

1.2 Problem Statement

Rwanda is prone to natural disasters mainly emerging from climatic disturbances (Warner et *al.*, 2015). Drought is a prominent and pronounced disaster in Rwanda especially in the Eastern Province (REMA, 2009). Climate change-induced drought is now impelling food security and poverty reduction. The quantity and quality of pasture has decreased in the Eastern Province due to shortfall of water, therefore, this has negatively affected livestock production (MIDIMAR, 2012).

Asumadu-Sarkodie, (2015) revealed that in Rwanda, more than 237 citizens out of a population of 4.16 million persons in the area died from 1900 to 2015 due to drought events. In 2015, in Nyagatare District 1,750 cows died due to lack of fodder and water. Even though several policies have been set to manage and reduce risks of droughts, droughts are still threatening the lives of people in Eastern Province.

1.3 Research Questions

1. How to characterize the past and future droughts in the eastern province of Rwanda?
2. explain the trends and variability of Standardized Precipitation Index (SPI) indices as an indicator for droughts in the Eastern province of Rwanda?
3. how skilful are the CORDEX models in simulating variability and trends of rainfall in Eastern province of Rwanda?
4. Describe the changes between the past and future drought over the Eastern Province region?

1.4 Objectives

The main objective of the research was to conduct an assessment of the past and future drought characteristics in the Eastern Province of Rwanda under a changing climate. The specific research objectives are:

1. To determine spatial-temporal rainfall characteristics over the Eastern province of Rwanda.
2. To examine the duration, severity, and frequency of past drought over the Eastern province of Rwanda.
3. To evaluate the skilfulness of CORDEX models in simulating variability and rainfall trends in Rwanda.
4. To determine the duration, severity, and frequency of future drought over the Eastern province of Rwanda.

1.5 Justification

Several types of research have been done on climatic change and how it has adversely increased drought thereby affecting livelihood. In the USA for instance, some studies (Feng et al., 2017) are composed of estimated variation based on model-based projections and drought indices of the future. The indices for drought and total modeled column soil moisture used indicated a widespread ongoing dryness over the USA Great Plains. This implies that climatic change is still a concern even among the developed economies. Such concerns imply that more researches should be conducted to determine the extent to climatic changes results to present and future droughts and provide amicable strategies that could avert the adverse effect of climatic change.

In Asia, future drought characteristics for regions prone to droughts in South Asia revealed an increase in conditions of drought mostly over the North-West areas. The North-West region in South Asia is susceptible to frequent droughts with increased duration and higher intensity. As per the study, sections of North-Central, North-East, and South-West sub-areas will also face future severe drought conditions. Based on these concerns, drought adaptation measures should be embraced to limit the adverse effect of drought not only in Asia but in developing nations as well hence the need for the current study.

Further, in Kenya and Tanzania, Statistical Down Scaling Model (SDSM) is utilized to initiate higher-resolution climatic projections to drive the impact of the models in the region. The literature points to evidenced precipitation increase in Kenya and a reduction in Tanzania in the 20s (2011–2040), 50s (2041–2070), and 80s (2071–2100), respectively. Based on such glaring concerns, recommendations have been made but the sustainability measures for adaptation are still inadequate. Hence it is in the interest of the current study to promptly bridge such deficiencies by providing site-specific measures and strategies that can match with the unpredictable climatic change in the region, Rwanda inclusive.

Moreover, the Eastern Province of Rwanda is a savannah region known to be the food basket of the country; people in this region are usually affected by the impact of climatic change. The accessibility of enough information on drought characteristics and their linked effects by the community on time in this region will reduce its vulnerability to droughts and will also lead to effective strategies for developing the adaptive capacity of the community to droughts (Karavitis, 2011).

Furthermore, there is a need for using drought indices, including SPI to determine the future drought characteristics over Eastern Province. This will contribute to policymaking and planning in agro-pastoralists as the main economic activities of Eastern Province are mostly affected by droughts. This will also lead to more appropriate solutions for the mitigation of droughts.

1.6 Area of study

At 26,338 km2, Rwanda is a landlocked nation in the south of the Equator, lying in two climatic regions east-central Africa with the latitudes of 1°4′ and 2°51′ south. The country’s longitudes are 28°53′ and 30°53′ east in the tropical belt (Henninger, 2013). In the North, Rwanda is boarded by Uganda, in the east by Tanzania. In the south, the county is boarded by Burundi, and in the west by the Democratic Republic of Congo.

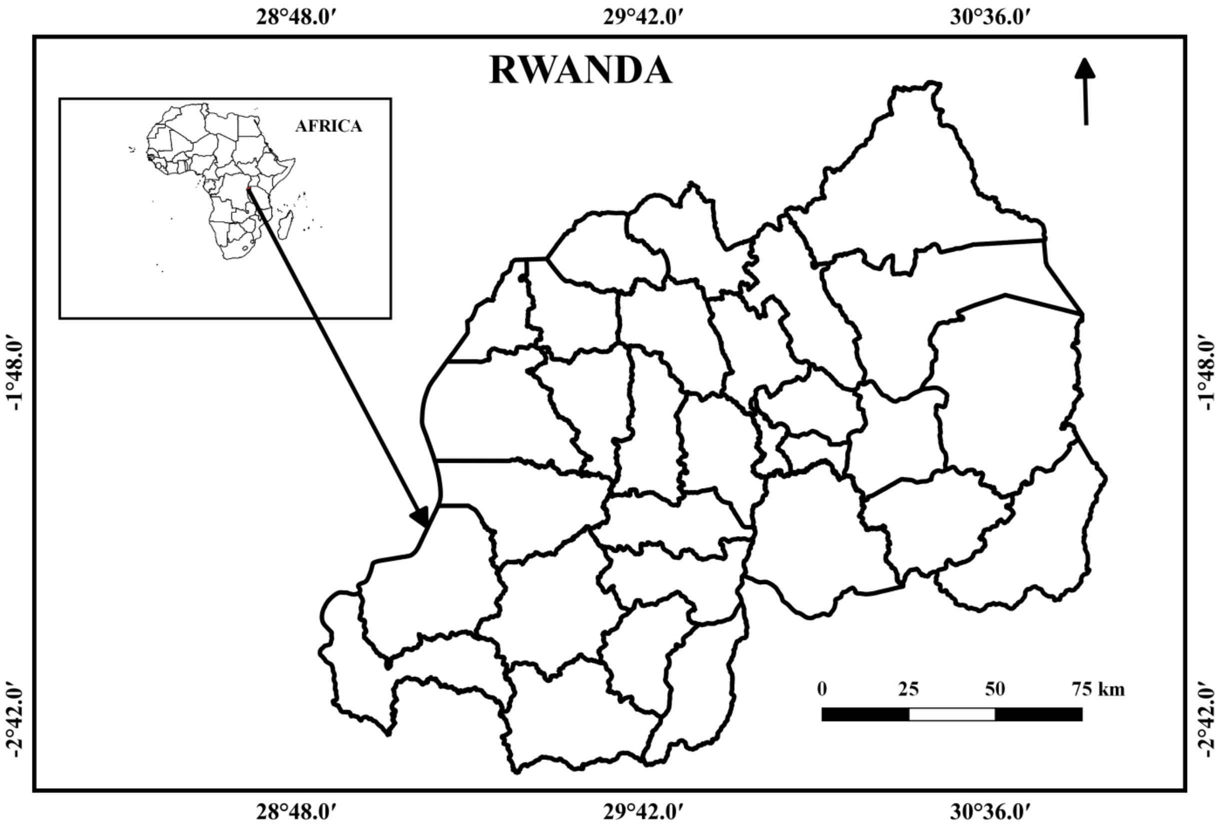

Figure 1: Location of Rwanda in Africa

The region between the Akagera River towards the middle section and the course of South-North of Akanyaru River is covered by high plains Eastern Province of Rwanda. The Central Highlands is a crystalline mountainous area at an elevation of 1800 m to almost 3000 m. Rwanda has earned the sobriquet "Land of a thousand hills due to the high relief intensity of the Central Highlands. Lake Kivu had been dammed up by volcanic lava flows, later filling a large portion of the roughly 40 km wide Rift zone. The Rusizi River forms the border with the Democratic Republic of Congo. It flows toward Lake Tanganyika, which sits at an elevation of only 773 meters. In the northwest, the Virunga volcanic chain runs along the border with Uganda and the Democratic Republic of Congo (Henninger, 2013).

The lowlands of Eastern Rwanda have a hot and relatively dry savanna climate, the central highlands have a temperate climate, the Nile-Congo Mountains have a cool and humid climate, and Lake Kivu has the land-lake climate (Henninger, 2013).

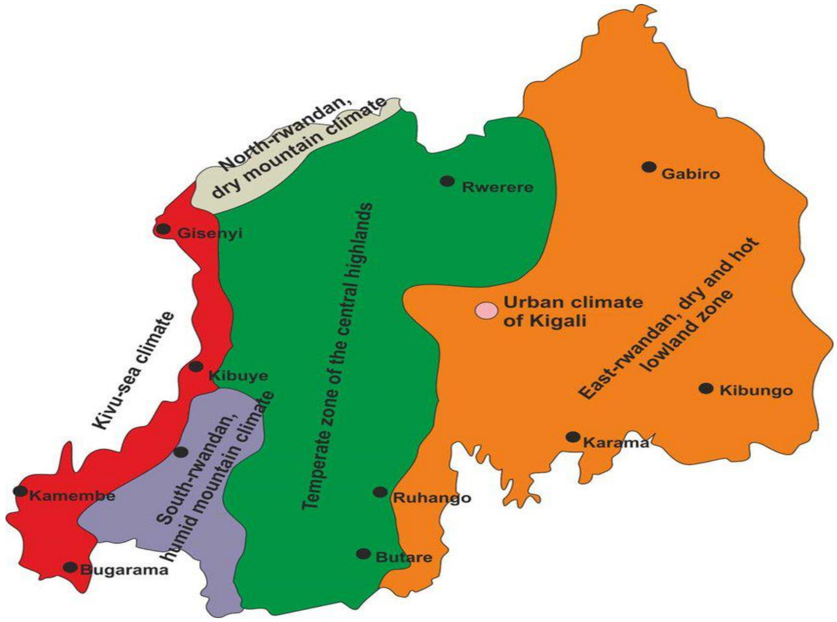

Figure 2: The new climatic classification of Rwanda, based on data from1996-2011 (Henninger, 2013)

This study was conducted in Eastern Province, the biggest among the five provinces of Rwanda with a total area of 9,813 km^2. It has seven districts: Bugesera, Rwamagana, Gatsibo, Kayonza, Kirehe, Ngoma, and Nyagatare. The capital city of the Eastern Province is Rwamagana, The Akagera National Park is situated in this province. The Eastern Province is bordered by Tanzania in the East, Uganda in the North, and the city of Kigali in the West.

The Eastern Province is a low mountain region with an altitude ranging between 1000m and 1,500m in altitude and receiving rainfall ranging between 700 and 1.100 mm. (Ilunga *et al,* 2004). The Eastern province is located between 1°45'00.0"S of latitude and between 30°30'00.0"E of longitude.

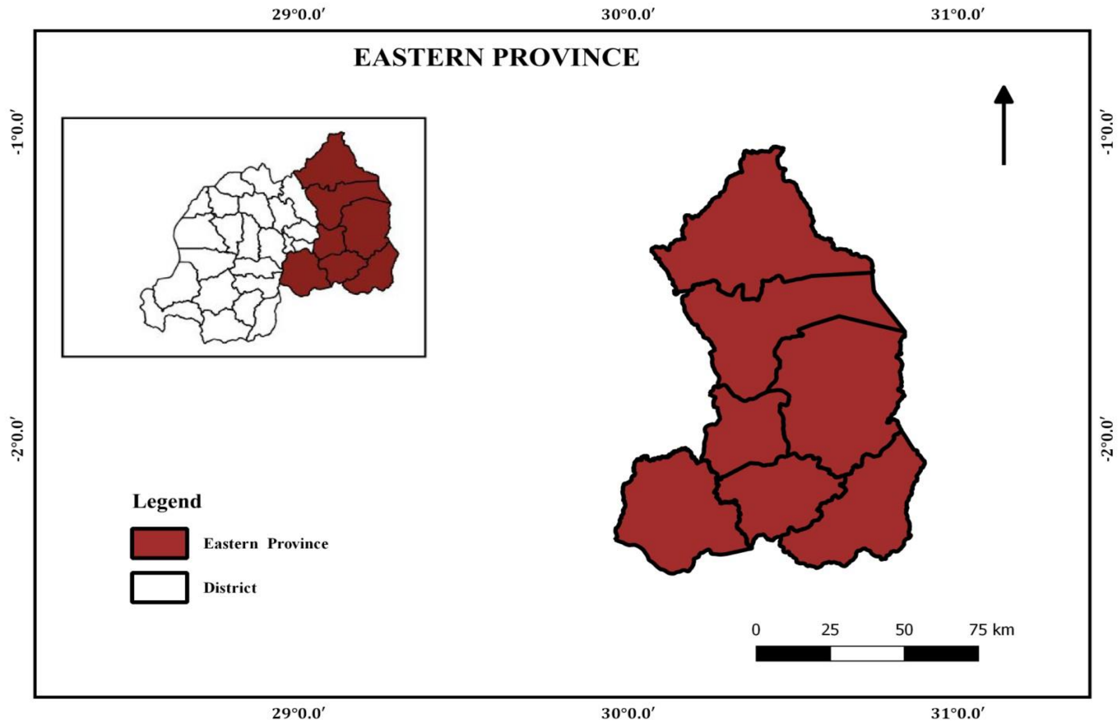

Figure 3: Map of Eastern Province of Rwanda

The weather influencing this province comes from Lake Victoria Basin and sometimes from the mesoscale system. In normal weather conditions, this region used to have sufficient rainfall, which resulted in the generation of sufficient production for some crops and shared with the rest of the country. This time where the weather condition is not good, the production decreases significantly because of droughts, this is due to climate change and climate variability which was observed globally and, in the region, particularly. The Eastern Province is the biggest province among the five provinces of Rwanda with 2,595,703 inhabitants.

CHAPTER TWO: LITERATURE REVIEW

2.0. Introduction

The chapter presents literature detailing spatial-temporal characteristics of rainfall, the duration, frequency, and severity of past and future drought, as well as the CORDEX models' skillfulness in simulating variability and rainfall trend over Eastern Rwanda. A Conceptual framework is also presented.

According to Gebremeskel and Kebede (2018), climate change that has resulted in increased drought and increasing population growth has become major inhibiting factors for the conservation of natural systems and the sustainability of human resources development (Haile *et al.*, 2020). As global warming increases, the impact of climate change's magnitude on society and the environment increases.

In Africa with a specific focus on Sudan, Tanzania, Somalia, South Sudan, Kenya, Uganda, and Ethiopian highlands, Haile *et al.* (2020) studied the future drought characteristics by utilizing Global Climatic Models (GCMs) in Coupled Model Inter-comparison Project (CMIP5). The study established those East African droughts could increase towards the closure of the 21st century by 16%, 36%, and 54% under RCP2.6, 4.5, and 8.5, respectively. Drought events, frequency, duration, intensity, and spatially will increase in South Sudan, Tanzania, Sudan, and Somalia. However, drought event, frequency, and duration, the intensity would reduce generally in Uganda, Ethiopian, and Kenyan highlands. The study has provided significant guidance that can help in improving identification causes, minimization of impacts, and improving the drought resilience in East Africa.

Furthermore, Dinku *et al.* (2014) assert that climate change is one of the primary challenges that the natural ecosystems and the people face globally (Van Loon *et al.*, 2016). Under climate change, especially during droughts, water, and food insecurity are most likely to escalate unless timely adoption of development programs and strategies are efficiently embraced.

Further, in order to determine future drought characteristics over areas susceptible to droughts such as South Asia, Zhai, *et al.* (2020) used a five-model ensemble from CMIP6 to project characteristics of drought for the period 2020–2099. The study found a significant increase in conditions of drought mostly over the North-West areas. The study projected a strong in the average drought frequency and duration. The North-West area was found to be the most susceptible to frequently experience droughts with prolonged duration and high intensity. Based on the study, the section of North-Central, North-East, and South-West sub-areas are also likely to face future severe droughts. The study suggests that the established results offer a foundation for developing South Asian adaptation measures for droughts.

Again, Jeong *et al.* (2014) studied the role of temperature in drought projections over Canada. The study found that future increase in the average temperature by over 2°C during the future period in comparison to the present period for the majority areas in Canada led to a large increase in PET and reduces in DIF for the future period, especially for low latitude regions of Canada. Such changes lead to significant increases in drought risks in the future for major regions in southern Canada. Despite those same outcomes are achieved with SPI, future drought characteristic increases are prone to future risks for droughts.

Additionally, to permit adaptation and mitigation of potential impacts of the future climatic change, Gebrechorkos *et al* (2019) applied Statistical Downscaling Model (SDSM) to compute higher-resolution climatic projection equivalence to future station data to drive assessment models to impact in Kenya and Tanzania. Regarding, SDSM, the study established an increase in precipitation in KenShed (15% - 86%) as well as reduction in TanShed (1.3% - 6.3%) in the 2020s (2011–2040), 2050s (2041–2070), and 2080s (2071–2100). It also found that T-min with up to 2.76 °C anomalies and T-max with up to 3.7 °C anomalies are likely to be warmer than the baseline period during the 21st century in the two countries. In general, the study suggests that sustainability measures for adaptation should be prepared in some site-specific criteria to match with unpredictable climatic change.

In yet another study, Gizaw and Gan (2017) used the “Palmer Drought Severity Index” (PDSI) to analyze drought characteristics changes in Sub-Saharan Africa (SSAF) from 1971–2000. “Representative Concentration Pathways” (RCP4.5, RCP8.5) climatic projections in GCMs (Global Climate Models) during periods of 2041–2070 and 2071–2100 were used. The study found the majority of parts in West Africa and South Africa shall experience dry climatic conditions during the 2050s and 2080s. Nevertheless, certain parts in the Horn of Africa are anticipated to experience relatively wet seasons in the 2050s and 2080s. Generally, the study suggests SSAF shall witness the driest climate in the 2050s and 2080s with increased drought vulnerability in some parts of the continent.

2.1. Rainfall Patterns over Rwanda

Eastern Rwanda is the most vulnerable prone area to climate change induced-droughts. Recurrent rainfall shortfalls have occurred in districts of the lowland of the Eastern province that include; Nyagatare, Bugesera, Gatsibo, Kayonza, Kirehe, and Ngoma (Taremwa et *al.,* 2016).

Generally, Rwanda has two rainy seasons, the long and short rains which contribute to nearly 75% of the rains of the country. The inter-tropical convergence zone (ITCZ) controls prolonged rains from March to May and shorter rains from September to December rains patterns over Rwanda to a great extent. It was remarkably observed that the long rains have reduced especially in eastern lowlands while the short rains have increased in the south-west as well as northern Rwandan highlands (Muhire and Ahmed, 2014).

In Rwanda, annual rainfall ranges from 800-1700 mm. Several factors impact the rainfall over Rwanda. These could include the ITCZ, Topography, Congo Air Masses, large water bodies, Tropical Cyclones, Sub Tropical Anticyclones, Monsoons among others. The most system controlling the rainfall season in Rwanda is the ITCZ. Notably, the subtropical anticyclones are areas with high pressure and these forms the wind sources.

The subtropical anticyclones thus act as pumps of moisture into the convergence areas. Their location and intensity influence the seasonal rainfall performance in the country. The country's rainfall normally occurs during rainy seasons that is during September, October, November, as well as December (SOND) and March, April and May. However, the ITCZ shifts from North to South to the equator and vice-versa (Mutai and Ward 2000).

It has been noted that the topography that are hilly of between 900 and 4507 m have exposed Rwanda to adverse erosion of soil particularly, during huge rainy conditions (Muhire and Ahmed, 2014). This has consequently led to continuous deforestation that has seen approximate loss of 1.35% of forest annually or 64% forest in Rwanda since the early 1960s. This loss leaves Rwanda with only a vegetation coverage of 240,746 ha in 2007 as opposed to 659, 000 hectares of vegetable in 1960 (FAO, 1999). The deforestation has made the country susceptible to floods coupled with environmental destruction, minimal crop productivity, and soil degradation.

It is, therefore, critical to evaluate the spatial-temporal rainfall distribution to estimate spatial characteristics of rainfall and the possible effects of its variability on drought characteristics (Hak and Haeng, 2011). Spatiotemporal investigations of rainfall characteristics for developing nations such as Rwanda, a country where above 85% workforce is committed in rain-led agricultural practices (NISR, 2011). Thus, the study was purposed to analyze spatial-temporal characteristics of rainfall over the Eastern province of Rwanda.

2.2 The Past Drought over the Eastern Province of Rwanda

Drought is mainly the key factor, which threatens various areas of Eastern Province. This tenor tends to decrease in agricultural production, food security, and poverty reduction (REMA, 2018). There are two dry seasons in Rwanda. The first major dry period is during June to August and the shorter dry season runs from the middle of December to the middle of February. The two dry seasons are because of the movement of ITCZ from North to South crossing the equator two times annually during the month of March and September respectively, and vice versa.

A study by Phaduli (2018) on the spatial-temporal characteristics of historical, current, as well as future meteorological drought in South Africa were computed using the SPI and “Standardized Precipitation Evapotranspiration Index” (SPEI). The trend as well as statistical analysis were conducted using time series for SPI derived from rainfall observations. The rainfall observations were used because most South African areas had experienced moderate droughts to severe droughts in between 1981 and 2015. The study used gridded monthly precipitation data based on Tropical Rainfall Measuring Mission (TRMM) satellite. TRMM was employed to compute SPI at each domain for grid point. SPI that was computed was utilize to get past drought monitoring indicators including drought severity (DS), drought frequency (DF), and drought duration (DD) during the period 1998-2015.

The results by Phaduli (2018) found that there was decreasing trend (negative) in DS and DD over most provinces in South Africa including Limpopo, Gauteng, North West, and Free State. Further, the study found that SPI/SPEI computed by use of in-situ observations data and SPI calculated through TRMM data reproduced major drought episodes that happened between 1981-2015. In addition, the trend and statistical analysis were conducted by use of drought, severity, frequency, and duration. In a nutshell, results established an overall increment in droughts during past period, 1998-2015 under RCP8.5.

In yet another study, Botai *et al.* (2017) assessed drought characteristics using SPI and drought Monitoring Indicators (DMI). The two categories were calculated based on precipitation data and weather stations in Western Cape Province were utilized as measures. The data was between 1985 and 2016. The study found that the analysis of SPI-3, SPI-6 together with SPI-12 showed that from 1985-2016, Western Cape Province exhibited recurrence of mild droughts. It could mean that the droughts noted in 2015 and 2016 is a manifestation of previous drought events. On the other hand, the DMI series trend analysis suggested evidenced spatio-temporal inter-dependence while western and southern areas witnessed extremely severe droughts in comparison to northern and eastern of Western Cape province.

Further, the study by Botai et al. (2017) found that the trends of past DMI exhibited ~8% variability during previous decades. Precisely, situation of droughts adversely continued to negatively impact production in the agriculture sector wherein water reservoirs were found at a lower capacity of less than 30%. This implies that droughts impact on the socio-economic activities will continue to recur for several months. The study concluded that the past drought characteristics analysis is integral initial move towards putting into perspective the present drought situations so as to trigger action and policy response thereof. The study findings are important because they lay foundation for monitoring drought and also contributes to initiation of early warning measures for droughts.

2.3 The Skillfulness of CORDEX Models in Simulating Variability and Trends of Rainfall

Future precipitation projections have in the past been investigated through CORDEX-Africa datasets. For instance, East Africa climatic simulation was done by Anyamba and Tucker (2012) by use of 25-member CORDEX-Africa RCM ensemble. The study found projected precipitation change across East Africa is mostly uncertain. The study also projected that the rainfall in northern and central Ethiopia parts to substantially reduce, in wet and the dry periods.

In the CORDEX-Africa project framework, RCMs' ability in simulating the rainfall in East Africa is presented in a study by Nguvava (2020). They demonstrated that the CORDEX models helps in simulating the critical rainfall climatology feature adequately, even though there were significant individual models' biases. The study found that the multi-model ensemble generally outperformed any single model found by Husak *et al.* (2007) who equally used multi regional climate model (multi-RCM) experiment CORDEX.

In yet another study, Endris *et al.* (2016) found that RCMs produced a biased quasi-systematic dry over Uganda and Tanzania. Their study called a thorough and advanced investigations to carry out an assessment that will determine the seasons that the biases are strongest by use of multi-RCM CORDEX models.

Kisembe *et al.* (2019) evaluated the CORDEX rainfall simulations in Ugandan climatic models. Study evaluated ten regional climatic models (RCMs) ability to simulate current-day rainfall in Uganda using CORDEX between 1990 to 2008. The CORDEX models' ability to reproduce space-time seasonal inter-annual, and yearly rainfall variability was diagnosed. Metrics series were utilized to quantify simulated RCM rainfall pattern biases, discrepancies, and this was compared to three datasets (gridded observational).

The study by Kisembe *et al*. (2019) established that most models used underestimated the rainfall pattern (annual) over the Uganda. In the contrary, the seasonal rainfall was reproduced properly using RCMs through bimodal component across most Uganda areas. Further, uni-modal component was also reproduced in northern region. CORDEX models also reproduce the interannual dry season variability in December, January, and February however, the models failed during longer and shorter rainy conditions even if "El Niño–Southern Oscillation" (ENSO) as well as Indian Ocean Dipole (IOD) signal were simulated correctly by majority of models. In a nutshell, the RCMs' ensemble means in ten regions reproduced rainfall climatic conditions in the country with acceptable CORDEX skill.

As study by Ilori and Balogun (2021) evaluated the new CORDEX-Africa regional climatic models' performance to simulate the rainfall in regions of West Africa. The study used RCMs that participated in CORDEX phase two based on data collected from Western Africa rainfall patterns during 1970s- 2005s. Through use of various climatological description and statistical methods at annual and seasonal scale, the models, "grand ensemble mean" (ENS-RCM) and downscaling institution-based ensembles mean was contrasted to mean ensemble (ENS-OBS) for two observations. Outputs of the three CMIP5 GCMs was downscaled using RegCM-ENSEMBLE and also RegCM- ENSEMBLE performed seamlessly better during spatial simulation of average seasonal rainfall in the region.

Further, the study by Ilori and Balogun (2021) observed that ensemble mean and some individual models from varied downscaled institutions outperformed grand ensemble imitating average seasonal rainfall in three climate zones as well as the whole Western African region. Additionally, the yearly statistical evaluation found that there was a poor performance over Guinea Coast region with minimal correlation values. In the contrary, all the CORDEX models obtained good outcome in Sahel region. The results are an indication that ensemble mean could help in amplifying or reducing uncertainty in climatic models. Simply put, the study concluded that using ensemble mean can lead to a reduction in climate models uncertainty during the projection of rainfall over Western African region across various periods.

With respect to Rwanda, Aminadab (2018) carried out a study that aimed in determining the drought characteristics over Rwanda. The CORDEX-Africa-0.44 for RCP4.5 and RCP8.5 was used to determine future drought and the model data was validated by use of observed data. The spatial-temporal drought analysis for future (2021-2050) was done by use of time series analysis, CDI software, and Coefficient of Variability. The study established that future drought severity under RC4.5 and RCP8.5 is increasing. It was evident that the long drought duration is anticipated in western province of Rwanda for RCPs8.5 and 4.5. Specifically, it was found that drought under RCP8.5 is very severe as opposed to RCP4.5, wherein the drought characteristics duration is longer for RCP4.5 in comparison to the RCP8.5. The study anticipated that drought is expected to begin earlier in the Southern and Western regions.

2.4 The Future Drought over the Eastern Province of Rwanda

To determine duration, severity, frequency of future droughty events over Rwanda, corresponding scenarios RCP2.6 and RCP8.5 for CMIP5 can be utilized to compare and to determine alterations and to improve the CMIP6 in Eastern province of Rwanda (Yang *et al*. 2018). The Varimax rotation method and Principal Component Analysis have been utilized to subdivide the research region into homogenous drought sub-regions. Therefore, elements such as drought frequency, severity, and duration can then be analyzed in line with the Run theory as supported by Zhai *et al*. (2020). The Sen's slope and Modified Mann-Kendall methods can then be incorporated to establish sub-regional future drought characteristics' trends (frequency, severity, and duration).

According to Gizaw and Gan (2017), the SPI for future meteorological droughts can be quantified at a 12-month (SPI12) timescale. In agreement, Feng, Trnka, Hayes, and Zhang (2017) say that the SPI is selected as it is commonly important in detecting meteorological drought conditions (severity, duration, and frequency) in arid-dominated areas such as Rwanda.

Further, Yang *et al*. (2018) indicates the future drought severity status can be determined by the use of SPI drought index levels. Accordingly, droughts can be evaluated through drought events, severity, frequency, duration, and intensity (Hosseini-Moghari *et al.,* 2019). However, this study will evaluate drought events using severity, frequency, and duration. Such drought parameters are normally employed to analyze the drought characteristics conditions under different spatial-temporal conditions. In a rejoinder, Ahmadi *et al.* (2020) argue that such parameters have been utilized to detect potential climatic change effects on characteristics of meteorological droughts.

Further, Ukkola *et al.* (2020) utilized boxplot to indicate the spread of future changes of drought events based on duration, severity, and frequency (Gebremicael et al., 2019). The boxplot has been widely used in showing the most extreme values such as the minimum, maximum, and outliers). It also shows the upper (75%) and lower (25%) quartile values.

A study by Haile *et al*. (2020) analyzed the future climatic change impacts on drought patterns in Eastern Africa. The 2011–2099 was the longer term projection relative to 1981–2010 which was the baseline period for every RCP. Study alterations in drought was calculated as change departure percent. The change was indicated change in percentages as divided by baseline period' magnitude. Study found that the future droughts indicated drought-vulnerable and drought event areas throughout the 21st century. The study findings help in driving an in-depth grasp on how metrological drought is impacted by the changes of climate critical in environmental policymaking to adopt viable mechanism to the drought menace.

In yet another study, Nguvava (2020) combined rains and Potential Evapotranspiration (PET) to assess characteristics of meteorological droughts for present and future climates at the regional and river basin scales over East Africa. The study combined PCA with wavelet analysis to establish Spatio-temporal structure for four dominant drought modes over the region. The study projected the future droughts' characteristics over Eastern Africa and its major river basins at varied global warming levels (GWLs). The projections also indicated that the increase in drought intensity, as well as frequency, can be mostly attributed to increased PET than to the reduction in precipitation. Among the four-vegetation usage considered, only shrubs and forestry indicate a substantial change in the drought indices. The study findings thus provide significant insight into the future drought characteristics over Eastern Africa.

2.5 Climate Change Profile over Rwanda

Rwanda has experienced changes in climates for the last three decades in form of droughts, floods, and landslides. The average temperature rose by up to 1.4°C since 1970, by the 2050s, the average temperature of Rwanda will be likely to increase by 2.5°C from the 1970 average. Climate change impacts are already costing lives, altering the environment, and intensely challenges water management (Warner *et al*., 2015).

Climate change impacts are expected to enlarge spans of crop animal pests and diseases; this will decrease agricultural production. According to climate projections, the highlands of north-west Rwanda will be exposed to erosion with average annual rainfall of 100 mm to +400 mm over 2000-2050 periods while areas of the east-southeast will be prone to droughts and desertification (REMA, 2009).

Rwanda is developing and among the most densely populated country in Africa and very prone to climatic changes. Nearly all activities related to agriculture are fed by rains, thus making the nation extremely susceptible to rainfall pattern changes. Activities related to agriculture accounted a 33% of Gross Domestic Product (GDP) and employed 90% Rwandan population in 2013. This sector also accounted for 40% of GDP and employed 80% of the country's inhabitants in 2015 (NISR, 2017).

Climate change has resulted in Rwanda experiencing recurrent droughts as never before. Droughts exacerbate the economy and environment of Rwanda on an extensive scale. Moreover, prolonged droughts have affected the agricultural sector in the eastern province of Rwanda. It has become very difficult to sustain production to cope with the increased demand for products. Drought in that region has affected livestock. Therefore, Rwanda has a tropical-temperate climate with a bimodal rainfall pattern. Rwanda has experienced increased annual average temperature of about 0.35°C each decade. These statistics are much higher than global annual average temperature increase of about 0.27°C that was witnessed between 1979-2005 (Asumadu-Sarkodie *et al*., 2015).

2.6 Meteorological Droughts Characteristics

Generally, droughts can last from weeks (flash droughts can occur during weeks interval) to years (megadroughts can occur during years interval). From this context, droughts are to be separated from water scarcity and aridity (Capecchi *et al.*, 2008). Droughts are the most complex hazards due to their vast spans, nature, and surge effects on human health, ecosystem, biodiversity, energy, agriculture, tourism, transportation, among others (Vogt *et al*., 2018). Droughts are non-structural and develop slowly, their related risks can last longer periods even after the droughts have ended (UNISDR, 2011).

Essentially, extreme weather events like meteorological drought present immense challenges across the globe. Drought monitoring and assessment have been established as an important drought management strategies component. Rwanda, especially the Eastern province faces the climatic change effect and the variability of climate variables such as rainfall. Such variations are majorly impacting the main contributor to the economy and agricultural sectors.

2.7 Types of Droughts

Normally, four types of droughts are differentiated according to their effects on society, hydrological cycle, and environment. The four types of droughts are the following:

"Meteorological Drought, Hydrological drought, Socioeconomic Drought, and Soil moisture (Agricultural) Drought" (Tsakiris, 2017).

2.7.1 Meteorological Drought

Meteorological drought occurs from weeks to years due to a prolonged deficit in precipitation over a certain area. Meteorological drought is in many instances accompanied by utmost temperatures that cause other droughts types. This type of drought results from tenacious anomalous wide-ranging atmospheric circulation patterns mainly caused by abnormal tropical sea surface temperatures (Tsakiris, 2017). Thus, the current study prefers the adoption of meteorological drought.

2.7.2 Soil Moisture (Agricultural) drought

Soil Moisture (agricultural) drought occurs when crops become affected and cannot access the water, they need to grow due to the reduction of soil moisture that results from less precipitation and increased evaporation (Tsakiris, 2017). Soil moisture drought often affects crop yields and livestock, native biodiversity, and water suppliers.

2.7.3 Hydrological Drought

Hydrological drought refers to a deficiency of river stream-flow and groundwater levels, lakes, and reservoirs generally after the accuracy of hydrological drought. Hydrological drought occurs at a slow speed and is frequently unnoticed with indirect and various impacts on irrigation systems, water quality, hydropower, and cooling water, waterborne transportation, among others (Van Loon, 2015).

2.7.4 Socioeconomic Drought

Socioeconomic Drought happens when supply does not meet demands for economic goods due to a shortfall in the water supply. Socioeconomic drought mainly occurs when a shortage of water starts to affect people in many ways such as food shortages, social warfare reduction, human mortality diseases, epidemics, emigration; it can also cause non-market impacts such as the impaired environment (Brázdil *et al*, 2018).

2.7.5 Relationship between Four Types of Droughts

Figure 4 indicates succession of impacts and occurrence of droughts. According to Van Loon *et al.*, (2016a, and b) droughty events results from "complex interactions between meteorological anomalies, land surface processes, and human inflows, outflows, and water storage changes".

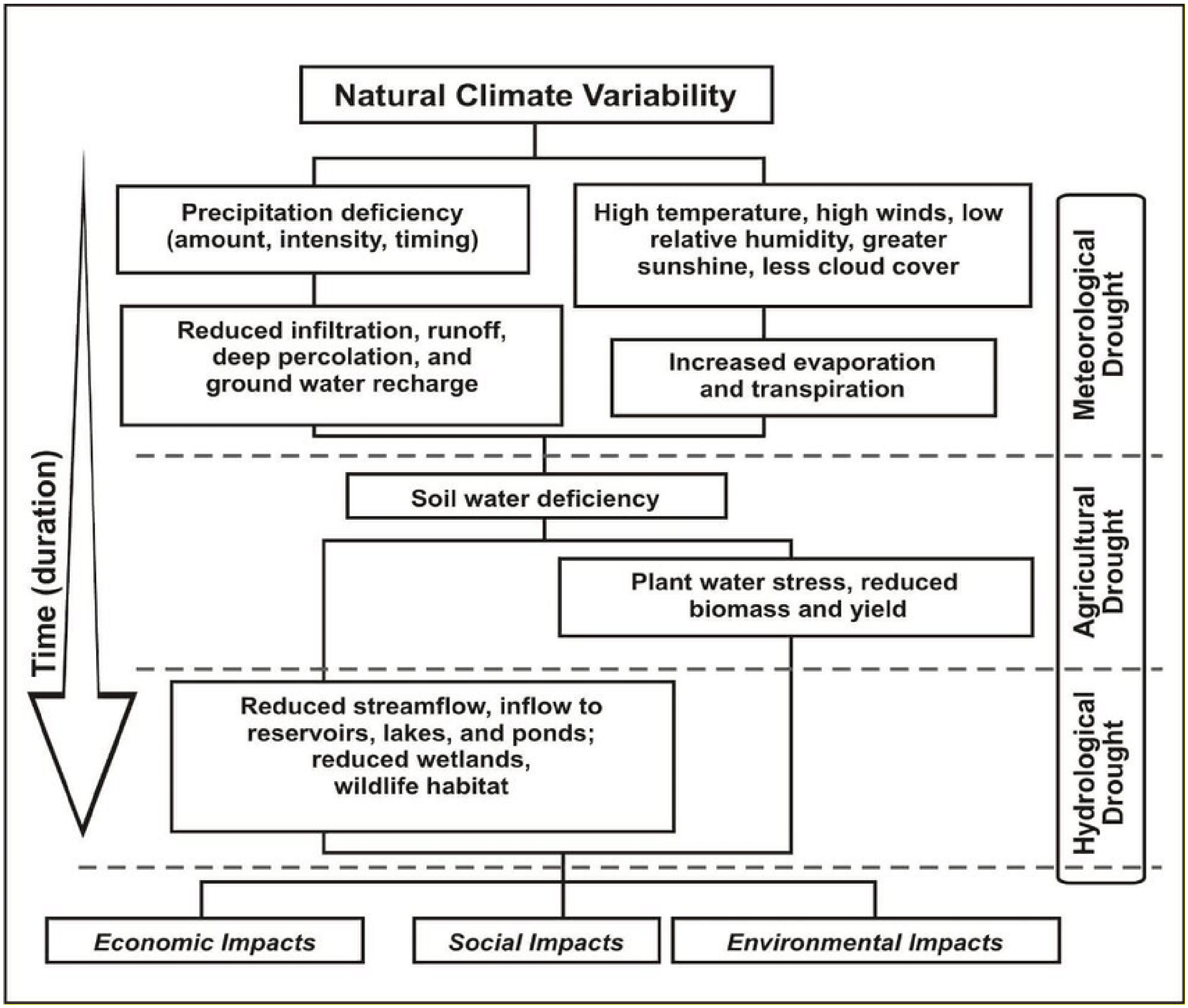

Figure 4: A succession of drought occurrence and their impacts (Brázdil, et al., 2018)

2.8 Drought Indicators

Drought indicators are very often designed to quantify, monitor, and analyze droughts in a given area; they are mainly presented in the form of standardized indices for droughts forecasting, water management, climate change studies, modeling droughts impacts, and droughts risk assessment (Beguería *et al*., 2014). According to McKee (1993), SPI is a widely and flexible index for drought which takes into account precipitation parameters to quantify meteorological drought on a span of timescales. Further, the SPEI (The Standardized Precipitation Evapotranspiration Index) is another indicator that was developed by Vicent-Serrano in 2010 as an extension of SPI designed to analyze meteorological drought, SPEI account for precipitation and Potential Evapotranspiration.

The third indicator is known as the "Palmer Drought Severity Index" (Palmer, 1965). The indicator uses precipitation and temperature datasets to characterize the dryness of a certain region. Flow Percentiles are Hydrological indicators designed to monitor daily flows of rivers shortfall, stream flows deficit (Cammalleri *et al*., 2017). Finally, the Normalized-Difference vegetation index (NDVI) uses remote sensing measurements to quantify drought impact on the vegetation cover.

2.9 The SPI

Several studies have used SPI for instantaneously analyzing droughts impacts, to monitor characteristics of meteorological drought in different parts of the world, to express Spatio-temporal analysis and climate impact studies, and examining groundwater (Shahid *et al.*, 2010). SPI uses Gamma distribution as a widely fitting model for analyzing rainfall data (Alvarez *et al*., 2011). Loukas (2004) used SPI to assess Spatio-temporal events of meteorological droughts in the Thessaly region, Greece. Palchaudhuri and Biswas (2013) used SPI (multi-temporal) to analyze meteorological drought in Puruliya District, the western part of Bengal, India. SPI was used to provide useful information in the Hirfanli Dam Basin to assess the spatiotemporal characteristics of droughts, one of the major water resources in Turkey and more exposed to droughts (Shiau, 2020). The table 1 indicates classes of SPI values to be used in the study (Karavitis *et al*., 2011).

Table 1: Classification of SPI Values

Drought Classes	**SPI values**
Extreme Drought	≤ -2.00
Severe Drought	[(-1.5) -(-1.99)]
Moderate Drought	[(-1.0) -(-1.49)]
Mild Drought	[(0.00) -(-0.99)]
No drought	>0.00

2.10 CORDEX Simulations

CORDEX (The Coordinated Regional Downscaling Experiment) is a program introduced by WCRP (World Climate Research) aimed to generate advanced regionally based-scale for climatic projections through global partnership (Giorgi and Gutowski, 2015). In addition, CORDEX provides the potential for impact assessment, coordination of modeling activities within the regional climate modeling and adaptation studies in different regions (Jones *et al*. 2011). Generally, regional climate models help to study climate processes in detail. The Figure below provides the Africa-Domain of CORDEX models.

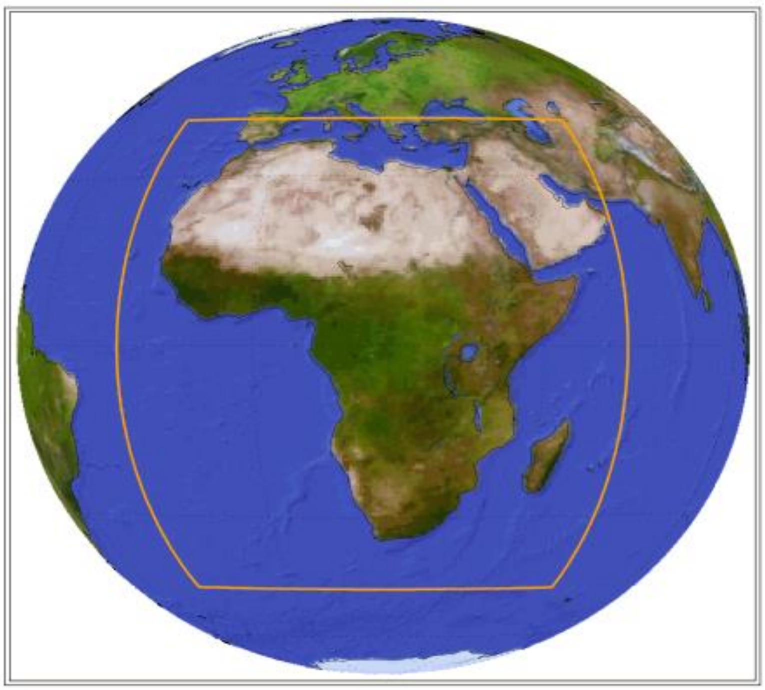

Figure 5: Africa-Domain of study under CORDEX Models (WCRP CORDEX,2015)

CHAPTER THREE: DATA AND METHODOLOGY

3.1 Introduction

The chapter is made up of the data collection procedures as well as the methodology that was used to analyze data so as to attain the objectives of this study are also presented. Various subsections regarding data and methodology are presented hereafter.

3.2 Data

This study used the 4km × 4km monthly gridded ENACTS rainfall data from 1981 to 2019 representing the Eastern province of Rwanda, and they were obtained from Meteo Rwanda for the periods, 1981-2019 and the 25 km x 25 km monthly CORDEX data from 2022-2099.

3.2.1 Observed Data

The current research used meteorological variables including monthly precipitation, for the baseline period 1981-2019 to calculate indices of drought. The SPI employs the precipitation datasets and is majorly suggested for meteorological droughts (Bagirov, *et al*, 2017). SPI assessed the spatial-temporal patterns of drought in the Eastern Rwandan Province for the period (1981-2019). Observational monthly gridded ENACTS rainfall data at a horizontal resolution of 5km × 5km for this study was obtained from Meteo Rwanda for the period, 1981-2019.

3.2.2. Climate Model Data

The CORDEX over Africa dataset was used in this study. The data used were in two categories: the historical dataset (1981-2019) that was validated against ground observations and the Future (2021-2100) scenarios dataset. They were downloaded from the ESGF portal. Further, the climate data was based on CORDEX model output. The CORDEX daily rainfall data for the Africa Domain (AFR-22) was extracted over Rwanda and aggregated to monthly for both the historical and future projections under this study. The CORDEX dataset had a spatial resolution of 25 km x 25 km from and the ENACTS had a spatial resolution of 4 km x 4 Km. Hence, the ENACTS were re-gridded using inverse distance weight to 25 km x 25 km spatial resolution in order to use it for CORDEX model validation.

The CORDEX dataset is suitable and was employed to assess future and past drought events in the Eastern Province by using selected regional climate modeling (RCMs) simulations with a high spatial resolution at 25 km (0.22°) (Ahmadi *et al.*, 2020). A simulation set is available in each CORDEX domain depending on the study area. During this study, the AFR-22 Domain dataset was selected and this dataset has 4 GCMs namely: MOHC-HadGEM2-ES, MPI-M-MPI-ESM-LR, NCC-NorESM1-M, and ECMWF-ERAINT with 3 RCMs namely: REMO2015, CCLM5-0-15, and ICTP-RegCM4-7 on each GCM.

3.3 Methodology

This section presents the methodology used in this study to attain its objectives. The SPI was utilized to indicate characteristics as well as to quantify the historical meteorological droughts over Eastern province of Rwanda.

3.3.1 The Spatial-Temporal Characteristics of Rainfall

The SPI was computed by employing gamma distribution fitting to past data based on chosen period, (1981-2020). It was computed by fitting a gamma distribution function on the frequency distribution of the monthly precipitation totals for the Eastern province of Rwanda for 3 months (3months SPI) and 12 months (SPI-12). This helped in showing the ensemble members' distribution on how patterns of meteorological droughts are likely to change in the future. The gamma distribution was consequently, transformed to a normal fitting on a single variance and a mean of zero (Shiau, 2020). The precipitation amounts were summed up over an accumulation period of monthly and were then normalized to the standard normal distribution.

The study used observed rainfall from specified stations to examine the SPI time series and identified drought from 1981-2020. The projected rainfall that was generated was thus assessed for drought characteristics through SPI. Therefore, to obtain values of SPI, the function was standardized and normalized.

In the current study, the SPI calculation begun with modeling of the monthly precipitation time series by use of different statistical distributions (Lloyd-Hughes and Saunders, 2002). Gamma distribution was used in the current study. The SPI was calculated based on monthly data for given periods.

3.3.2 The Past Drought Characteristics in terms of Duration, Severity, Frequency

In the current study, the variability of SPI indices as indicator of droughts in the Eastern province of Rwanda was computed. To compare patterns of interannual and seasonal SPI changes, the datasets (1981-2019) was used. The past drought Frequency were computed as number of each drought category over total years from baseline period (1981-2019).

The SPI calculation was anchored on long-term precipitation over a given duration. The computation of SPI values included the calculation of the cumulative gamma distribution. The SPI is computed by dividing the variation between normalized seasonal precipitation and long-term seasonal average by standardized deviation.

Thus,

SPI $= (Xij - Xim)/\sigma$ *Equation (1)*

Xij indicates the precipitation (seasonal) at ith rainfall gauge station and jth observation. While, Xim symbolizes long-term seasonal average and σ is standardized deviation.

3.3.3 The Future Characteristics of Drought under Changing Climate

This objective assessed the major areas in Eastern Province of Rwanda that are drought-prone. The research used the CORDEX-Africa-0.22° output that consisted of rainfall time series at various spatial, climatic conditions, and time resolutions. Individual model simulations from the CORDEX datasets was analyzed based on the period of 2022-2099 for each 26-year period. The simulation's capability to reproduce the rainfall over the Eastern province was evaluated. The future changes in SPI drought characteristics over Eastern province was compared with past drought characteristics to understand the behavior of future drought with reference to these in past.

The CORDEX over Africa dataset was used in this study where the daily-simulated data was aggregated to monthly rainfall from 2022 to 2099 using low emission representative pathway of RCP2.6 and extreme RCP8.5 were considered (Van Vuuren *et al*., 2011). Study used the monthly data to calculate SPI for the future and comparison of how CORDEX performs over the eastern province of Rwanda was performed in terms of drought duration, severity and frequency.

3.3.4. Analysis of the skill of the CORDEX model

Precipitation patterns over Eastern Province of Rwanda are complex. Therefore, a good grasp of spatio-temporal variability of rainfall can be achieved by running climatic models. Model validation are required to obtain climatic projections confidence that analyses global climatic changes affecting precipitation as well as impacts associated with it (Van Vooren *et al.* 2018). In this study, model projection from the CORDEX is evaluated for Eastern Province of Rwanda against observational data sets (ENACTS) from 1981 to 2005. The statistical methods used to validate models, include Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Mean Error (ME), and Correlation coefficient (r), as indicated below:

$$\boldsymbol{r} = \frac{\sum(\boldsymbol{P_i}-\bar{\boldsymbol{P}})(\boldsymbol{O_i}-\bar{\boldsymbol{O}})}{\sqrt{\sum(\boldsymbol{P_i}-\bar{\boldsymbol{P}})^2\sum(\boldsymbol{O_i}-\bar{\boldsymbol{O}})^2}} \qquad \textit{Equation (2)}$$

$$\mathbf{RMSE} = \frac{\sqrt{\sum_{i=1}^{n}(P_i-O_i)^2}}{n} \qquad \textit{Equation (3)}$$

$$\mathbf{MAE} = \frac{\sum_{i=1}^{n}[P_i-O_i]}{n} \qquad \textit{Equation (4)}$$

$$\mathbf{ME} = \frac{\sum_{i=i}^{n}(P_i-O_i)}{n} \qquad \textit{Equation (5)}$$

Where P_i denotes the predicted from monthly data of CORDEX models and O_i denotes the monthly observed data from ENACTS.

3.3.5 Conceptual Framework

The prolonged increasing change in rainfall, temperature, draught, floods, and extreme events are influenced by climate change. ENACTS rainfall and temperature products are important in analysis of Droughts. ENACTS datasets help to obtain reliable droughts information for decision making. To manage these risks, adaptation policies on different levels can look at the strategies which can help farmers and all other exposed people to cope with droughts impacts.

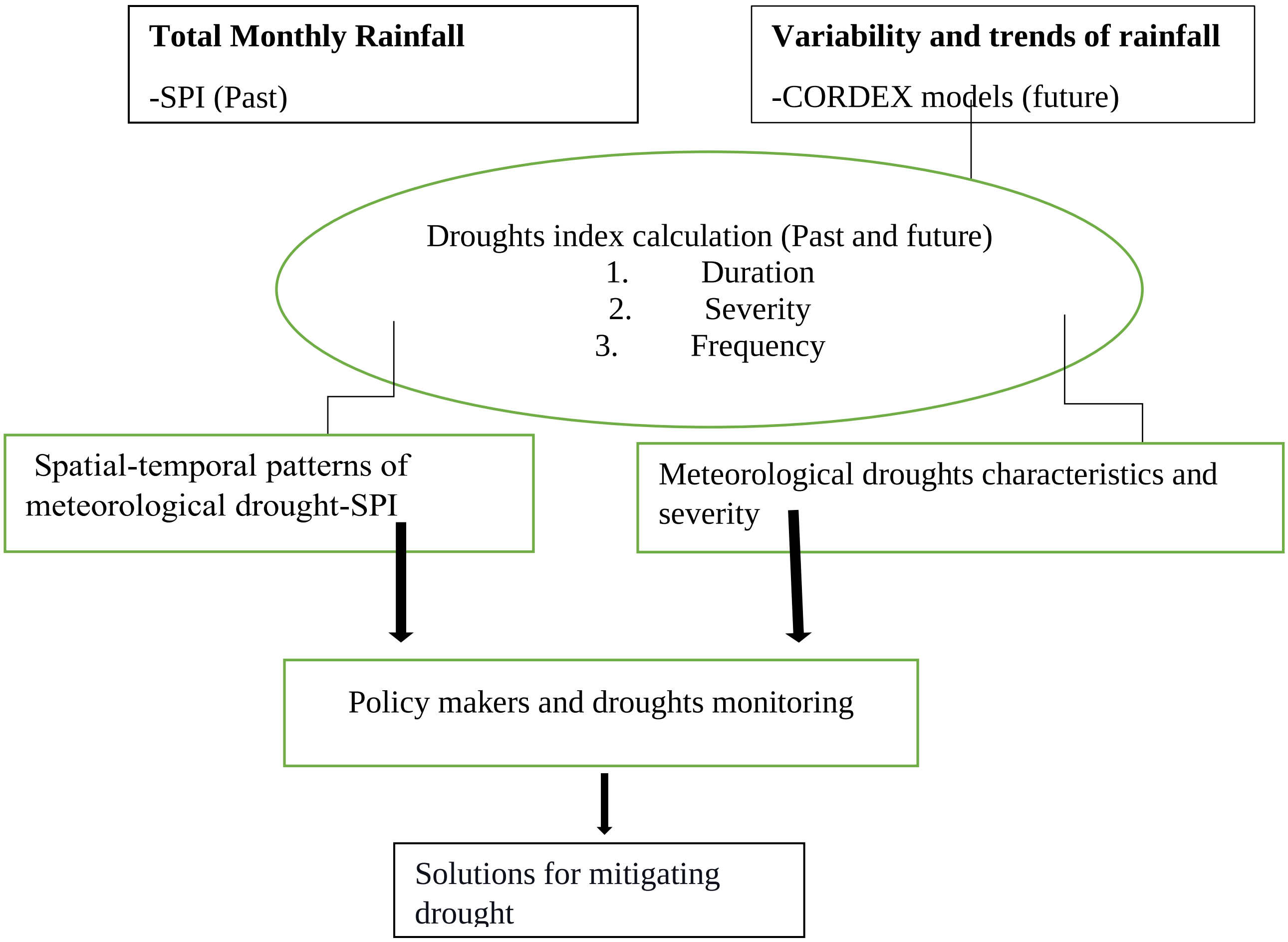

Figure 6: Conceptual Framework

3.4 SPI Algorithm Application

SPI was calculated using the monthly gridded ENACTS rainfall data from 1981 to 2020 representing the eastern province as its input. Precipitation deficit depends on regional characteristics is described by indices quantified by time scales of 1, 3, 6, 12, 24 and 48 monthly variables. Every data set was fitted to gamma probability density time series function of precipitation using scale parameter of β and shape parameter of α to describe relationship between probability and precipitation.

The density functional probability is calculated as follows:

$$g(x, \alpha, \beta) = \frac{1}{\beta^{\alpha}\tau(x)} x^{\alpha-1} e^{\frac{-x}{\beta}} \qquad \textit{Equation } \textbf{(6)}$$

When x ≥ 0, otherwise g(x) =0

Where, β and α assure β >0, α >0

$\alpha > 0$ indicates shape parameter;

$\beta > 0$ symbolizes scale parameter;

$x > 0$ indicates precipitation amount;

$\Gamma(\alpha)$ symbolizes function of gamma.

Therefore, when $\alpha > 0$, the gamma function $\Gamma(\alpha)$ is described as follows:

$$\boldsymbol{\Gamma}(\alpha) = \int_{\mathbf{0}}^{\infty} \boldsymbol{y^{\alpha-1} e^{-y} dy} \qquad \textit{Equation } \mathbf{(7)}$$

Parameters β and α are necessarily needed to set gamma distribution to dataset for being optimally estimated.

$$\alpha = \frac{1}{4A}\left[1 + \sqrt{1 + \frac{4A}{3}}\right] \qquad \textit{Equation } \mathbf{(8)}$$

$$\beta = \frac{X}{\alpha} \qquad \textit{Equation } \mathbf{(9)}$$

For n observation;

$$\mathbf{A=ln}(\boldsymbol{\overline{x}})\text{-}\frac{\sum \boldsymbol{ln(x)}}{\boldsymbol{n}} \qquad \textit{Equation } \mathbf{(10)}$$

The distribution function of the cumulative probability G(x) is provided using incorporated probability density function attached to α and β parameters and with respect to x.

$$\boldsymbol{G(x) = \int_0^x g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{\frac{-x}{\beta}}}\mathbf{dx} \qquad \textit{Equation } \mathbf{(11)}$$

Since gamma function is not defined for x=0 and q= p (x=0)> 0.

P (x=0) is the null precipitation probability

Hence, cumulative probability is indicated as:

$$\mathbf{H(x) = q + (1-q)\, G(x)} \qquad \textit{Equation } \mathbf{(12)}$$

Therefore, cumulative probability distribution functions are transformed to standardized normal cumulative distribution so that they both possess similar probability.

SPI is computed by dividing the variation among the normal seasonal precipitation and the long-term seasonal mean by standard deviation.

Thus,

$$\mathbf{SPI} = (Xij - Xim)/\sigma \qquad \textit{Equation } \mathbf{(13)}$$

Thus, Xij indicates seasonal precipitations at the ith rain gauge station that is observed at the jth. While, Xim symbolizes a long-term seasonal mean and standardized deviation is σ.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.0 Introduction

The chapter provides findings from analysis for each specific objective. The discussions for the results of each objective are also presented in the section. The results are presented in table and figures as shown below.

4.1 The Spatial-Temporal Characteristics of Rainfall over the Eastern Province of Rwanda

This section presents the results and discussion of the spatial and temporal characteristics of rainfall based on the seven locations in the eastern province of Rwanda.

4.1.1 Temporal Characteristics of Rainfall over the Eastern Province of Rwanda

The temporal characteristics of rainfall based on the standardized precipitation index (SPI) over seven locations during the March-May, September – November, December – February and June – August season are presented below on Figure 7 to Figure 20.

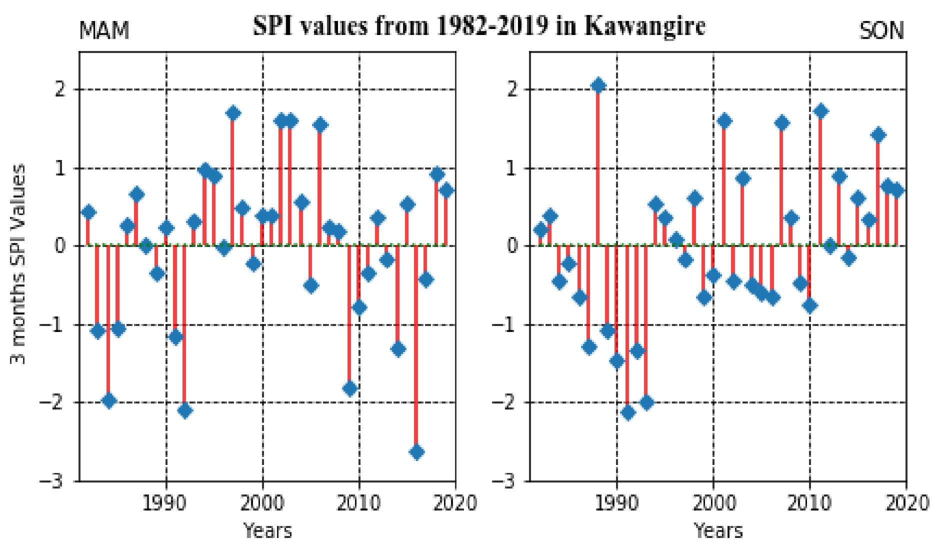

Figure 7: March - May and September - November seasonal SPI over Kawangire from 1982 – 2019

The Kawangire station exhibits drought events in the past from 1982 – 2019 during March- May and September – November seasons where extreme droughts are observed in 1992 and 2016 during MAM and 1991 during SON.

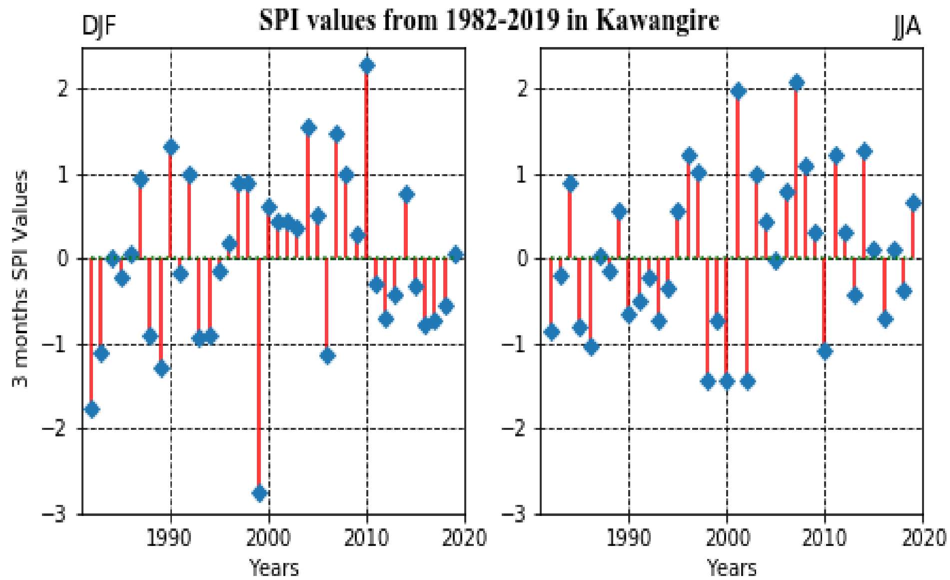

Figure 8: December - February and June - August Seasonal SPI Over Kawangire from 1982 - 2019

The Kawangire station exhibited drought events in the past from 1982 – 2019 during both the December - February and June – August seasons where extreme drought is observed in 1999 during DJF season.

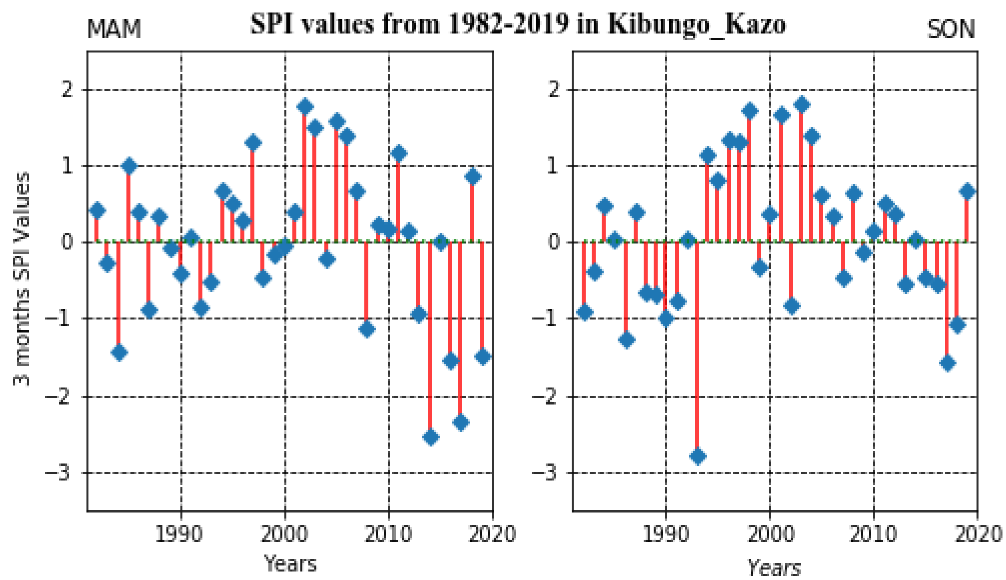

Figure 9: March - May and September - November Seasonal SPI Over Kibungo Kazo from 1982 – 2019

The Kibungo_Kazo station in Eastern Rwanda previously depicted droughts from 1982 to 2019. The most hit years were 2014 and 2017 for MAM and 1993 for SON seasons.

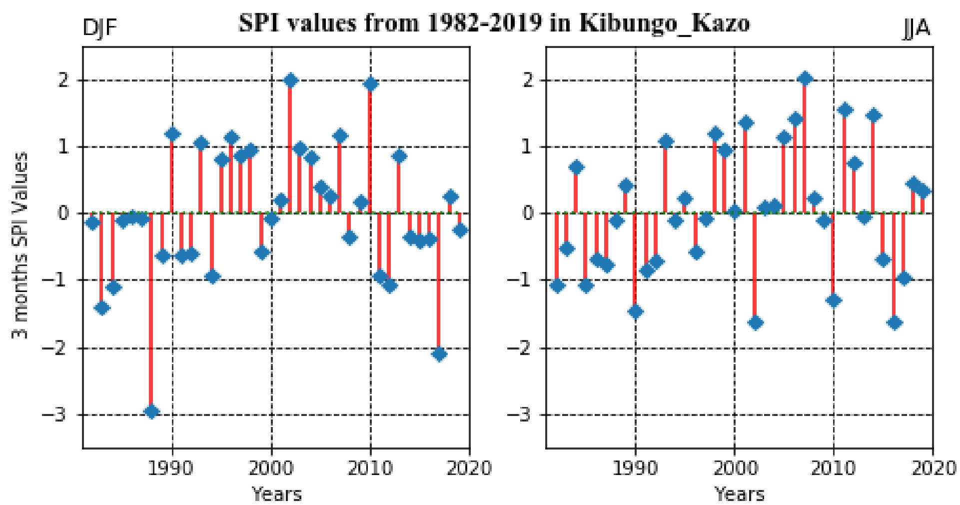

Figure 10: December - February and June - August seasonal SPI over Kibungo Kazo from 1982 – 2019

The results show that Kibungo_Kazo stations exhibited past droughts in some years from 1982 to 2019. Specifically, extreme drought was reported in 1988 followed by the year 2017 for DJF and severe drought during June - August seasons of 2002 and 2016.

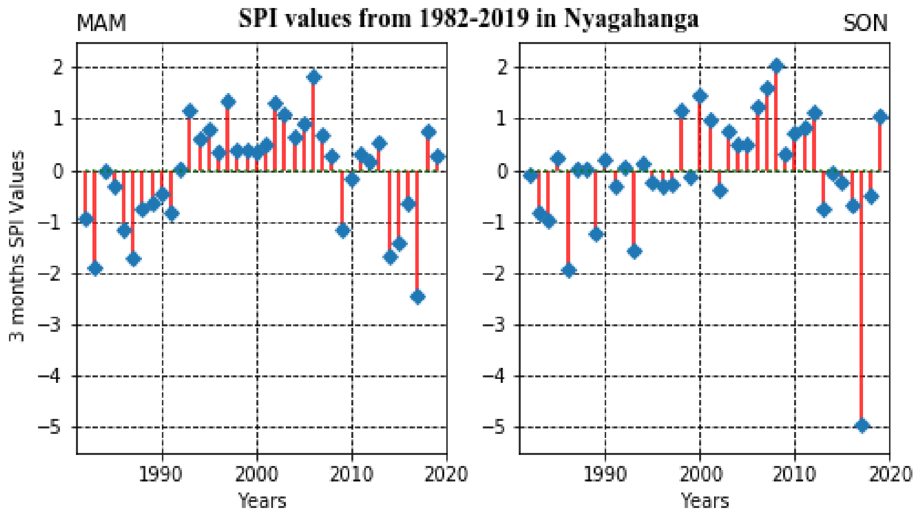

Figure 11: March - May and September - November seasonal SPI over Nyagahanga from 1982 – 2019

As indicated in figure 11, Nyagahanga station reported drought in 1982 to 2019 in March - May and September – November. Extreme drought was recorded during the year of 2017 for both SON and MAM.

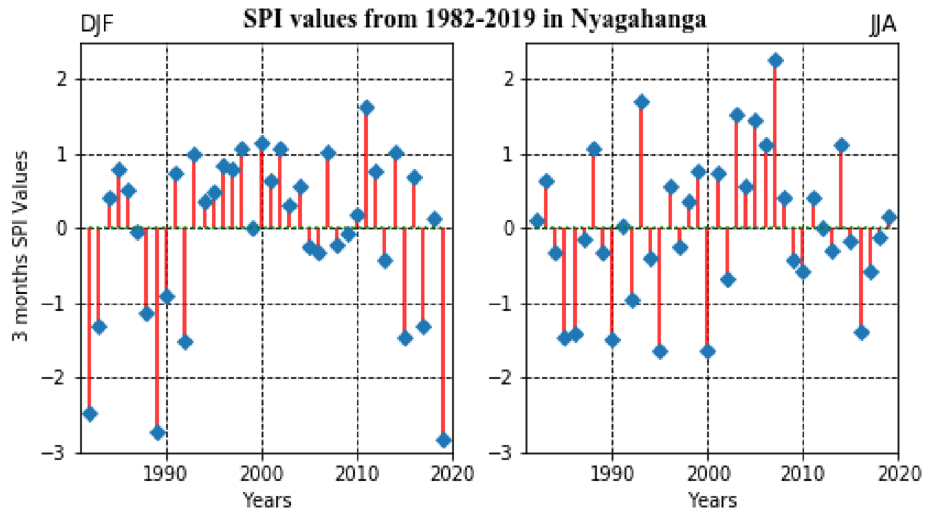

Figure 12: December - February and June - August seasonal SPI over Nyagahanga from 1982 - 2019

Again, Nyagahanga station depicted in 1982 to 2019 in the seasons of December - February and June – August. Particularly, 2019, 1989, and 1982 depicted the extreme droughts during DJF while the year 2000 was the worst during JJA.

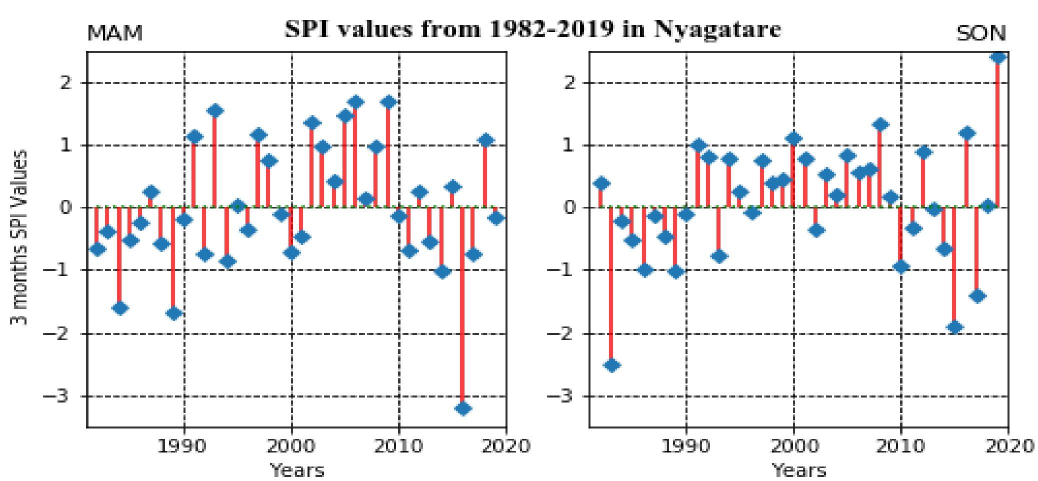

Figure 13: March - May and September - November seasonal SPI over Nyagatare from 1982 – 2019

The Figure 13 indicates that Nyagatare station experienced droughts from 1982 – 2019 during the seasons of March - May and September – November. However, 2016 was the worst extreme drought during MAM while 1983 was the worst extreme drought during SON.

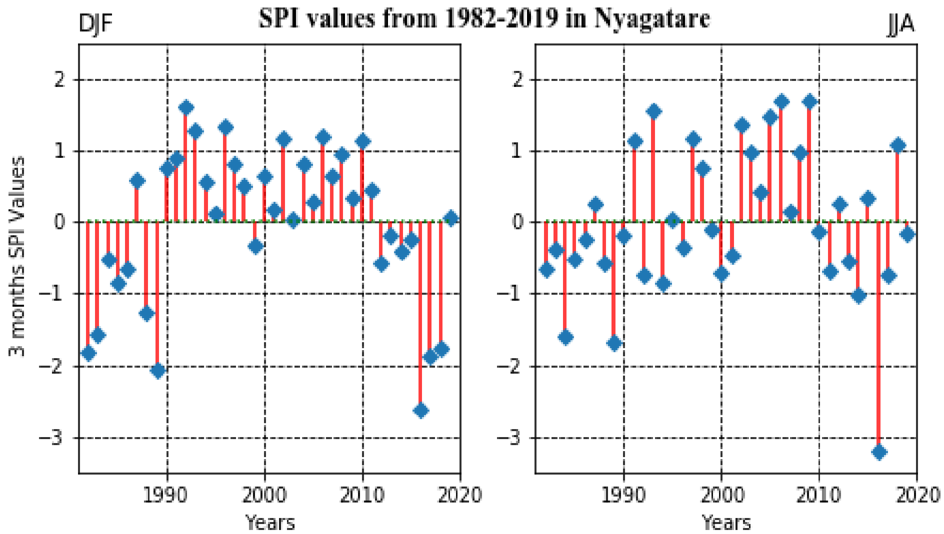

Figure 14: December - February and June - August seasonal SPI over Nyagatare from 1982 - 2019

Again, it was also revealed that Nyagatare station experienced droughts during December - February and June - August seasons. The extreme drought occurred during the year of 2016 for both DJF and JJA.

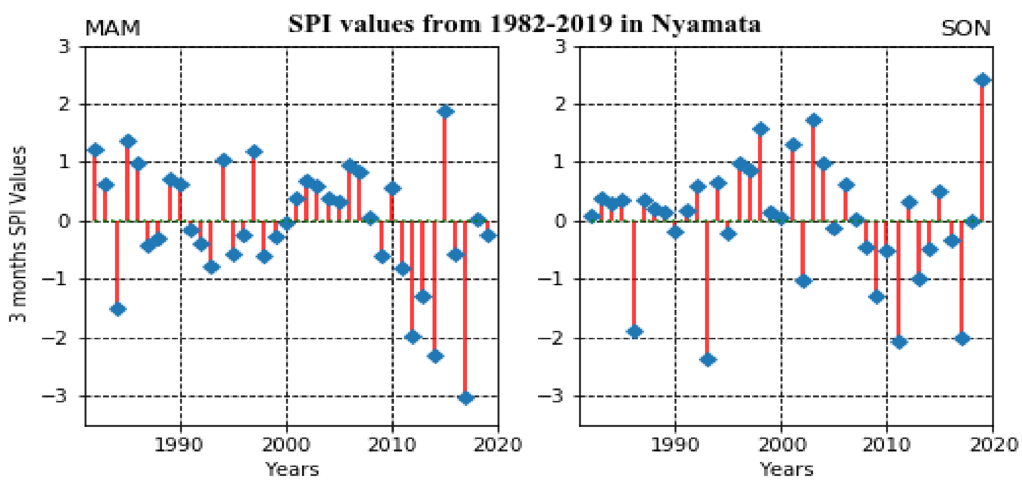

Figure 15: March - May and September - November seasonal SPI over Nyamata from 1982 - 2019

Nyamata station also exhibited drier seasons during March - May and September – November in the period from 1982 to 2019. The extreme drought affected years were 2012, 2014, 2017 and 1993 during MAM and SON respectively.

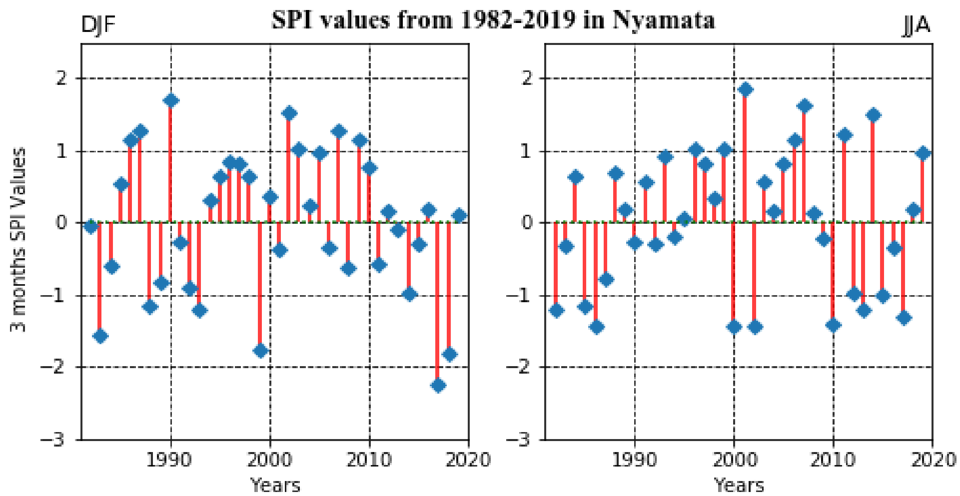

Figure 16: December - February and June - August seasonal SPI over Nyamata from 1982 – 2019

The study established that Nyamata station experienced past droughts in 1982 to 2019 during December - February and June – August seasons. The year 2017 experienced the extreme drought during DJF.

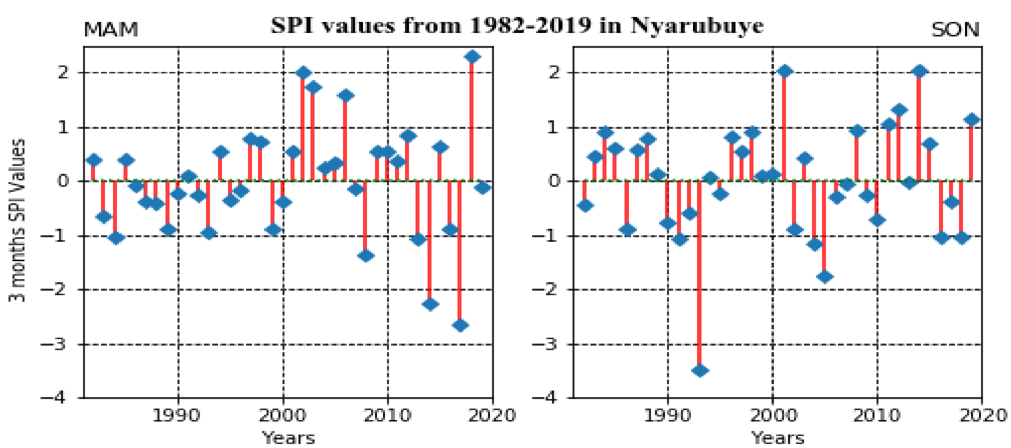

Figure 17: March - May and September - November seasonal SPI over Nyarubuye from 1982 – 2019

The results indicates that Nyarubuye station also exhibited drought from 1982 – 2019, especially from March - May and September – November. Extreme droughts were recorded in 2017 and 1993 in MAM and SON, respectively.

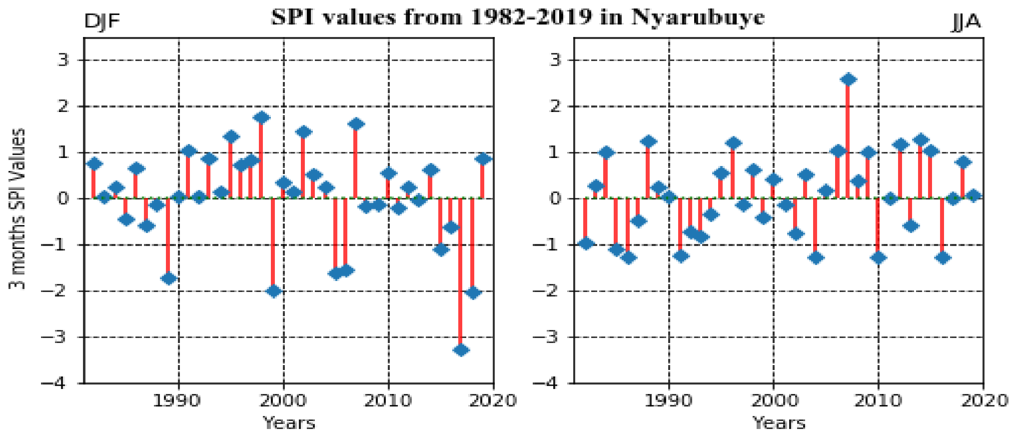

Figure 18: December - February and June - August seasonal SPI over Nyarubuye from 1982 – 2019

It was established that Nyarubuye station had past drought from 1982 – 2019 during December - February and June – August seasons. The year 2017 was characterized by the extreme drought during DJF season.

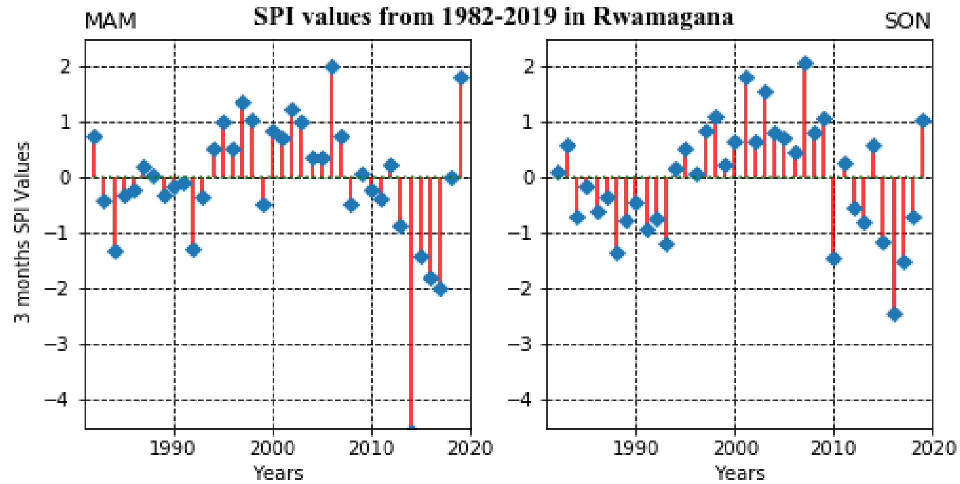

Figure 19: March - May and September - November seasonal SPI over Rwamagana from 1982 – 2019

Rwamagana station also experienced droughts from 1982 – 2019 during the seasons of March - May and September – November. The extreme drought was observed in 2014 for MAM and 2016 during SON.

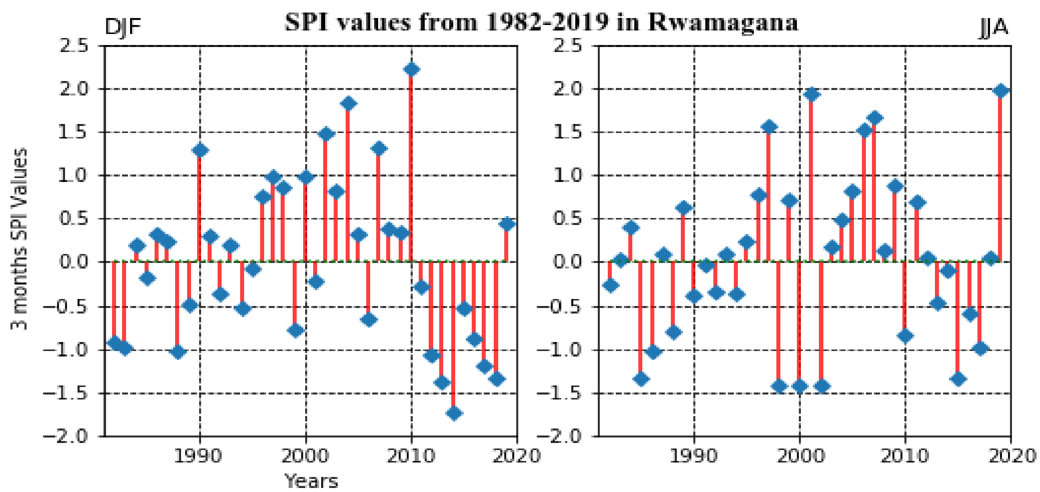

Figure 20: December - February and June - August seasonal SPI over Rwamagana from 1982 – 2019

Further, Rwamagana station depicted past droughts from 1982 – 2019. The specific season was December - February and June – August with the severe drought of 2014 during DJF.

4.1.2 Spatial Characteristics of Rainfall over the Eastern Province of Rwanda

The spatial variability of rainfall over the Eastern Rwanda based on the Standardized Precipitation Index (SPI) is presented below on Figure 20 to Figure 29 based on Annual (12-Months SPI) and seasonal timescale (3- Months SPI). The analysis is based on two sample years, which were selected based on two conditions: one condition being that of near recent years and the second one being drier years.

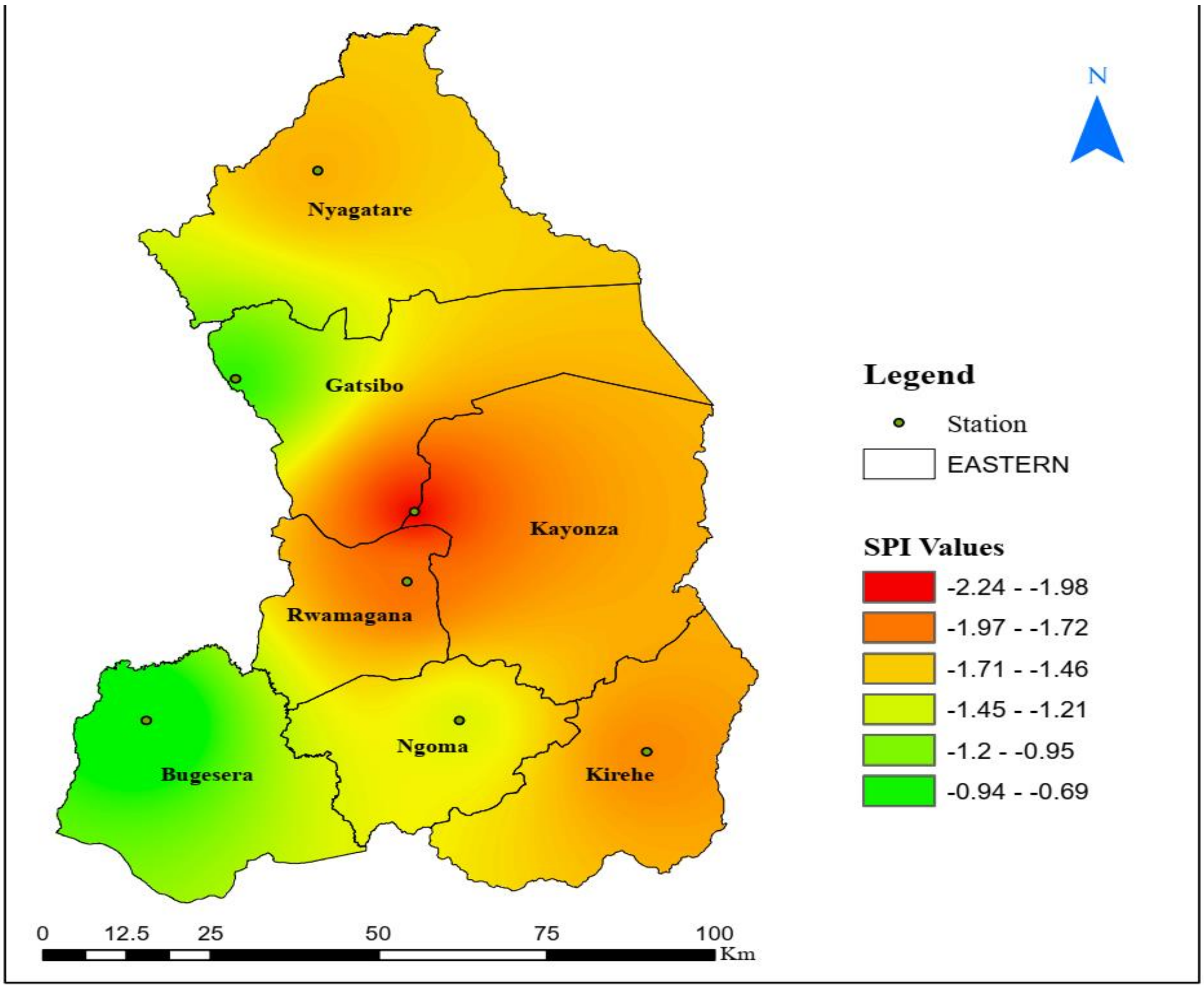

Figure 21: Standardized Precipitation Index for 2016 over Eastern Rwanda

The study used the year 2016 as a sample for the near recent years and the results for the SPI over the Eastern Rwanda based on annual past drought distribution is shown on figure 20. Results show that the borders of Gatsibo, Kayonza, and Rwamagana experienced extreme droughts in 2016.

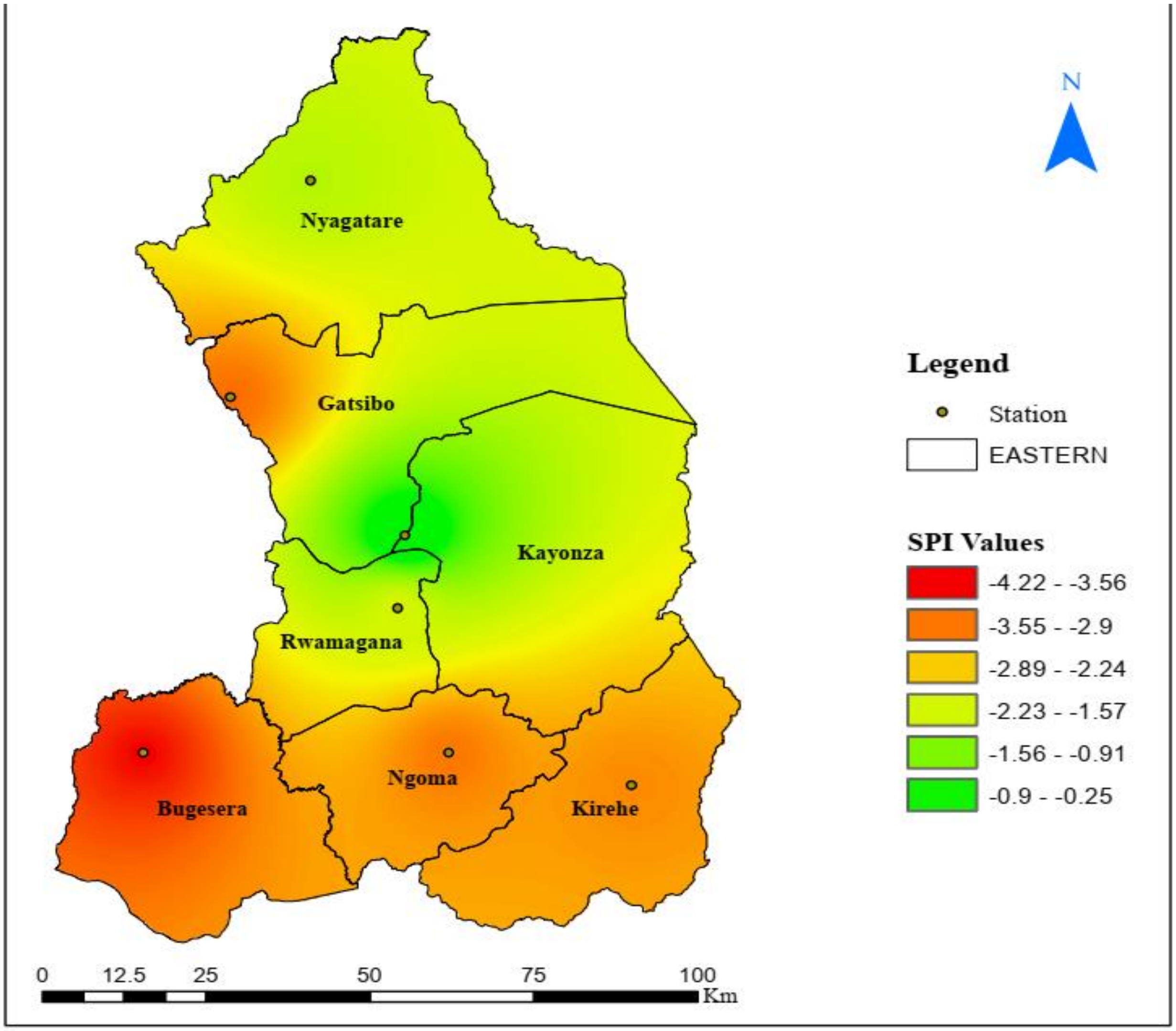

Figure 22: Standardized Precipitation Index for 2017 over Eastern Rwanda

The year 2017 was used as the year that was severely affected by droughts in Eastern Rwanda. The results in figure 21 indicate the SPI values showing the severity of the drought across various stations on annual basis. Bugesera experienced extreme droughts in 2017 as shown in figure 21. Also, parts of Ngoma, Kirehe, and Gatsibo also exhibited extreme to severe droughts in 2017.

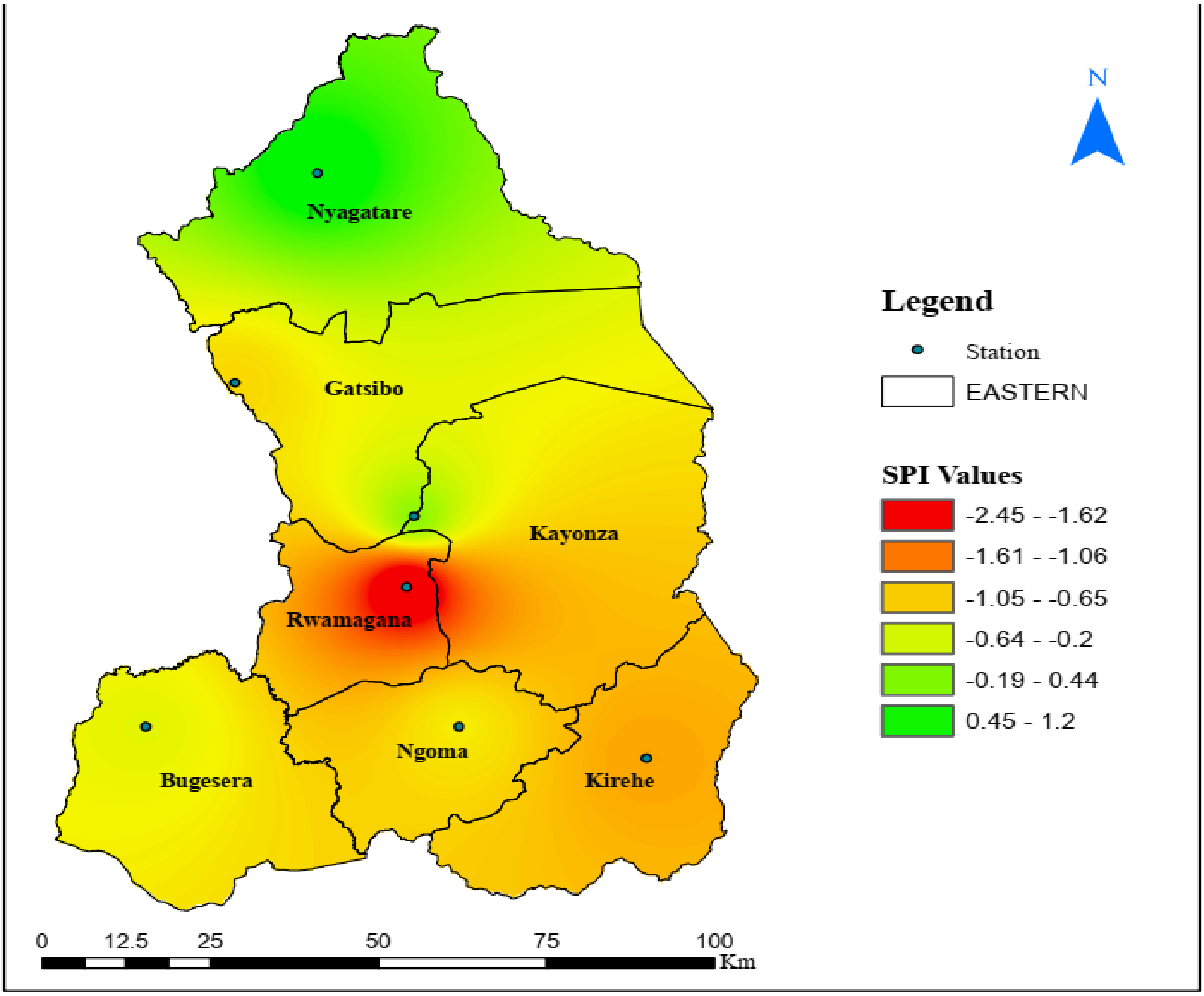

Figure 23: Standardized Precipitation Index for September - November 2016 season over Eastern Rwanda

The 3-month SPI results for SON over Eastern Rwanda for the 7 stations shows that Rwamagana station exhibited extreme droughts in 2016 during September – November seasons. Koyonza also experienced extreme droughts along its borders with Rwamagana.

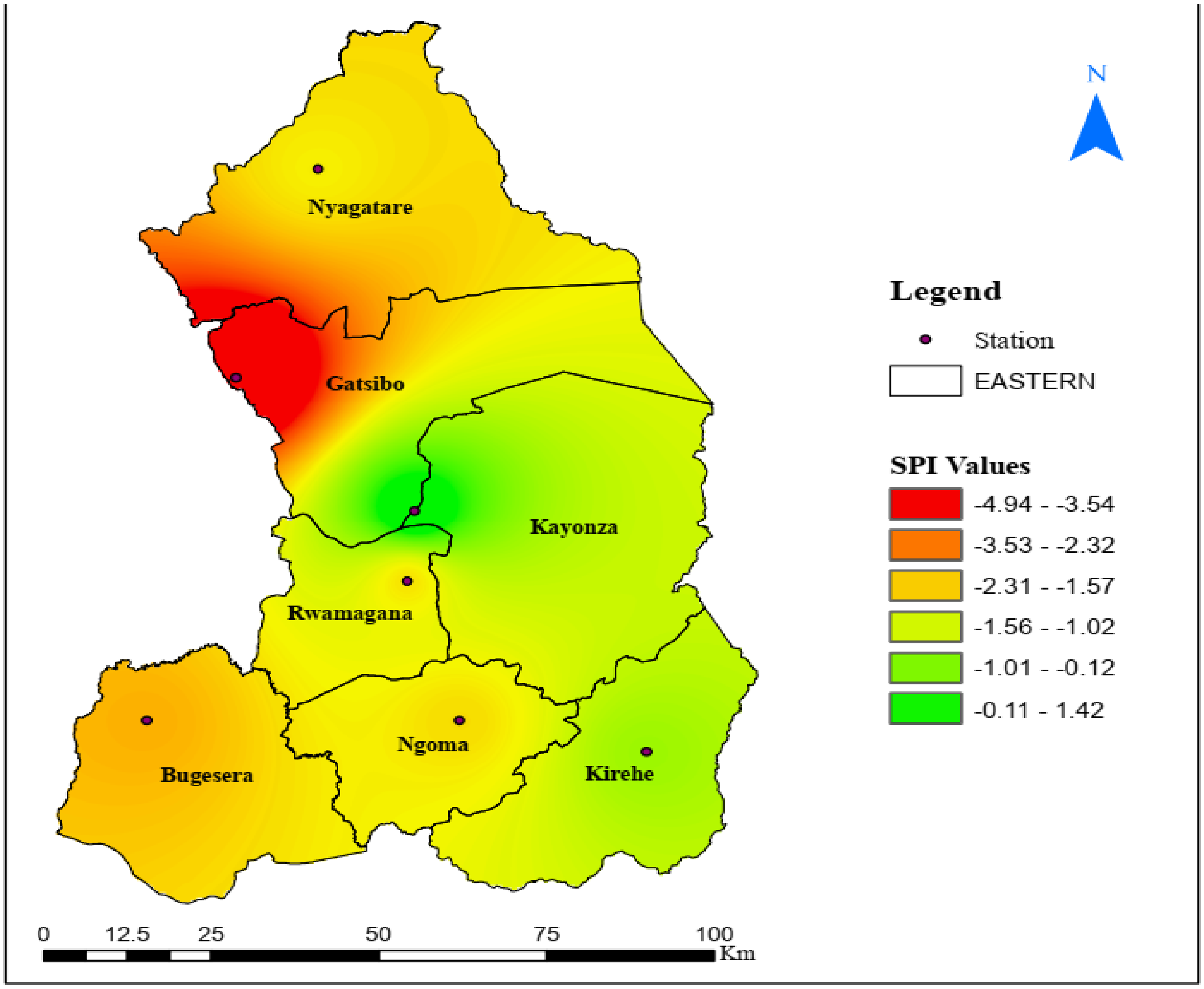

Figure 24: Standardized Precipitation Index for September - November 2017 Season Over Eastern Rwanda

The results in figure 23 shows the 3-month SPI over Eastern Rwanda. The droughts were extreme in Gatsibo and Nyagatare but with severe concentration along the borders of the two stations during the September – November seasons.

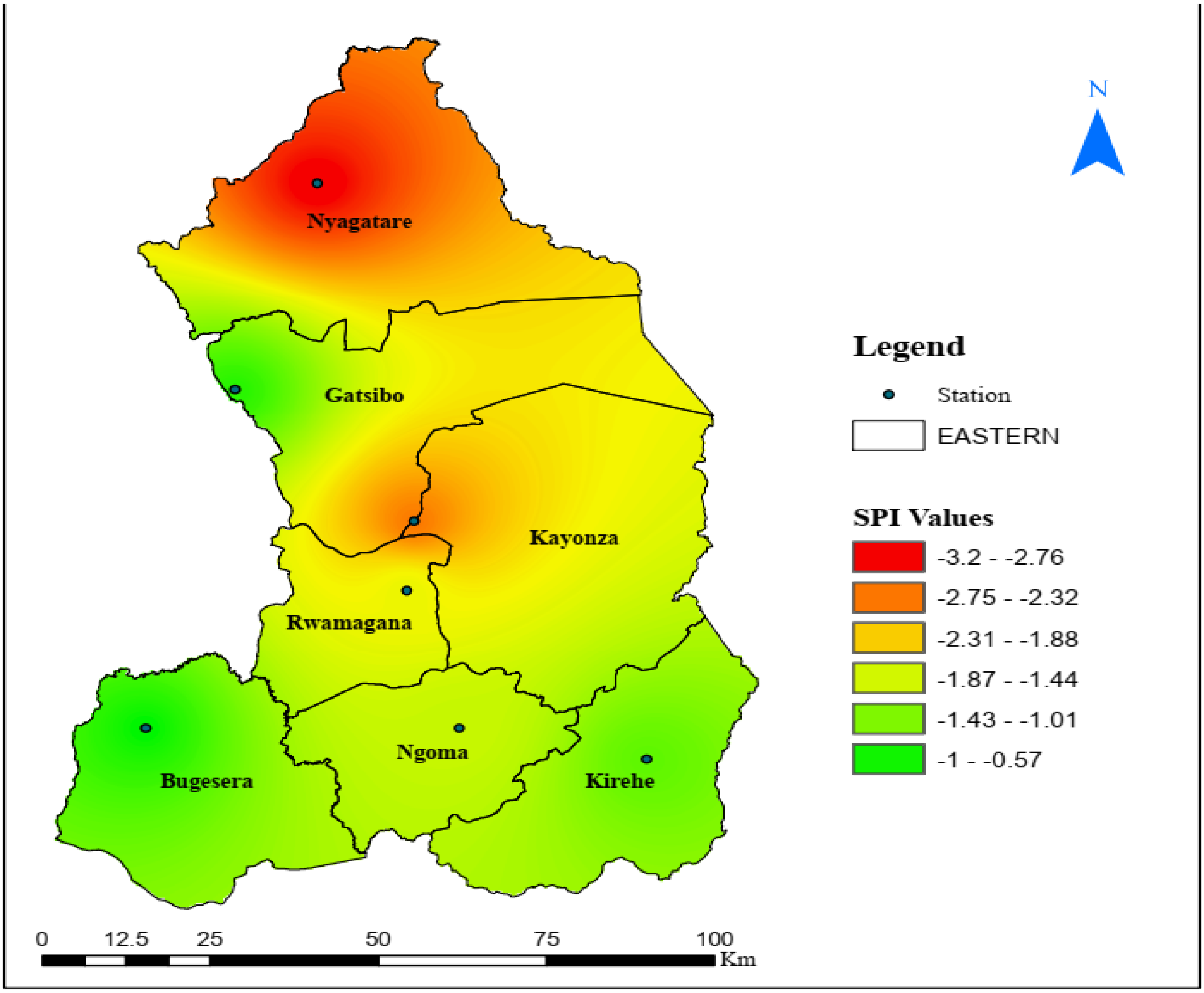

Figure 25: Standardized Precipitation Index for March - May 2016 Season Over Eastern Rwanda

As presented in figure 24, the 3-month SPI for MAM in 2016 showed that extreme drought was witnessed in Nyagatare during March – May seasons over the Eastern Rwanda.

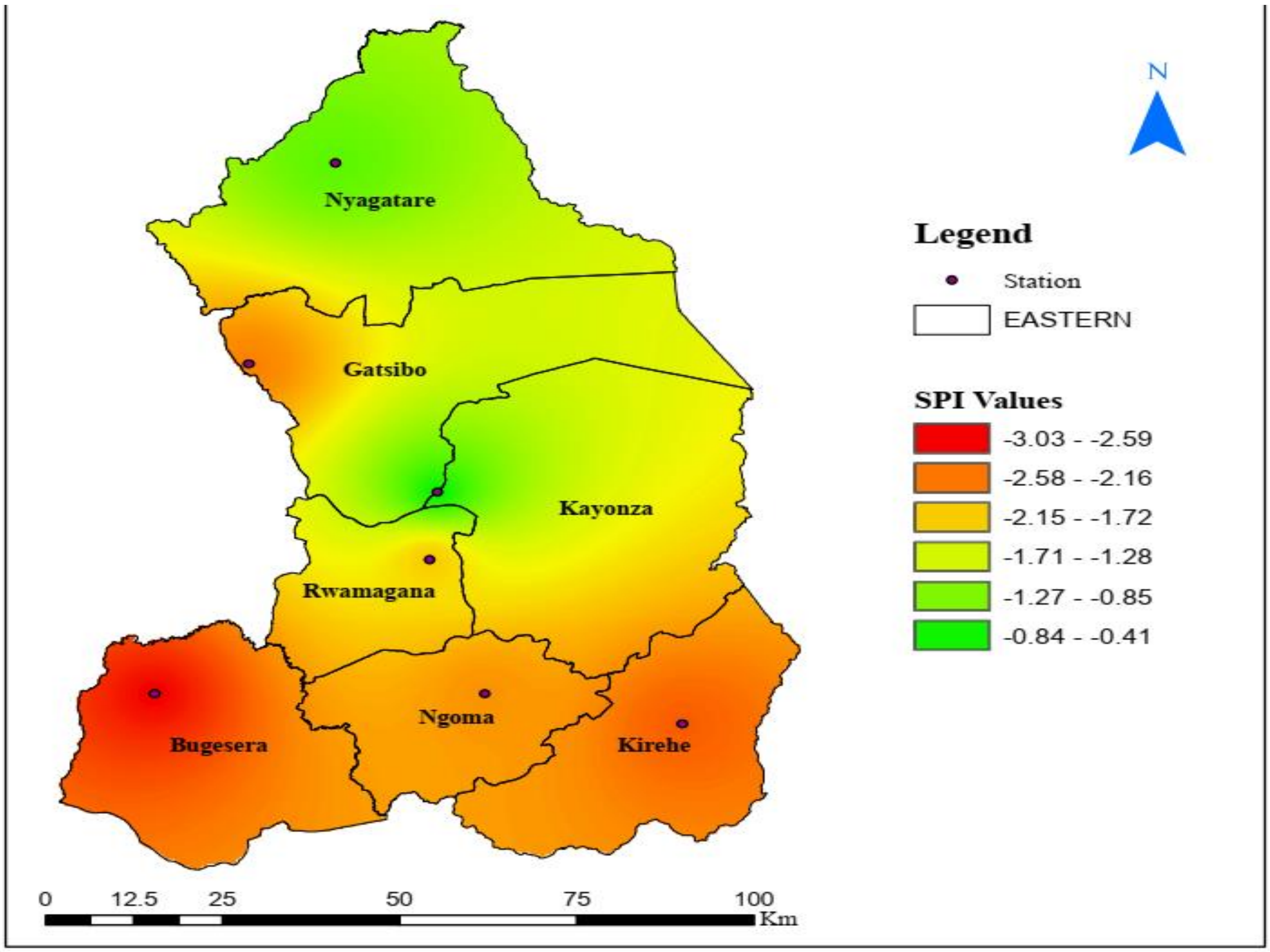

Figure 26: Standardized Precipitation Index for March - May 2017 Season Over Eastern Rwanda

The results for 3-month SPI for MAM for 2017 over the Eastern Rwanda shows that small part of Bugesera and Kirehewas worst hit with extreme drought, especially during the March - May 2017 season.

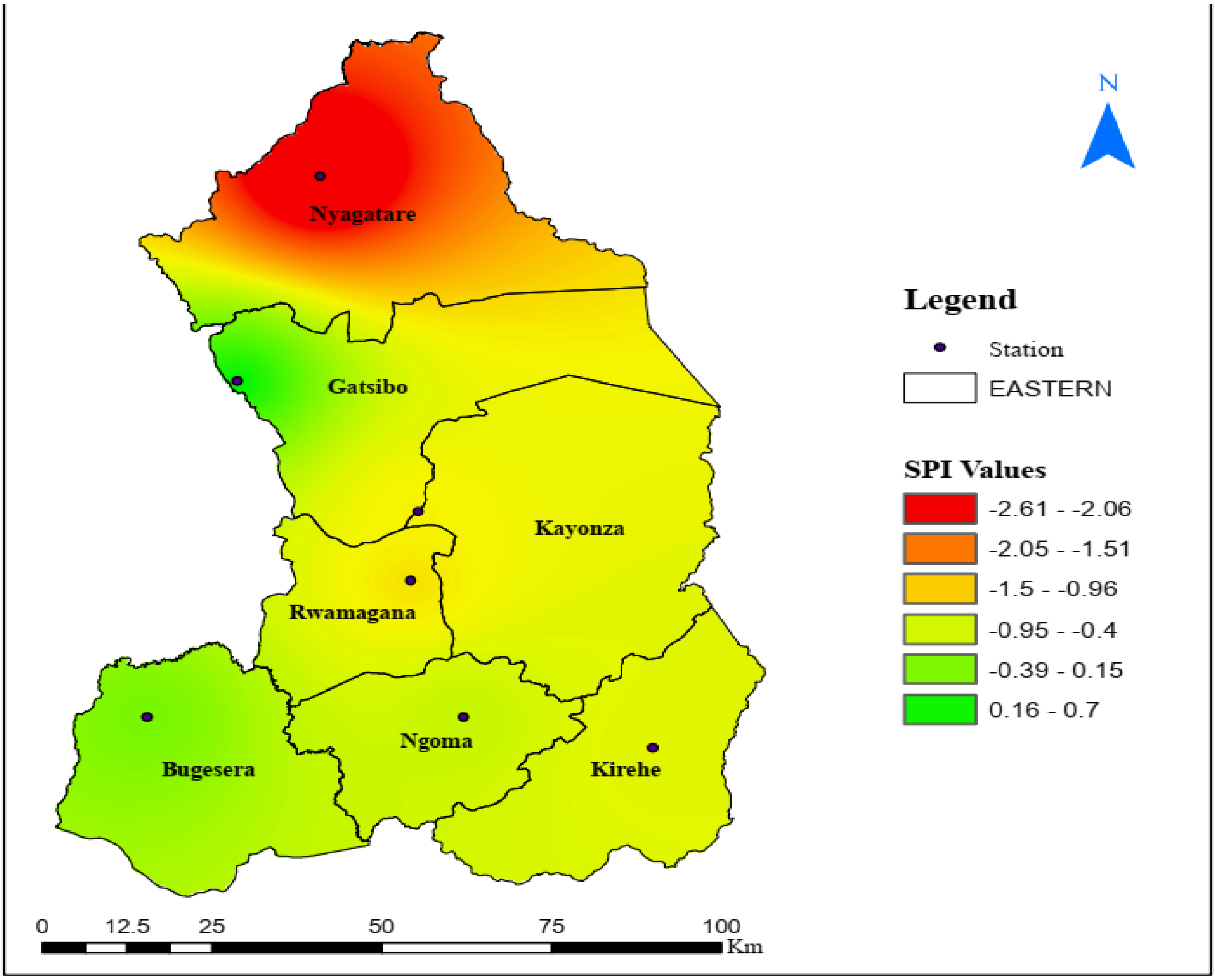

Figure 27: Standardized Precipitation Index for December - February 2016 Season Over Eastern Rwanda

Further, the 3-month SPI for DJF over Eastern Rwanda indicate that sections of Nyagatare was the worst hit with extreme droughts as opposed to its borders with Gatsibo and other stations during December - February 2016 season.

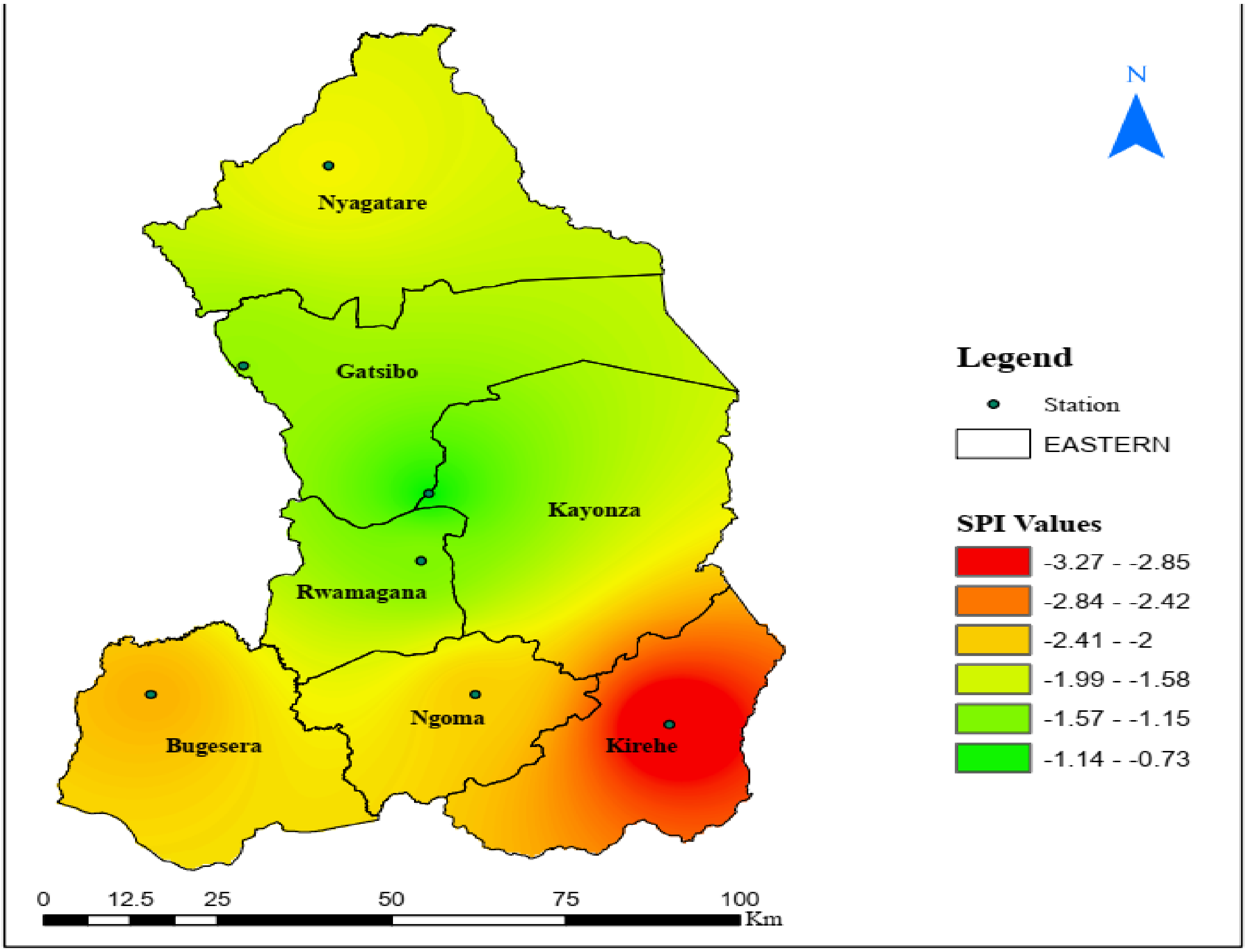

Figure 28: Standardized Precipitation Index for December - February 2017 season over Eastern Rwanda

The 3-month SPI for DJF for 2017 over the Eastern Rwanda indicate the severity of droughts in the seven stations. The drought was spread across the seven stations with extreme droughts exhibited in Kirehe during the December - February 2017 season.

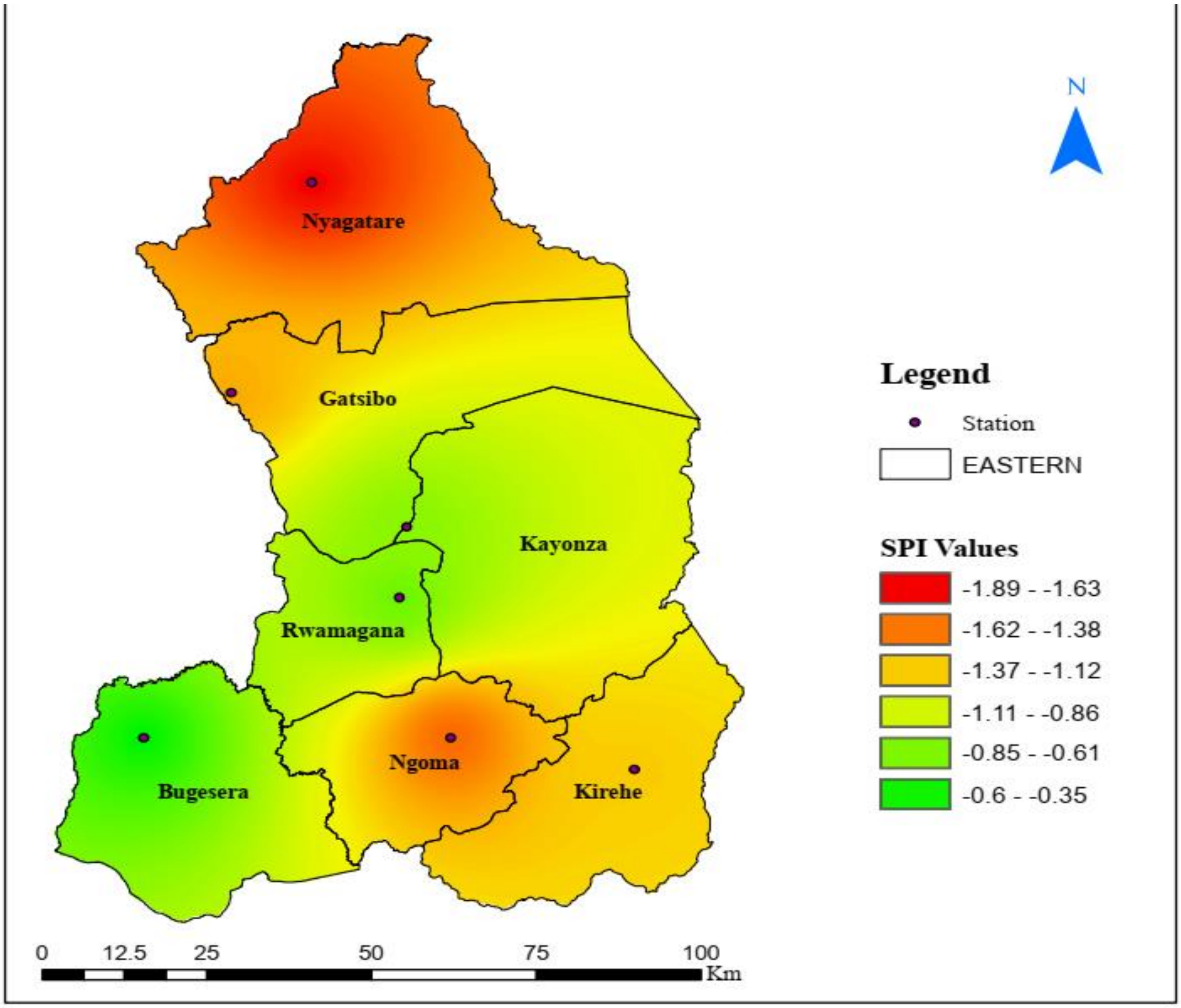

Figure 29: Standardized Precipitation Index for June - August 2016 Season Over Eastern Rwanda

The results presented in figure 28 shows the 3-month SPI for JJA over Eastern Rwanda in 2016. It shows that Nyagatare station experienced severe drought June - August 2016 seasons.

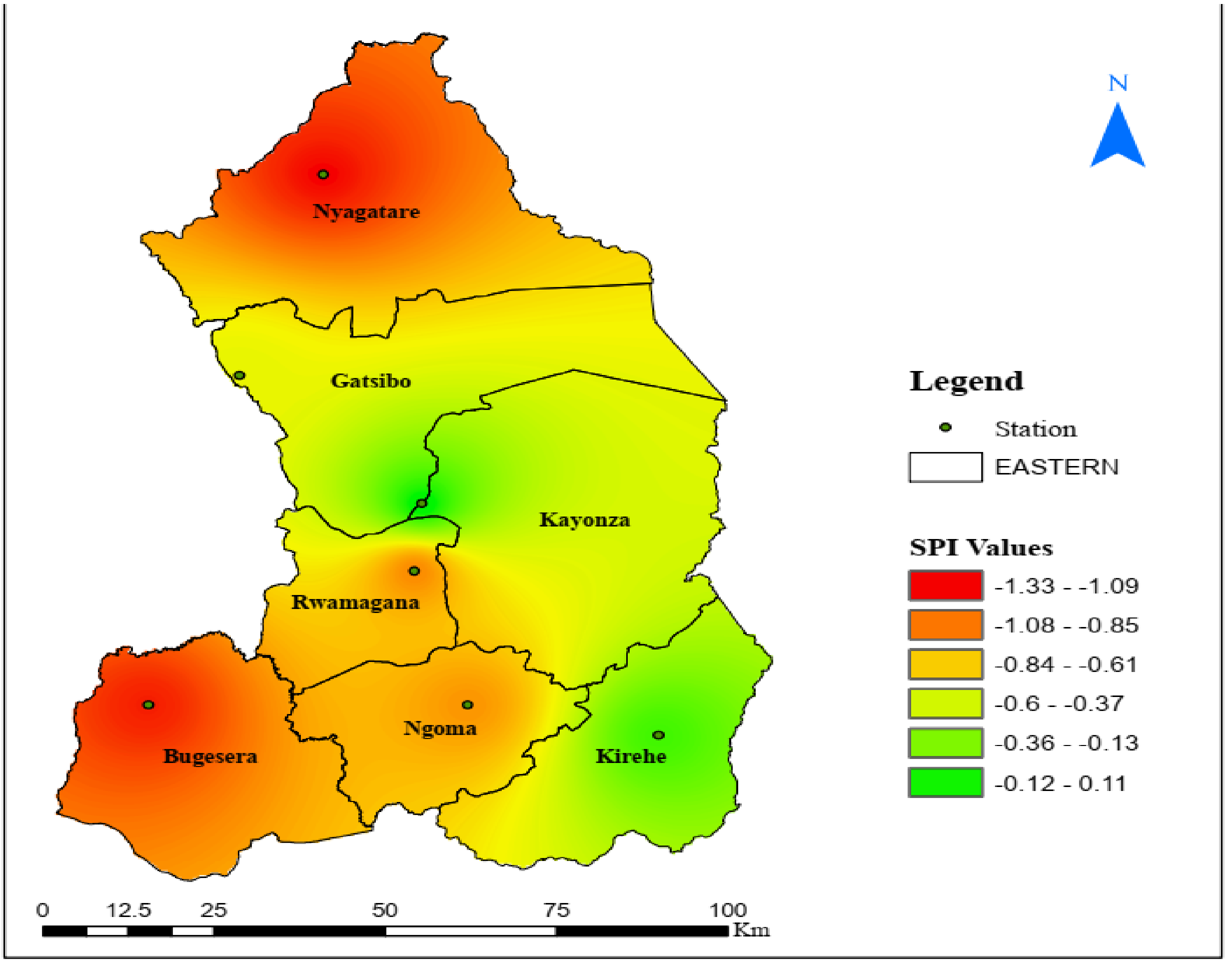

Figure 30: Standardized Precipitation Index for June - August 2017 Season Over Eastern Rwanda

The study presented results for 3-month SPI for SPI over Eastern Rwanda. Again, several parts of Nyagatare and Bugesera stations experienced severe droughts than other stations.

4.2 The Duration, Severity, and Frequency of Past Drought over the Eastern Province of Rwanda

The results for the duration, severity, and frequency of past drought over the Eastern province of Rwanda from 1981 – 2019 for the 7 locations are presented in Table 2 below.

Table 2: Drought Frequency from 1981 - 2019 over Each Location in the Eastern Province

N	Station	Season/ annual	No Drought	Mild Drought	Moderate drought	Severe drought	Extreme drought
1	**Kawangire**	**DJF**	20	13	3	1	1
		MAM	23	8	4	2	2
		JJA	19	15	5	0	0
		SON	20	13	4	0	2
		Annual	17	16	3	1	2
2	**Kibungo Kazo**	**DJF**	17	16	3	0	2
		MAM	21	12	2	2	2
		JJA	20	13	4	2	0
		SON	21	13	3	1	1
		Annual	19	17	1	1	1
3	**Nyagahanga**	**DJF**	23	7	4	1	3
		MAM	23	9	3	3	1
		JJA	20	13	4	2	0
		SON	20	15	1	2	1
		Annual	21	12	3	2	1
4	**Nyagatare**	**DJF**	23	8	1	4	2
		MAM	18	17	1	2	1
		JJA	24	7	6	2	0
		SON	21	13	2	1	2

		Annual	22	11	2	4	0
5	**Nyamata**	**DJF**	20	12	2	3	1
		MAM	20	14	1	2	2
		JJA	21	9	9	0	0
		SON	23	9	3	1	3
		Annual	21	13	3	1	1
6	**Nyarubuye**	**DJF**	23	8	1	3	3
		MAM	19	15	3	0	2
		JJA	21	12	6	0	0
		SON	20	13	4	1	1
		Annual	21	11	5	1	1
7	**Rwamagana**	**DJF**	19	13	5	1	0
		MAM	20	12	3	2	1
		JJA	22	10	7	0	0
		SON	21	12	4	1	1
		Annual	17	16	3	2	1

The drought severity are as follows: mild drought ranges between 11 and 17 out of 39 years on annual basis for the 7 locations whereas moderate drought ranges between 1 and 3 out of 39 years on annual basis. The extreme drought is observed on average once in the last 39 years at every location. Extreme drought occurs at seasonal timescale rather than annual scale. It was also found that Kawangire was the driest location followed by Rwamagana station. Further. Nyagatare was revealed to be the rainiest location in comparison to other stations.

4.3 The Skillfulness of CORDEX Models in Simulating Rainfall in Eastern Rwanda

The models reproduced well the monthly climatology of in terms of annual cycle of rainfall over the Eastern Rwanda. The results are indicated on the Figure 30 below.

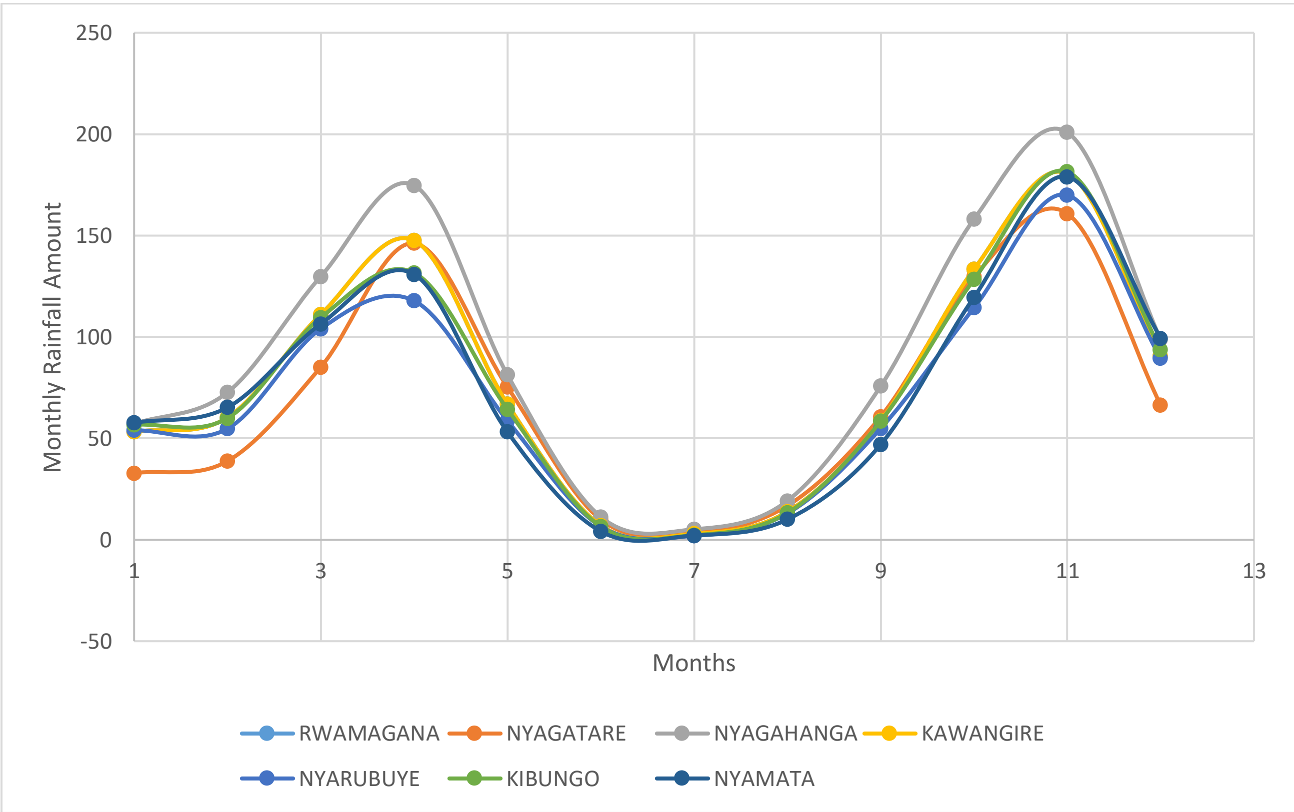

Figure 31: Monthly Climatology of the Eastern Rwanda rainfall from the ICTP-RegCM4-7

The model shows that the month of July experienced the least rainfall across all the seven locations from the selected RCM. The peaks of rainfall were witnessed during April for the March – May season and November for the September – December Season over Eastern province of Rwanda. The highest correlation (64.2%) between the model and the observed were recorded over Kibungo Kazo station. The RCM with a good skill was the ICTP-RegCM4-7 with a driving GCM of MPI-M-MPI-ESM-LR with the lowest mean absolute error of 0.00354 over Nyarubuye station. A summary table of the skill of each RCM against the ENACTS dataset is provided in Annex.

4.4 The Duration, Severity, and Frequency Future Drought over the Eastern Province of Rwanda

The results for the duration, severity, and frequency of future drought over the Eastern province of Rwanda for the year 2022 to 2099 are presented in Tables, 3, 4, 5, 6, 7 and 8.

Table 3: Drought Frequency from 2022 - 2047 Over Each Location in the Eastern Province under RCP2.6

N	Station	Season/ annual	No Drought	Mild Drought	Moderate drought	Severe drought	Extreme drought
1	**Kawangire**	**DJF**	13	9	2	0	2
		MAM	10	12	2	2	0
		JJA	14	6	3	1	2
		SON	13	9	2	1	1
		Annual	10	11	4	1	0
2	**Kibungo Kazo**	**DJF**	12	9	4	0	1
		MAM	10	13	1	2	0
		JJA	13	7	3	1	2
		SON	10	11	3	1	1
		Annual	9	12	4	0	1
3	**Nyagahanga**	**DJF**	13	9	2	2	0
		MAM	9	12	5	0	0
		JJA	15	6	2	2	1
		SON	13	8	3	2	0
		Annual	13	8	4	1	0
4	**Nyagatare**	**DJF**	12	9	3	1	1
		MAM	12	10	2	1	1
		JJA	14	7	2	2	1
		SON	13	10	1	2	0
		Annual	10	11	4	1	0
5	**Nyamata**	**DJF**	13	7	4	1	1

		MAM	9	13	4	0	0
		JJA	14	6	4	1	1
		SON	12	10	2	1	1
		Annual	11	10	3	2	0
6	**Nyarubuye**	**DJF**	13	9	3	1	0
		MAM	11	13	1	1	0
		JJA	13	8	1	3	1
		SON	10	12	1	2	1
		Annual	8	14	3	1	0
7	**Rwamagana**	**DJF**	13	9	2	0	2
		MAM	10	12	2	2	0
		JJA	14	6	3	1	2
		SON	13	9	2	1	1
		Annual	10	11	4	1	0

The results show that mild drought for 2022 to 2047 will range from 8 to 14 on annual basis for the 7 locations in Eastern Rwanda over the 26-year period. The moderate drought is witnessed at a range of 3 and 4 on annual basis for the 7 locations in Eastern Rwanda. Severe drought occurs on a range of 1 and 2 for the seven locations in Eastern Rwanda over the 26 years. However, extreme droughts will not occur in six stations expect in Kibungo Kazo that the annual extreme drought will be 1 on average. From the results, Nyarubuye will be the driest station in the same period followed by Kibungo Kazo while Nyagahanga will the rainiest station over Eastern province under RCP2.6.

Table 4: Drought Frequency from 2048 - 2073 Over Each Location in the Eastern Province under RCP2.6

N	**Station**	**Season/ annual**	**No Drought**	**Mild Drought**	**Moderate drought**	**Severe drought**	**Extreme drought**
1	**Kawangire**	**DJF**	14	8	4	0	0
		MAM	13	10	2	1	0

		JJA	9	11	3	3	0
		SON	14	10	1	0	1
		Annual	14	9	1	1	1
2	**Kibungo Kazo**	**DJF**	14	8	3	1	0
		MAM	14	8	3	0	1
		JJA	12	9	2	3	0
		SON	14	8	3	0	1
		Annual	15	6	3	1	1
3	**Nyagahanga**	**DJF**	15	9	2	0	0
		MAM	12	12	1	0	1
		JJA	8	11	6	1	0
		SON	14	9	2	0	1
		Annual	15	7	1	2	1
4	**Nyagatare**	**DJF**	13	11	1	1	0
		MAM	13	10	2	0	1
		JJA	9	12	5	0	0
		SON	14	9	1	1	1
		Annual	15	8	1	0	2
5	**Nyamata**	**DJF**	14	9	2	0	1
		MAM	12	11	2	1	0
		JJA	9	11	5	1	0
		SON	13	10	1	1	1
		Annual	15	7	2	1	1
6	**Nyarubuye**	**DJF**	15	7	2	2	0
		MAM	15	9	1	0	1
		JJA	11	11	1	3	0
		SON	14	9	2	1	0
		Annual	17	4	3	1	1
7	**Rwamagana**	**DJF**	14	8	4	0	0

		MAM	13	10	2	1	0
		JJA	9	11	3	3	0
		SON	14	10	1	0	1
		Annual	14	9	1	1	1

As shown in Table 4, mild drought occurs at the range of 4 to 9 annually for the seven stations for the 26 year-period while moderate drought ranges from 1 to 3 for the seven stations over the Eastern Rwanda during the 26-year period. Severe drought was one for nearly all the stations except for Nyagahanga and Nyagatare that has 2 severe and no extreme droughts, respectively. Further, extreme drought is averagely one for the seven stations except for Nyagatare that had 2 extreme droughts during the 26 year-period. According the results, Kawangire and Rwamagana will experience most droughts in the same period (2048 - 2073) while Nyarubuye will be the least dry station.

Table 5: Drought Frequency from 2074 - 2099 Over Each Location in the Eastern Province Under RCP2.6

N	Station	Season/ annual	No Drought	Mild Drought	Moderate drought	Severe drought	Extreme drought
1	**Kawangire**	**DJF**	10	13	2	1	0
		MAM	12	8	5	1	0
		JJA	14	11	0	1	0
		SON	17	6	3	0	0
		Annual	15	9	2	0	0
2	**Kibungo Kazo**	**DJF**	12	9	3	2	0
		MAM	12	8	3	3	0
		JJA	10	14	1	0	1
		SON	15	11	0	0	0
		Annual	12	12	2	0	0
3	**Nyagahanga**	**DJF**	9	14	2	1	0
		MAM	11	11	2	2	0
		JJA	13	11	1	1	0

		SON	16	8	2	0	0
		Annual	14	8	4	0	0
4	**Nyagatare**	**DJF**	10	11	3	2	0
		MAM	11	10	3	2	0
		JJA	12	13	0	1	0
		SON	16	8	2	0	0
		Annual	13	9	3	1	0
5	**Nyamata**	**DJF**	11	12	2	1	0
		MAM	13	8	2	3	0
		JJA	12	13	0	0	1
		SON	17	6	3	0	0
		Annual	18	6	2	0	0
6	**Nyarubuye**	**DJF**	11	9	5	1	0
		MAM	10	10	4	2	0
		JJA	10	14	0	1	1
		SON	17	9	0	0	0
		Annual	13	11	2	0	0
7	**Rwamagana**	**DJF**	10	13	2	1	0
		MAM	12	8	5	1	0
		JJA	14	11	0	1	0
		SON	17	6	3	0	0
		Annual	15	9	2	0	0

The results in Table 5 indicate that the annual mild drought ranges from 6 to 12 for the seven stations over the 26 year-period under RCP2.6. Meanwhile, annual moderate drought for the seven locations ranges from 2 to 4 for the 26 years over the Eastern Rwanda. However, there will be no annual severe drought for all the seven locations except Nyagatare that has one. The annual extreme drought is not observed in the future of the 26 years for all locations. Further, it was found that Kibungo Kazo will exhibit most droughts in the same period (2074 - 2099) while Nyamata will exhibit the least droughts over Eastern Rwanda under RCP2.6.

Table 6: Drought Frequency from 2022 - 2047 Over Each Location in the Eastern Province under RCP8.5

No.	Station	Season/ annual	No Drought	Mild Drought	Moderate drought	Severe drought	Extreme drought
1	**Kawangire**	**DJF**	12	13	1	0	0
		MAM	14	8	1	2	1
		JJA	14	5	5	2	0
		SON	13	11	1	0	1
		Annual	11	11	3	1	0
2	**Kibungo Kazo**	**DJF**	13	12	1	0	0
		MAM	13	9	1	2	1
		JJA	16	6	0	3	1
		SON	12	12	1	1	0
		Annual	12	11	3	0	0
3	**Nyagahanga**	**DJF**	15	10	1	0	0
		MAM	15	6	3	0	2
		JJA	13	7	3	3	0
		SON	13	9	3	1	0
		Annual	12	8	5	1	0
4	**Nyagatare**	**DJF**	14	10	2	0	0
		MAM	17	4	3	1	1
		JJA	13	5	7	1	0
		SON	11	11	3	1	0
		Annual	14	6	4	2	0
5	**Nyamata**	**DJF**	14	11	1	0	0
		MAM	15	7	1	2	1

		JJA	15	5	5	1	0
		SON	14	9	2	0	1
		Annual	16	8	1	0	1
6	**Nyarubuye**	**DJF**	14	9	3	0	0
		MAM	15	7	1	2	1
		JJA	15	6	2	1	2
		SON	11	13	1	1	0
		Annual	13	8	5	0	0
7	**Rwamagana**	**DJF**	12	13	1	0	0
		MAM	14	8	1	2	1
		JJA	14	5	5	2	0
		SON	13	11	1	0	1
		Annual	11	11	3	1	0

In Table 6, the annual mild drought for the seven locations ranges from an average of 6 to 11 for the 26 years under RCP8.5. Further, the annual moderate drought average from 1 to 5 for the seven locations during the 26 year-period. The extreme drought for all the seven locations is 1 and 2 on annual basis over the Eastern Rwanda. Again, the results indicate that the annual average extreme droughts for the 7 stations is nil except for Nyamata that has annual average of 1 in the Eastern Province under RCP8.5. The results show that Kawangire and Rwamagana will face more droughts than other stations in the period of 2022 - 2047 over Eastern Province under RCP8.5 while Nyamata will be the least dry station.

Table 7: Drought Frequency from 2048 - 2073 Over Each Location in the Eastern Province Under RCP8.5

No.	**Station**	**Season/ annual**	**No Drought**	**Mild Drought**	**Moderate drought**	**Severe drought**	**Extreme drought**
1	**Kawangire**	**DJF**	15	9	1	0	1
		MAM	8	10	6	1	1
		JJA	13	9	2	2	0

		SON	16	3	5	1	1
		Annual	12	8	3	1	2
2	**Kibungo Kazo**	**DJF**	12	10	3	1	0
		MAM	11	9	4	1	1
		JJA	15	7	3	1	0
		SON	16	4	3	2	1
		Annual	11	11	1	1	2
3	**Nyagahanga**	**DJF**	13	10	1	1	1
		MAM	9	9	6	2	0
		JJA	11	11	3	1	0
		SON	16	3	4	3	0
		Annual	12	9	1	2	2
4	**Nyagatare**	**DJF**	13	10	1	1	1
		MAM	10	9	6	0	1
		JJA	10	13	1	1	1
		SON	17	4	4	1	0
		Annual	15	6	2	2	1
5	**Nyamata**	**DJF**	14	9	2	0	1
		MAM	9	8	6	3	0
		JJA	14	9	2	1	0
		SON	15	4	5	2	0
		Annual	11	9	3	1	2
6	**Nyarubuye**	**DJF**	16	7	3	0	0
		MAM	9	10	5	1	1
		JJA	13	9	3	0	1
		SON	14	8	2	1	1
		Annual	12	11	0	1	2
7	**Rwamagana**	**DJF**	15	9	1	0	1
		MAM	8	10	6	1	1

		JJA	13	9	2	2	0
		SON	16	3	5	1	1
		Annual	12	8	3	1	2

According to the results in Table 7, the annual average mild drought for the seven stations is 6 (being the least annual average) to 11 (being the highest annual average) for the 26 year-period in the Eastern Province under RCP8.5. Results show that Rwamagana will exhibit the driest seasons as opposed to other stations and this is followed by Kibungo Kazo during the same period (2048 – 2073) over the Eastern province under RCP8.5. Nyagatare appears to be the least dry over the same period.

Table 8: Drought Frequency from 2074 - 2099 Over Each Location in the Eastern Province under RCP8.5

N	**Station**	**Season/ annual**	**No Drought**	**Mild Drought**	**Moderate drought**	**Severe drought**	**Extreme drought**
1	**Kawangire**	**DJF**	12	11	1	1	1
		MAM	15	7	4	0	0
		JJA	11	12	2	1	0
		SON	18	3	2	2	1
		Annual	17	8	1	0	0
2	**Kibungo Kazo**	**DJF**	13	10	0	2	1
		MAM	17	5	4	0	0
		JJA	11	10	4	1	0
		SON	17	4	3	2	0
		Annual	16	9	1	0	0
3	**Nyagahanga**	**DJF**	13	8	3	1	1
		MAM	15	9	2	0	0
		JJA	12	12	2	0	0
		SON	17	4	2	2	1
		Annual	18	7	0	1	0

4	**Nyagatare**	**DJF**	13	8	2	2	1
		MAM	14	9	3	0	0
		JJA	12	9	4	1	0
		SON	18	4	2	2	0
		Annual	17	8	0	1	0
5	**Nyamata**	**DJF**	15	8	1	1	1
		MAM	16	7	3	0	0
		JJA	10	14	2	0	0
		SON	17	4	2	3	0
		Annual	19	6	1	0	0
6	**Nyarubuye**	**DJF**	12	10	1	1	2
		MAM	18	5	2	1	0
		JJA	9	12	3	2	0
		SON	17	4	3	2	0
		Annual	16	9	1	0	0
7	**Rwamagana**	**DJF**	12	11	1	1	1
		MAM	15	7	4	0	0
		JJA	11	12	2	1	0
		SON	18	3	2	2	1
		Annual	17	8	1	0	0

Based on the results, the annual average for mild drought is between 6 and 9 for the seven stations for the 26 years in the Eastern Province under RCP8.5. Results show that the annual average moderate drought for the 7 locations in Eastern province of Rwanda is 1 except Nyagahanga and Nyagatare that have no annual average moderate drought. Again, only Nyagahanga and Nyagatare had annual average severe drought of 1 while the rest of the stations had no annual severe droughts in the Eastern Province of Rwanda under RCP8.5. Lastly, no annual extreme drought is witnessed in all the seven stations for the 26-year period. Both Kibungo Kazo and Nyarubuye locations will experience more mild droughts than other stations while Nyamata will exhibit least droughts for the period 2074 – 2099 under RCP8.5.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

This chapter presents the conclusions based on the research findings. The recommendations for policy makers as per the findings are also presented hereafter.

5.1 Conclusions

Regarding the duration, severity, and frequency of past drought over the Eastern province of Rwanda (1981-2019), the study concludes that Nyagatare was the least droughty station with 22 years experiencing no drought and Nyagahanga and Nyamata that did not experience droughts in 21 years out of the 39 years followed this. Kawangire location over Eastern province of Rwanda was the most droughty stations in the past 39 years followed by Rwamagana. The study concludes that 2017 was the most droughty year with all of the seven locations experiencing mild to extreme droughts except along the borders of Kayonza and Gatsibo that had some wet seasons during the 39-year period (1981-2019).

Concerning the duration, severity, and frequency of future drought over the Eastern province of Rwanda (2022-2099) under RCP2.6, the study concludes that Nyarubuye followed by Kibungo Kazo were the driest locations with only 8 and 9 years, respectively experiencing no drought while the rest of the years reported mild to extreme droughts. However, under RCP8.5, Kawangire and Rwamagana locations will be the driest stations. Further, regarding the drought frequency from 2048 - 2073 over each location in the Eastern Province under RCP2.6, the study concludes that Kawangire and Rwamagana will experience drier seasons with only 14 years out of the 26 year-period exhibiting no droughts. However, under RCP8.5, Kibungo Kazo will experience most droughts in the same period. Moreover, on the drought frequency from 2074 - 2099 over each location in the Eastern Province under RCP2.6, the study concludes that Kibungo_Kazo will only have 12 wet years followed by Nyagatare and Nyarubuye with only 13 years each that will be mostly hit with droughts during the period as opposed to other stations. However, under RCP8.5, Nyarubuye and Kibungo Kazo will the most hard-hit stations with mild to moderate droughts in the same period.

In connection to the skillfulness of CORDEX models in simulating rainfall in Eastern Rwanda, the study concludes that Nyagahanga experienced the higher monthly rainfall amount with the stations' monthly rainfall peak being the month of April for the March – May season and also in November for the September – December Season.

5.2 Recommendations

The study used observational data from ENACTS that has the potential of providing reliable, valid, and quality climatic information that are good for both local and national meteorological planning. Therefore, the study recommends that the climatic related institutions in the country should ensure the preservation of the ENACTS data to support future analysis for related research works by ensuring accessibility and availability of information regarding drought characteristics in Eastern province of Rwanda.

The study also recommends that Meteorological department in Rwanda should carry out further tests using model techniques such as regression analysis and correlation analysis to determine the relationship between the independent and dependent variables for both past and future droughts as well as for the rainfall analysis.

In any numerical climatic/weather research, initialization is the key element and this is pegged on the observed data quality. Based on the study, the seven stations in the region were sparsely networked as result of the geographical feature of Eastern province of Rwanda. Therefore, the study recommends that the weather institutions and other policy makers in the same field should ensure that strategies are adopted to increase the number of locations and ensure that the stations are placed strategically. To achieve this, there should be enough resources (both financial and human resources) and increase capacity building to promote climate related researches and for empowering the human workforce.

Further, for analysis of droughts using SPI in areas where observed data are scarce, the study recommends the utilization of other satellite such as Tropical Application for Meteorology using Satellite data (TAMSAT) can also be employed.

In the current study, droughts (past and future) and rainfall were assessed using SPI and CORDEX; the study recommends that remotely sensed drought indices such as NDVI can also be used in the future to add value to the outcome of the study.

Furthermore, the study was limited to the assessment of the past and future meteorological drought characteristics in the Eastern province of Rwanda under a changing climate. The study recommends that a future similar study should include all stations in Rwanda rather than Eastern province only.

Annex : Tables of summarized skill of the CORDEX models against the ENACTS observations over the Eastern Rwanda from 1981 – 2005

RegCM4 (All Global Circulation Models)

NYAGATARE	KAWANGIRE	NYARUBUYE	KIBUNGOKAZO	NYAGAHANGA	NYAMATA	RWAMAGANA
RegCM47_MPI	RegCM47_MOHC	RegCM47_MPI	RegCM47_MPI	RegCM47_MPI	RegCM47_MPI	RegCM47_MPI
correlation	correlation	Correlation	Correlation	Correlation	Correlation	Correlation
0.518536	0.445931	0.44683	0.641947	0.469127	0.565967	0.549677368
ME	ME	ME	ME	ME	ME	ME
0.068563	-20.856	3.404067	-23.6893	-5.52619	-8.95901	-12.82315
RMSE	RMSE	RMSE	RMSE	RMSE	RMSE	RMSE
58.48597	58.54582	61.19933	65.39373	81.24362	61.3125	65.5588371
MAE	MAE	MAE	MAE	MAE	MAE	MAE
0.11782	0.07915	0.003453	0.004567	0.17547	0.012273	0.063123333

CCLM4-0-15 (All Global Circulation Models)

NYAGATARE	KAWANGIRE	NYARUBUYE	KIBUNGOKAZO	NYAGAHANGA	NYAMATA	RWAMAGANA
CCLM_MPI	CCLM_MPI	CCLM_MPI	CCLM_MPI	CCLM_MPI	CCLM_MPI	CCLM_MPI
Correlation	Correlation	Correlation	Correlation	Correlation	Correlation	Correlation
0.487132	0.483727	0.376009	0.504966	0.436219	0.482128	0.494142443
ME	ME	ME	ME	ME	ME	ME
9.142527	4.283417	-0.12092	-32.6531	9.860447	3.757413	-11.09325
RMSE	RMSE	RMSE	RMSE	RMSE	RMSE	RMSE
68.88214	71.48667	66.50127	78.6565	98.11526	77.31242	74.26616505
MAE	MAE	MAE	MAE	MAE	MAE	MAE
0.043227	0.006583	0.08416	0.184187	0.08162	0.217403	0.11325

REMO2015 (All Global Circulation Models)

NYAGATARE	KAWANGIRE	NYARUBUYE	KIBUNGOKAZO	NYAGAHANGA	NYAMATA	RWAMAGANA
REMO2015_MPI	REMO_NCC	REMO_NCC	REMO2015_MPI	REMO2015_MPI	REMO_NCC	REMO_NCC
Correlation	Correlation	Correlation	Correlation	Correlation	Correlation	Correlation
0.443734	0.477747	0.402619	0.479466	0.392792	0.511318	0.437339694
ME	ME	ME	ME	ME	ME	ME
-24.7042	-28.6665	-24.3485	-55.5683	-53.0493	-33.9779	-44.04318
RMSE	RMSE	RMSE	RMSE	RMSE	RMSE	RMSE
52.64979	58.45004	58.40621	87.4474	84.50369	63.6415	74.15567226
MAE	MAE	MAE	MAE	MAE	MAE	MAE
0.000323	0.034757	0.117363	0.325487	0.177297	0.230833	0.141423333

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