



EVALUATING THE EFFECTS OF CLIMATE CHANGE ON DROUGHT TRENDS IN
BUGESERA DISTRICT, EASTERN PROVINCE OF RWANDA

BY

NZUMVIRUMUKIZA Adrien

REG No: 215037734

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ANNOUNCEMENT

I hereby declare that I completed my master's degree with honors in the Physics Department at UR-College of Science and Technology in part by working on my thesis, "**Evaluating the effects of climate change on Drought Trends in Bugesera District, Eastern Province of Rwanda**" from 1985 to 2020, under the guidance of Prof. Bonfils SAFARI in the Physics Department during the academic year 2020–2022. I additionally declare that my project is entirely original with no submissions to other universities for degree awards, and that all data sources used in the study have been properly credited.

The candidate's name

Name: NZUMVIRUMUKIZA Adrien

REG No: 215037734

Signature:

Date of submission: .../...

APPROVAL

This certifies that NZUMVIRUMUKIZA Adrien, working under the supervision of my supervisor, completed the original research for his dissertation, "**Evaluating the effects of climate change on Drought Trends in Bugesera District, Eastern Province of Rwanda**" from 1985 to 2020.

Prof. Bonfils SAFARI

Department of Physics

University of Rwanda /College of Science and Technology

Signature: _____ Date: .../.../2024

Head of department: Dr. Innocent Nkurikiyimfura

Signature:.....

Date:/...../2024

DEDICATION

- To my Jehovah God
- To my family member
- To my supervisors and all staff board
- To my friends and colleagues

ACKNOWLEDGEMENT

Foremost, special thanks are raised to the Jehovah God for his abundant blessings knowledge, strength and protection granted me during all of my studies. First we wish to thank all the lectures in the Physics Department who took their time to share their knowledge and encouraged me to persevere in our studies. Their understanding, kindness and wisdom were absolutely helpful.

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I am so blessed to have such amazing friends who have constantly and continually provided for me and supported me all through the journey of life, for all they have contributed to this project, and also being in prayers as well as in financial support.

I would want to thank every one of my classmates for all of their help during the course of our three years together. I would also want to thank the authors of the books, papers, research projects, and conference reports that I was able to find online and used as references.

My Jehovah God bless you everyone!

ABSTRACT

This study evaluates the effects of climate change on drought trends in Bugesera District, Eastern Province of Rwanda, utilizing the Standardized Precipitation-Evapotranspiration Index (SPEI) as a comprehensive tool for assessing drought conditions. The research analyzes historical climate data, including temperature and precipitation records, to calculate the SPEI over multiple time scales, reflecting seasonal and interannual variations in drought severity and frequency. Our findings indicate a significant increase in drought intensity and duration in Bugesera over the past few decades, correlating with rising temperatures and altered precipitation patterns attributed to climate change. The analysis reveals that prolonged dry spells have intensified, affecting agricultural productivity, water resources, and local livelihoods.

The Earth System Grid Federation (ESGF) site's monthly rainfall datasets from 1980 to 2100 from CORDEX-Africa-22 Domain and the monthly gridded rainfall dataset known as ENACTS dataset for a 35-year period (1985 to 2020) will be utilized. In order to assess the historical drought across the Eastern Province of Rwanda, Bugesera District based on the four stations. Based on the verified models' CORDEX-Africa-22 projection on the two Representative Concentration Pathways (RCPs), RCP2.6 and RCP8.5, future drought aspects will be examined. Finally, to understand changes.

Based on historical data, it was found that Ruhuha and Nyamata experienced drought-free periods in 17 of the 35 years, Karama and Juru stations had drought-free periods in 22 of the 35 years from 1985 to 2020. All four regions with mild to extreme droughts had drier conditions in 2017, the year with the worst drought on record.

These trends underscore the need for adaptive strategies to mitigate the impacts of drought in the region, including improved water management practices and climate-resilient agricultural techniques. The study contributes to the understanding of climate change impacts on drought dynamics in Bugesera District and provides a framework for future research and policy.

LISTING OF ACRONYMS

AFR-22:	African-22
ANOVA:	Analysis of Variance
IPCC-AR4:	Intergovernmental Panel on Climate Change's Fourth Assessment Report
BAMS:	Bulletin of the American Meteorological Society
C2ES:	Center for Climate and Energy Solutions
CCLM5-0-15:	Model of climate5-0-15
CDT:	Climate Information Instrument
CMIP5:	Version 5 of the Coupled Model Intercomparison Project
CMIP6:	Coupled Model Intercomparison Project, Version 6
CDI:	Combined Drought Index,
CORDEX:	Coordinated Regional Downscaling Experiment
DJF:	December to February
DD:	Drought Duration
DF:	Annual Drought Frequency
DMI	Drought Monitoring Indicators
DS	Severity of the drought
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño–Southern Oscillation
ENACT:	Enhancing Nature Based solution for an Accelerated Climate Transformation
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 Elevations
ENS-RCMs	Ensemble Mean of the Regional Climate Model
GWP CEE	Central and Eastern Europe in the Global Water Partnership.
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
IPCC	Intergovernmental Panel on Climate Change

ITCZ	Inter-Tropical Convergence Zone
IRI	Inter-Tropical Research Institute for Climate and Society
JJA	June through August
MAM:	March to May
MAE	Mean Absolute Error
ME	Mean Error
MINIRENA	Rwanda's Ministry of Natural Resources
NCC-NorESM1-M	Max-Planck-Institut für Meteorologie Earth System Model
NCCESM	Norwegian Climate Center's Earth System Model,
NDVI:	Normalized Difference Vegetation Index;
MOHC-HadGEM2-ES:	Met Office Hadley Centre-Hadley Centre Global Environment Model version 2-Earth system
NIR:	Near-Infrared Light
NISR:	National Institute of Statistics of Rwanda
NMHS:	National Meteorological and Hydrological Services
NDVI:	Normalized-Difference Vegetable Index
PDSI :	Palmer Drought Severity Index
PET:	Potential Evaporated Transpiration.
PCA:	Principal Component Analysis
RCP:	Representative Concentration Pathway
REMA:	Rwanda Environment Management Authority
REMO:	Report on State of Environment
RegCM-ENSEMBLE:	Regional Climate Model-ENSEMBLE
RMSE:	Root Mean Squared
SOND:	September, October, November and December
SON:	September, October, and November
SPEI :	Standardized Precipitation Evapotranspiration Index
SPI:	Standardized Precipitation Index
SDSM:	Statistical Downscaling Model
SSAF:	Sub-Saharan Africa
TRMM:	Tropical Rainfall Measuring Mission
UNFCCC :	United Nations Framework Convention on Climate Change is known
UNISDR:	United Nations International Strategy for Disaster Reduction
US:	United States of America

WMO : World Meteorological Organization

WWAP: World Water Assessment Program

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CHAPTER 1: INTRODUCTION

This chapter looks into the problem description, research questions, objectives, justification, surface area of the study, and study background.

1.0 Overview

Drought is an increasingly severe climatic event that affects many regions globally, with significant consequences for water resources, agriculture, and socio-economic stability. In Rwanda, and specifically in Bugesera District, drought has emerged as a critical issue impacting agricultural productivity and water availability. The effects of climate change are anticipated to exacerbate these conditions, making it essential to understand how future climatic shifts might influence drought patterns. *IPCC. 2021.*

Because humans have modified the characteristics of drought, it may not be viewed as a completely "natural hazard." Instead, the key tactics for managing drought have been determined by monitoring and assessing the drought. It has been noted that Rwanda's pastoral activities and food security are significantly impacted by the drought. (Miková, 2017) state that Rwanda experienced a drought from 1902 to 1903, with a return duration of more than ten years that decreased to three years in 2008. This may indicate that droughts are occurring more regularly in the country.

Using the Combined Drought Index (CDI), (Niyonsenga et al., 2024) evaluated the features of the drought throughout Rwanda and found that the drought was longer in Nyagatare and had a higher temporal and spatial concentration in the Eastern Province. According to the study, most of the nation shows mild to moderate drought symptoms throughout the first two years of the timeframe. The study found that the western province is expected to experience a long drought, and that the characteristics of the drought under RCP8.5 were judged to be more severe than those under RCP4.5.

The Standardized Precipitation Evapotranspiration Index (SPEI) is a widely recognized tool for assessing drought by integrating both precipitation and potential evapotranspiration (PET). This index provides a comprehensive measure of drought conditions by accounting for the water balance, thus offering a more nuanced understanding of drought severity compared to traditional precipitation-only indices. *Vicente-Serrano, S. M., et al. 2010.*(Henninger, 2013)

Bugesera District, located in Rwanda's Eastern Province, is characterized by its semi-arid climate and reliance on agriculture, making it particularly vulnerable to drought. The district

has experienced increasing drought frequency and intensity, affecting local water resources and agricultural productivity. Analyzing how climate change might influence future drought conditions in this region is essential for effective planning and adaptation (Nkurunziza et al., 2019).

Thus, the current research provide suggestions for mitigating the effects of improving Rwanda's drought adaptation. Therefore, the current study may add to the discussion by assessing the past and future drought aspects in BUGESERA District Rwanda's eastern province in light of climate change.

1.1 Problem Synopsis

According to Warner et al. (2015), Rwanda is vulnerable to natural disasters, which are mostly brought on by climate changes. Drought is a significant and serious disaster in Rwanda, especially in the Eastern Province (REMA, 2013). Climate change-related drought is currently a significant role in ensuring food security and reducing poverty.

Due to a lack of water, the Eastern Province's pasture supply has declined in both quantity and quality, which has had a detrimental impact on cattle output.

Evaluating the effects of climate change on drought trends in Bugesera District is crucial for developing adaptive strategies that enhance resilience to future droughts. This study will contribute to the understanding of how climate change might alter drought conditions and support informed decision-making for sustainable water and agricultural management. (Mastrorillo et al., 2020).

Droughts remain pose a threat to people's lives in Rwanda's Eastern Province, despite the implementation of several policies aimed at managing and reducing their dangers.

1.2.The research questions

1. How have historical drought trends in Bugesera District evolved over time?
2. What are the projected impacts of climate change on drought severity and frequency in Bugesera District?
3. What are the most effective adaptation strategies currently used in Bugesera District to combat drought?

1.3 Goals

The study objective is Evaluating the effects of climate change on drought trends in Bugesera District using the SPEI. The specific objectives include:

- ✓ Assessing past drought conditions in Bugesera District using historical precipitation and PET data.
- ✓ Integrating climate change projections to evaluate how future climatic shifts might affect drought patterns in the district.
- ✓ Offering Conclusion and recommendations for mitigating the impacts of projected drought scenarios.

1.4 Rationale

Numerous studies have been conducted on the impact of climate change on drought and how it has negatively impacted livelihood. For instance, several studies conducted in the USA (Feng et al., 2017) comprise projected variance derived from future drought indices and model-based projections. The entire modeled column soil moisture and drought indices that were employed suggested a persistently dry region across the USA Great Plains. This shows that concerns about climate change persist even in developed economies, and it suggests that further research be done to find out how much climate change contributes to current and future droughts and to develop mitigation measures for its positive effects.

Future drought features for the drought-prone surface areas of South Asia indicated an increase in drought conditions, mostly in the northwest of the country. Droughts that are more frequent, intense, and continue longer can occur in North-West South Asia. Additionally, the study projects that there will be severe drought conditions in the future in certain sections of the North-Central, North-East, and South-West sub-areas. These concerns need the current study because drought adaptation measures should be implemented to decrease the benefits of drought in Asia and developing countries.

In Eastern African countries such as Kenya and Tanzania, higher-resolution meteorological forecasts are evaluated using the Statistical Down Scaling Model (SDSM) to see how the models impact the surface area. The study found that during the 20s (2011–2040), 50s (2041–2070), and 80s (2071–2100), precipitation increased in Kenya and decreased in Tanzania.

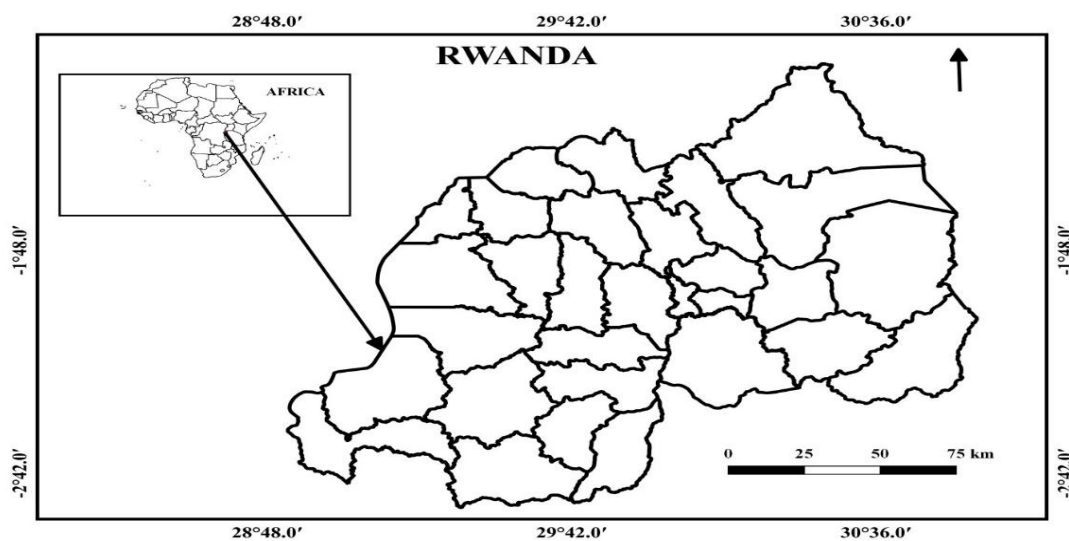
Though recommendations have been made in light of these obvious challenges, the sustainability measures for mitigation and adaptation remain insufficient. Therefore, it is

imperative that the current study quickly address these gaps by offering site-specific policies and plans that can adapt to the region's unexpected climate change, with Rwanda included. Furthermore, the people who live in BUGESERA District Rwanda's Eastern Province, a savannah region recognized as the nation's food basket, are typically impacted by climate change. In addition to lowering the region's susceptibility to droughts, timely community access to sufficient knowledge on drought characteristics and their associated effects would facilitate the development of drought-adaptive community solutions (Karavitis et al., 2011). SPEI will be used to calculate drought indices and predicted drought features over BUGESERA District Rwanda's Eastern Province. Evaluating the effects of climate change on drought trends in Bugesera District is crucial for developing adaptive strategies that enhance resilience to future droughts. This study will contribute to the understanding of how climate change might alter drought conditions and support informed decision-making for sustainable water and agricultural management(Mastrorillo et al., 2020). Additionally, this will result in better-suited strategies for drought adaptation and mitigation.

1.5 Field of inquiry

With a land area of 26,338 km², Rwanda is a landlocked nation in east-central Africa that is situated between latitudes 1°4' and 2°51' south. It is landlocked south of the Equator. In the tropical belt, the nation's longitudes are 28°53' and 30°53' east (Henninger, 2013). Rwanda's boundaries are as follows: Uganda borders Rwanda from the north, Tanzania borders Rwanda from the east, Burundi borders Rwanda from the south, and the Democratic Republic of the Congo borders Rwanda from the west (RDC)

Figure 1: Rwanda's location within Africa



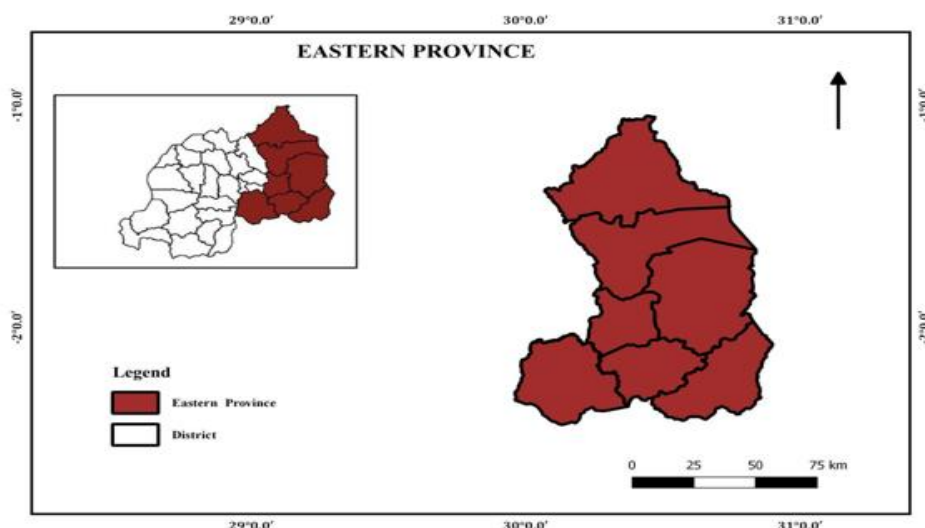
The high plains of Rwanda's Eastern Province encompass the area between the Akagera River in its central portion and the course of the Akanyaru River to the north and south. A region of crystal-clear mountains, the Central Highlands range in elevation from 1800 meters to nearly 3000 meters. Because to the Central Highlands' extreme relief, Rwanda is known as the "Land of a Thousand Hills." Volcanic lava flows had dammed up Lake Kivu, which later filled a substantial chunk of the Rift zone, which is around 40 km wide. The Democratic Republic of the Congo is bordered by the Rusizi River. It flows in the direction of Lake Tanganyika, which is barely 773 meters above sea level.

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

With a total area of 9,813 km², Eastern Province is the largest of Rwanda's five provinces, where this study was carried out. Bugesera, Rwamagana, Gatsibo, Kayonza, Kirehe, Ngoma, and Nyagatare are its seven districts. The Eastern Province's capital is Rwamagana, and it is home to the Akagera National Park. Tanzania to the east, Uganda to the north, and Kigali to the west are the borders of the Eastern Province.

Eastern Province is a low-lying mountain region that receives rainfall between 700 and 1.100 mm. The Eastern Province lies between latitudes of 1°45'00.0"S and longitudes of 30°30'00.0"E.

Figure 2: Map of Rwanda's Eastern Province



The mesoscale system and the Lake Victoria Basin both contribute to the province's weather. This area used to receive enough rainfall under typical weather circumstances, which led to the production of enough foodstuffs to share with the rest of the nation. Due to climate change and variability, which have been seen both generally and specifically in the region, production has

considerably decreased during this period of bad weather due to droughts. With 2,595,703 residents, the Eastern Province is the largest of Rwanda's five provinces.

Figure 3: Map of Bugesera District



Bugesera is a district (*akarere*) in Eastern Province, Rwanda. Its capital is Nyamata. The district is named after the old Kingdom of Bugesera, (Twagilimana, Aimable (2007)).

The area is prone to droughts as it has a higher average daytime temperature than the Rwandan average, and lower precipitation.

CHAPTER 2: LITERATURE REVIEW

2.0. Overview

This chapter presents details on the rainfall's spatial-temporal characteristics, the length, regularity or frequency, and intensity of past and future droughts, and the capacity of CORDEX models to accurately simulate variability and rainfall trends over Rwanda's Eastern Province. Gebremeskel and Kebede (2018) claim that because climate change has accelerated drought and population growth, it poses a serious risk to both the sustainability of human resource development and the preservation of natural systems (Haile, Tang, Hosseini-Moghari, et al., 2020). With global warming, the impact of climate change on the environment and civilization becomes more significant.

(Haile, Tang, Hosseini-Moghari, et al., 2020) studied the future drought features in Africa, with a focus on Sudan, Tanzania, Somalia, South Sudan, Kenya, Uganda, and Ethiopian highlands, using Global Climatic Models (GCMs) in the Coupled Model Inter-comparison Project (CMIP5). The study estimates that under RCP2.6,4.5, and 8.5, respectively, the probability of such East African droughts increasing by 16%, 36%, and 54% by the end of the twenty-first century. It is projected that drought occurrences will become more frequent, prolonged, intense, and dispersed geographically across South Sudan, Tanzania, Sudan, and Somalia.

However, in the highlands of Kenya, Ethiopia, and Uganda, the frequency, duration, and intensity of drought events would largely decrease.

Historically, drought has been a recurring issue in East Africa, including Rwanda. Studies such as (Uwimbabazi et al., 2022) highlight the impact of drought on agricultural productivity and socio-economic conditions in the region. Drought leads to reduced crop yields, water shortages, and increased vulnerability of local communities.

Significant recommendations from the study can aid in better identifying the causes, minimizing the effects, and enhancing East Africa's resilience to drought.

(Dinku et al., 2014) claim that one of the main issues facing people and natural ecosystems worldwide is climate change (A. F. Van Loon et al., 2016). Water and food insecurity are projected to increase under climate change, particularly during droughts, unless development initiatives and measures are effectively adopted on time.

The study discovered a notable rise in drought conditions, primarily in the North-West. The average frequency and duration of droughts were predicted by the study to be strong. It was

discovered that the North-West region was more vulnerable to droughts that were intense and lasted a long time. The North-Central, North-East, and South-West sub-areas are also expected to have severe droughts in the future, according to the report. According to the study, the existing findings provide a basis for creating drought adaptation strategies in South Asia.

Once more, (Jeong et al., 2014) investigated how temperature affected drought forecasts for Canada. The study discovered that, for the majority of Canadian locations, a future period average temperature increase of more than 2°C relative to the current period will result in a significant increase in PET and a decrease in DIF, particularly for the country's low-latitude areas. Future drought risks for important southern Canadian regions are significantly increased as a result of these changes. Even though the SPI yields the same results, increases in future drought characteristics are vulnerable to changes in future drought risks.

In order to facilitate adaptation and mitigation of potential effects of future climate change, (Gebrechorkos et al., 2019) also used the Statistical Downscaling Model (SDSM) to compute higher-resolution climatic projection equivalency to future station data to drive assessment models to impact in Kenya and Tanzania.

According to the study, precipitation in KenShed increased between 15 and 86 percent and decreased in TanShed between 1 and 6.3 percent in the 2020s (2011–2040), 2050s (2041–2070), and 2080s (2071–2100) with respect to SDSM.

The study generally recommends that in order to cope with unforeseen climate change, sustainability measures for adaptation should be designed in accordance with certain site-specific requirements. Climate change significantly impacts drought patterns globally, with effects varying by region. Understanding these impacts requires analyzing how changes in temperature and precipitation alter drought frequency, intensity, and duration. IPCC (2021).

The Palmer used Drought Severity Index (PDSI) to look at variations in drought features in Sub-Saharan Africa (SSAF) between 1971 and 2000. The "Representative Concentration Pathways" (RCP4.5, RCP8.5) were used to anticipate the climate for the years 2041–2070 and 2071–2100 in Global Climate Models (GCMs). The study predicted that in the 2050s and 2080s, most of West Africa and South Africa would experience dry weather. However, it is projected that in the 2050s and 2080s, some parts of the Horn of Africa might see rather wet seasons.

The study predicts that the driest periods for SSAF will occur in the 2050s and 2080s, with certain areas of the continent being more susceptible to drought.

2.1. Patterns of Rainfall over Rwanda

Research has highlighted significant drought events in Rwanda's history, influenced by both natural climate variability and human activities. Recent studies focus on how these trends have evolved over time and the implications for agricultural and water resources. (Nkurunziza et al., 2019).

The Rwandan province in the east is the most susceptible to droughts brought on by climate change. Districts in the Eastern Province's lowlands, including Nyagatare, Bugesera, Gatsibo, Kayonza, Kirehe, and Ngoma, have had recurring rainfall deficits (Taremwa et al., 2016)(Karavitis et al., 2011).

Rwanda generally experiences two distinct rainy seasons, with the long (March to May) and short (September to December) rains accounting for roughly 75% of the nation's total precipitation and is regulated by the Inter-Tropical Convergence Zone (ITCZ).(*RelationshipsbetweenRwandanseasonalrainfallanomalies.Pdf.Crdownload*, n.d.2014) reported that there has been a decrease in long rains, particularly in the Eastern Lowlands, and an increase in brief rainfall in the South-West and Northern highlands of Rwanda.

The ITCZ is the primary system controlling the rainfall season in Rwanda. Other factors that affect rainfall over Rwanda include topography, Congo Air Masses, large bodies of water, tropical cyclones, subtropical anticyclones, monsoons, and others. Annual rainfall in Rwanda ranges from 800-1700 mm. Notably, high pressure regions known as subtropical anticyclones serve as wind generators and moisture pumps in the convergence zones.

The country's seasonal rainfall performance is influenced by their location and intensity. Rainfall in the nation typically falls in the rainy seasons, which are March, April, and May MAM and September, October, November, and December (SOND). But according to Mutai and Ward (2000)(Naumann et al., 2018), the ITCZ moves from the north to the south to the equator and vice versa.1960s Rwanda's geography, which ranges from 900 to 4507 meters, makes it susceptible to harmful soil erosion, especially during periods of intense rainfall (*RelationshipsbetweenRwandanseasonalrainfallanomalies.Pdf.Crdownload*, n.d.).

After this loss, Rwanda's vegetation covering decreased to 240,746 hectares in 2007 from 659,000 hectares in 1960 (FAO, 1999)(Heim, 2002). Together with environmental damage, low

crop output, and degraded soil, the nation is now more vulnerable to floods as a result of deforestation.

Therefore, it is essential to evaluate the spatial-temporal distribution of rainfall in order to ascertain the regional characteristics of rainfall and the possible effects of its variability on drought characteristics (Haeng, 2011)(Heim, 2002). For developing nations like Rwanda, where over 85% of the labor force is involved in rain-led agriculture, spatiotemporal studies of rainfall aspects are important (Gudakahriz et al., 2011). Thus, the study's objective was to investigate the spatiotemporal characteristics of the rainfall across the Eastern Province of Rwanda.

2.2 The Previous Drought in BUGESERA DISTRICT, Rwanda's Eastern Province

Bugesera District in Rwanda's Eastern Province has faced significant challenges with droughts, particularly in recent years. This region is known for its agricultural activities, which are heavily reliant on consistent rainfall. When droughts occur, they can have severe impacts on local farming, water availability, and overall livelihoods.

The previous droughts in Bugesera have often been characterized by prolonged periods of low rainfall, which disrupts the growth of crops and reduces water supplies.

The socio-economic impacts of drought, including effects on agriculture, water resources, and livelihoods, are critical for understanding the broader implications of climate change. Studies focus on how drought affects different sectors and what strategies can mitigate these impacts. (Mastrorillo et al., 2020).

Agriculture in Rwanda is predominantly rain-fed, making it highly susceptible to drought. (Munyaneza et al., 2014)analyze the impact of drought on agricultural productivity and food security in Rwanda. Their study highlights the need for effective drought management strategies and underscores the significance of understanding historical drought trends to improve agricultural resilience.

The primary cause putting much of BUGESERA District's surface areas in jeopardy is drought. In terms of food security, poverty alleviation, and agricultural productivity, this trend tends to be downward (REMA, 2019) . Rwanda has two distinct arid seasons. The shorter dry season spans from the middle of December to the middle of February, whereas the first significant dry period lasts from June to August. The ITCZ moves from North to South, crossing the equator

twice a year in the months of March and September, respectively, and vice versa, causing the two dry seasons.

(Phaduli, 2018) conducted a study wherein the "Standardized Precipitation Evapotranspiration Index" (SPEI) and the SPI were used to calculate the spatial-temporal characteristics of past, present, and future meteorological droughts in South Africa. The trend and statistical analysis were carried out with SPI time series that were obtained from observations of rainfall. Because much of South Africa had suffered from moderate to severe droughts between 1981 and 2015, the rainfall observations were used. Monthly gridded precipitation data from the Tropical Rainfall Measuring Mission (TRMM) satellite were used in the study.

To calculate SPI at each domain for each grid point, TRMM was used. The computed SPI was used to obtain historical drought monitoring indicators for the years 1998–2015, such as drought severity (DS), frequency (DF), and duration (DD).

According to (Phaduli, 2018) findings, DS and DD were on the decline (negative trend) in the majority of South Africa's provinces, including Gauteng, North West, Free State, and Limpopo. Furthermore, the study discovered that major drought periods that occurred between 1981 and 2015 were replicated by SPI/SPEI computed using in-situ observation data and SPI calculated using TRMM data. In addition, drought, severity, frequency, and duration were used in the trend and statistical analysis. In summary, the findings demonstrated a general increase in droughts over the previous period, 1998-2015, under RCP8.5.

Using SPI and drought Monitoring Indicators (DMI), (Botai et al., 2017) evaluated drought features in yet another study. Weather stations in the Western Cape Province were used as measurements and precipitation data to establish the two groups. The information was from 1985 to 2016. The study discovered that the Western Cape Province experienced minor drought recurrences from 1985 to 2016 based on the analysis of SPI-3, SPI-6, and SPI-12. It's possible that the dry spells observed in 2015 and 2016 are a result of earlier dry spells. In contrast to the northern and eastern regions of the Western Cape Province, the western and southern regions experienced exceptionally severe droughts; nonetheless, the DMI series trend analysis revealed significant spatio-temporal inter-dependence.

Furthermore, (Botai et al., 2017)'s analysis discovered that the DMI trends from earlier decades showed fluctuation of about 8%. Drought conditions specifically continued to have a detrimental influence on agriculture sector production, with water reservoirs reported to have a capacity of less than 30%. This suggests that the effects of droughts on socioeconomic activities will keep happening for a few months. The study came to the conclusion that

analyzing previous drought features is a crucial first step in placing the current drought problems into perspective and igniting appropriate policy and action responses. The study's conclusions are significant because they provide a framework for tracking droughts and help with the implementation of early warning systems.

2.3 The Capability of CORDEX Models to Represent Rainfall Variability and Trends

CORDEX-Africa records have been used in the past to study future precipitation estimates. For example, Anyamba and Tucker (2012) used the 25-member CORDEX-Africa RCM ensemble to simulate the climate of East Africa. According to the study, most of East Africa's predicted shift in precipitation is unknown. Additionally, the study predicted that throughout both rainy and dry seasons, rainfall in northern and central Ethiopia will significantly decrease. RCMs have the ability to replicate the rainfall in East Africa, according to a study by (Nguvava, 2020), which is related to the CORDEX-Africa project. They demonstrated that the CORDEX models are useful in properly recreating the important rainfall climatology element, despite considerable biases in individual models. Based on the CORDEX multi-regional climate model (multi-RCM) experiment, **Husak et al. (2007)** found that the multi-model ensemble performed better overall than any single model. In another study, Endris et al. (2016) found that RCMs produced a biased quasi-systematic dry over Tanzania and Uganda. In order to undertake an evaluation that will use multi-RCM CORDEX models to identify the seasons with the biggest biases, their research required an abundance of advanced analysis.

The CORDEX rainfall simulations in Ugandan climate models were assessed by (Kisembe et al., 2019). Using CORDEX, the study assessed ten regional climate models' (RCMs) capacity to replicate Uganda's existing rainfall patterns from 1990 to 2008. The diagnosis of the space-time seasonal inter-annual, yearly, and seasonal rainfall variability reproducibility of the CORDEX models was made. The simulated RCM rainfall pattern biases and discrepancies were quantified using metrics series, and the results were compared to three datasets (gridded observational).

According to (Kisembe et al., 2019) study, the majority of models understated Uganda's annual rainfall pattern. On the other hand, throughout the majority of Uganda, the seasonal rainfall was accurately replicated using RCMs through a bimodal component. Additionally, the northern region similarly replicated the uni-modal component. Even though the majority of models accurately simulated the Indian Ocean Dipole (IOD) signal and the "El Niño–Southern

Oscillation" (ENSO), CORDEX models were unable to replicate the interannual dry season variability in December, January, and February. In summary, the country's rainy climate conditions were satisfactorily replicated by the ensemble means of the RCMs in ten regions, according to CORDEX.

(Ilori & Balogun, 2022)'s study evaluated how well the new CORDEX-Africa regional climate models reproduce rainfall in West African regions. The study employed RCMs that participated in CORDEX phase two, and the data came from patterns of rainfall in Western Africa from 1970 to 2005. Using a range of climatological descriptions and statistical approaches at the yearly and seasonal scale, two observations were compared between the mean ensemble (ENS-OBS) and the models, "grand ensemble mean" (ENS-RCM) and downscaling institution-based ensembles mean. The three CMIP5 GCMs were downscaled using RegCM-ENSEMBLE.

Furthermore, the Ilori and Balogun (2021) study found that in three climate zones as well as the entire Western African region, the ensemble mean and some individual models from various downscaled institutions fared better than the grand ensemble simulating average seasonal rainfall. Furthermore, the annual statistical assessment revealed that the Guinea Coast region performed poorly, with low correlation values. On the other hand, in the Sahel region, every CORDEX model had positive results. The findings suggest that the ensemble mean may be useful in increasing or decreasing the degree of uncertainty in climate models. In summary, the study found that when rainfall is projected over the Western African region over different time periods, the use of ensemble means can reduce the uncertainty in climate models.

(Munyaneza et al., 2014) conducted a study with a focus on Rwanda in order to identify the features of the drought there. Future drought was predicted using CORDEX-Africa-0.44 for RCP4.5 and RCP8.5, and the model's output was verified using observational data. Using time series analysis, coefficient of variability, and CDI software, a spatial-temporal drought analysis was carried out for the years 2021–2050. The study predicts that future drought intensity under RCP8.5 and RC4.5 will rise.

It was clear that RCPs 8.5 and 4.5 in Rwanda's western province would experience a prolonged drought. In particular, it was discovered that the drought conditions under RCP8.5 are far worse than those under RCP4.5, with the latter having extended drought features.

According to the report, drought is predicted to start early in the Western and Southern regions.

2.4 The future Drought in BUGESERA District, Rwanda's Eastern Province

Future projections of drought in Bugesera District, located in the Eastern Province of Rwanda, are crucial for planning and implementing effective adaptation strategies. The projections typically involve using climate models to simulate future climate conditions, assess changes in precipitation and temperature, and evaluate their impact on drought occurrences. This section synthesizes current knowledge and projections related to future drought trends in Bugesera District, supported by relevant sources and methodologies. **IPCC (2021)**.

Climate models are used to project future climate scenarios, including changes in temperature, precipitation, and drought frequency. These models help predict how climate change will affect drought conditions in specific regions, including Bugesera District.

General Circulation Models (GCMs): GCMs simulate climate systems to predict future temperature and precipitation based on different greenhouse gas emission scenarios (RCP4.5, RCP8.5) and **Regional Climate Models (RCMs):** RCMs provide higher-resolution projections and are used to downscale GCM outputs to specific regions like Bugesera District will be used.

The Standardized Precipitation Evapotranspiration Index (SPEI) is used to assess drought severity by combining precipitation and evapotranspiration data.(Santiago Beguería, Sergio M. Vicente-Serrano, Fergus Reig, 1994). By using the historical precipitation and temperature data to calibrate the SPEI model,

The future climate scenarios to the SPEI model shall be project the changes in drought severity and frequency.

In order to compare, identify changes, and improve CMIP6 in BUGESERA District, Rwanda's Eastern province, the comparative scenarios RCP2.6 and RCP8.5 for CMIP5 can be utilized to determine the duration, intensity, and frequency of future droughty episodes over the nation (Feng et al., 2017).

Furthermore, Yang et al. (2018) show that the SPI drought index levels can be used to estimate the future drought severity condition. As per Hosseini-Moghari et al. (2019), drought occurrences can be used to assess the severity, frequency, length, and intensity of droughts. Nonetheless, the severity, frequency, and duration of drought occurrences will be used in this study's evaluation. These drought parameters are typically used to examine the circumstances of the drought under various spatial and temporal constraints. Ahmadi et al. (2020) respond that these metrics have been used to identify possible impacts of climate change on meteorological drought features.

Additionally, (Ukkola et al., 2020) used boxplots to show how future changes in drought episodes will spread according to factors including duration, intensity, and frequency (Gebremicael et al., 2019). A common tool for displaying the most extreme numbers, including the minimum, maximum, and outliers, is the boxplot. The data for the higher (75%) and lower (25%) quartiles are also displayed.

(Haile, Tang, Li, et al., 2020) examined how drought patterns in Eastern Africa may be affected by future climate change. The longer term projection for each RCP was 2011–2099, compared to the baseline period of 1981–2010. Change departure % was used to compute the study's adjustments for the drought.

The change was expressed as a percentage change divided by the magnitude of the baseline period. Research revealed that drought-vulnerable and drought-event locations for the 21st century were predicted by the droughts in the future. The study's conclusions contribute to a deeper understanding of how climatic changes affect metrological drought, which is important for environmental policymakers looking to implement workable solutions to the threat of drought.

In a different study, (Nguvava, 2020) combined rainfall and Potential Evapotranspiration (PET) to assess the characteristics of meteorological droughts for present and future climates at the regional and river basin sizes across East Africa.

By integrating wavelet analysis and PCA, the study determined the spatiotemporal structure for four main drought modes throughout the region. Degrees of global warming (GWLs). The study predicted the features of future droughts across the major river basins of Eastern Africa at different levels of global warming (GWLs). The projections also showed that elevated PET rather than decreased precipitation is primarily responsible for the increase in drought frequency and intensity. Only forestry and shrubs, out of the four vegetation types taken into consideration, show a significant shift in the drought indices. Thus, the study's findings offer important new information about the characteristics of the upcoming drought over Eastern Africa.

2.5 Eastern Province Rwanda's Climate Change Profile

The Eastern Province has a semi-arid climate with relatively lower rainfall compared to other regions in Rwanda. It experiences significant temperature variations and periodic droughts, which are exacerbated by climate change. Water management is already severely challenged

by the effects of climate change, which are also causing environmental changes and human casualties (Warner et al., 2016).

The effects of climate change are predicted to extend the range of crop and animal pests and illnesses, which would reduce agricultural output. Climate estimates indicate that while parts of east-south Rwanda will be vulnerable to droughts and deserts, the highlands in the northwest of the country will be subject to erosion with an average annual rainfall of 100 mm to +400 mm over the period of 2000–2050 (REMA, 2009).

Rwanda is a rapidly developing nation that is home to some of Africa's densest populations and is very vulnerable to climate change. Rainfall is the primary source of energy for almost all agricultural activities, making the country very vulnerable to variations in rainfall patterns. 90% of Rwandans were employed in agriculture-related jobs in 2013, which contributed for 33% of the country's GDP. In 2015, this industry employed 80% of the workforce and contributed 40% of the GDP to the nation (Nisar et al., 2017). Rwanda is now facing more frequent droughts than it has ever had due to climate change. The economy and environment of Rwanda are severely aggravated by droughts. Furthermore, the agricultural sector in Rwanda's eastern area has been impacted by protracted droughts. It is now exceedingly difficult to maintain production levels in order to meet the rising demand for goods. Livestock in that area has been impacted by the drought.

As a result, Rwanda experiences bimodal rainfall and a tropical-temperate climate. The average yearly temperature in Rwanda has risen by roughly 0.35°C every ten years. These figures surpass the 0.27°C annual global average temperature increase seen between 1979 and 2005 (Asumadu-Sarkodie & Owusu, 2017).

2.6 Characteristics of Meteorological Droughts

Drought is a prolonged period of abnormally low precipitation, resulting in water scarcity that affects agriculture, water supply, and socio-economic stability. Historically, drought has been a recurring issue in East Africa, including Rwanda. Studies such as Kahimba et al. (2020) (Tumbo et al., 2012) highlight the impact of drought on agricultural productivity and socio-economic conditions in the region. Drought leads to reduced crop yields, water shortages, and increased vulnerability of local communities and their consequences on human health, ecosystems, biodiversity, energy, agriculture, tourism, and transportation, among other domains (Naumann et al., 2018).

Due to their non-structural nature and delayed development, droughts carry associated risks that may persist for extended periods of time even after they have stopped (Aitsi-Selmi et al., 2016).

Fundamentally, severe weather conditions like as droughts pose enormous concerns all around the world. It has been recognized that one of the key components of drought management techniques is drought monitoring and assessment. The Eastern Province of Rwanda is particularly vulnerable to the effects of climate change and the unpredictability of climate factors like rainfall. These differences are having a significant effect on the agricultural and economic sectors.

2.7 Types of Dry Spells

Droughts are typically classified into four categories based on how they affect the environment, hydrological cycle, and society. According to (Lévy et al., 1971), there are four different types of droughts: meteorological, hydrological, socioeconomic, and soil moisture (agricultural) droughts.

2.7.1 Meteorological Drought

Meteorological drought is a long-term lack of precipitation over a certain area that might last for weeks or even years. Extreme temperatures that result in different types of drought are frequently associated with meteorological droughts. The main cause of this type of drought is abnormally high tropical sea surface temperatures, which lead to consistently anomalous, widely-ranging atmospheric circulation patterns (Lévy et al., 1971). The current study supports the application of meteorological drought because of this.

2.7.2 Drought in Soil Moisture for Agriculture

Drought in soil moisture (agricultural) occurs when crops suffer from low soil moisture due to reduced precipitation and increased evaporation, making it difficult for them to acquire the water they need to grow (Lévy et al., 1971).

Droughts in soil moisture frequently have an impact on water sources, livestock, natural biodiversity, and crop productivity.

2.7.3 Water-Related Drought

When a hydrological drought is accurately identified, a shortage of river streamflow, groundwater levels, lakes, and reservoirs is referred to as a hydrological drought. Hydrological droughts, which are slow-moving and occasionally invisible, have a number of unexpected consequences on irrigation systems, water quality, hydropower, cooling water, and aquatic transportation (J. J. A. van Loon et al., 2015).

2.7.4 SocioEconomic Drought

A socioeconomic drought occurs when there is insufficient water supply to meet demand for economic products. Socioeconomic drought mostly arises when a lack of water begins to negatively influence people in non-market ways, such as the environment being harmed, food shortages, social unrest, disease outbreaks, and emigration (Brázdil et al., 2018).

2.8 Indicators of Drought

Drought indicators are frequently created to measure, track, and evaluate droughts within a specific region; they are primarily offered as standardized indices for climate change studies, drought forecasting, water management, impact modeling, and risk assessment (Santiago Beguería, Sergio M. Vicente-Serrano, Fergus Reig, 1994). McKee (1993) claims that the SPI is a commonly used, adaptable drought index that measures meteorological drought over a range of periods by accounting for precipitation characteristics. Additionally, Vicente-Serrano created the Standardized Precipitation Evapotranspiration Index (SPEI) in 2010 as an expansion of the SPI, which was initially intended to assess meteorological droughts. SPEI takes precipitation and potential evapotranspiration into consideration.

The "Palmer Drought Severity Index" (Palmer, 1965) is the third indicator. The indicator describes a region's level of dryness by utilizing temperature and precipitation measurements. According to (Cammalleri et al., 2016), flow percentiles are hydrological indicators used to track daily river shortfalls and stream flow deficits. Lastly, the Normalized-Difference plant Index (NDVI) measures the effects of drought on the plant cover using data from remote sensing.

2.9 The SPEI

The Standardized Precipitation-Evapotranspiration Index (SPEI) is a robust tool for assessing drought severity as it integrates both precipitation and potential evapotranspiration. According to **Vicente-Serrano et al. (2010)**, SPEI offers a comprehensive measure of drought by considering the atmospheric demand for moisture, which makes it more effective in capturing the full spectrum of drought conditions compared to traditional indices that focus solely on precipitation.

The Standardized Precipitation Evapotranspiration Index (SPEI) is a drought index that integrates both precipitation and potential evapotranspiration (PET) to assess drought conditions. It was developed for identifying and monitoring drought trends over multiple time scales, which is crucial for understanding the severity and impacts of drought events. For instance, **Bolaños et al. (2018)** used SPEI to analyze drought trends in East Africa and found that it provides a more accurate picture of drought severity compared to precipitation-based indices. This supports the relevance of using SPEI for a detailed analysis of drought trends in the Eastern Province of Rwanda.

Bugesera District in the Eastern Province of Rwanda experiences a semi-arid climate with distinct wet and dry seasons. The region is vulnerable to variability in precipitation and increasing temperatures, which affects both water resources and agriculture. **Ntakiyiruta, G., & Mukamurera, J. (2018)**.

Table below displays the classes of SPEI values that will be used in the study. (Heim, 2002).

Table: SPEI Value Classification

MOSITURE CATEGORY	SPEI VALUE
Extremely wet	2.00 and above
Very wet	1.50 to 1.99
Moderately wet	1.00 to 1.49
Near normal	-0.99 to 0.99
Moderately dry	-1.00 to -1.49
Severely dry	-1.50 to -1.99
Extremely dry	-2.00 and less

2.10 Simulations of CORDEX

The goal of WCRP's (World Climate Research) CORDEX (Coordinated Regional Downscaling Experiment) program is to create sophisticated regionally based-scale climate projections through international collaboration (Giorgi, 2014). Furthermore, according to Jones et al. (2011), CORDEX offers the possibility of effect assessment, modeling activity coordination within regional climate modeling, and adaptation research in various regions. In general, detailed studies of climatic processes are aided by regional climate models. The CORDEX models for the Africa-Domain are shown in the figure below.

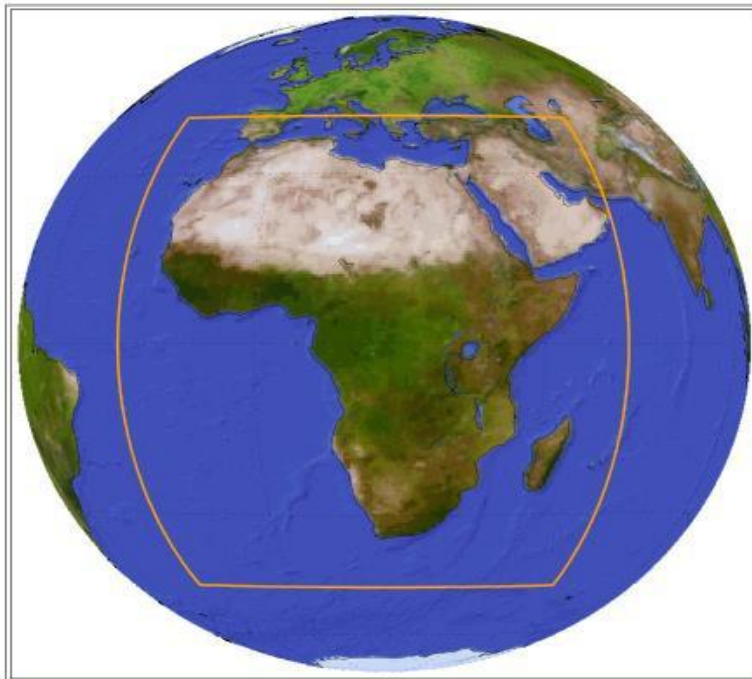


Figure 3: Study domain within the CORDEX models: Africa (WCRP CORDEX)

CHAPTER 3: DATA AND METHODS

3.0 Overview

The methods utilized for data collecting and analysis, along with the technique employed to meet the study's goals, comprise this chapter. Thus, several subsections pertaining to data and methods are provided.

3.1 The Data

The Rwanda Meteorological Agency provided monthly 4 km × 4 km gridded ENACTS rainfall data from 1980–2020 for the Eastern province of Rwanda, and the monthly 25 km x 25 km CORDEX data from 2022–2099 were used in this analysis.

3.1.1 Observed Data

In order to determine drought indices, this study will employ meteorological information, such as monthly rainfall, over the baseline period of 1980–2020. According to (Dinku et al., 2014), the SPEI is primarily recommended for meteorological droughts and uses the Rainfall datasets. SPEI evaluated the drought's spatiotemporal trends in the Eastern Rwandan Province, Bugesera District between 1985 and 2020. Meteo Rwanda provided observational monthly gridded ENACTS rainfall data for the years 1985–2020, with a horizontal resolution of 5 km × 5 km.

3.1.2. Data from Climate Models

The Africa dataset was used by the CORDEX in this study. The Future (2021-2100) scenarios dataset and the Historical (1985-2020) dataset, which was corroborated by field observations, were the two sets of data used. They were downloaded from the ESGF portal. Furthermore, the climatic data were derived from the output of the CORDEX model. The daily rainfall data from CORDEX for the Africa Domain (AFR-22) was extracted across Rwanda and aggregated to a monthly level for the historical and projected estimations included in this paper. The ENACTS dataset had a spatial resolution of 4 km x 4 Km, but the CORDEX dataset had a spatial resolution of 25 km x 25 km. As a result, the ENACTS were re-gridded using an inverse distance weight to measure 4 km by 4 km.

In the Eastern Province of Rwanda, the CORDEX dataset was utilized to assess historical and future drought experiences using particular regional climate modeling (RCMs) simulations at a high geographical resolution of 25 km (0.22°) (Ahmadi et al., 2020). Based on the study surface area, a simulation set is accessible for every CORDEX domain. For this research, the AFR-22 Domain dataset was utilized, which consists of three RCMs (REMO2015, CCLM5-0-15, and ICTP-RegCM4-7) and four GCMs (MOHC-HadGEM2-ES, MPI-M-MPI-ESM-LR, NCC-NorESM1-M, and ECMWF-ERA-INT) on each GCM.

3.2 The Methods

The method used in this study to achieve its goals is presented in this section. The SPEI was used to quantify the past climatic droughts within Rwanda's Eastern Province and to determine their characteristics.

3.2.1 The Rainfall's Spatial-Temporal Characteristics

Using historical data from the selected period (1985-2020), gamma distribution fitting was used to calculate the SPEI. The computation involved the fitting of a gamma distribution function to the frequency distribution of the monthly precipitation totals for three months (Three months SPEI) and Six months (Six months SPEI) in the Eastern province of Rwanda, Bugesera District. This aided in illustrating to the ensemble members' distribution how future trends in meteorological drought patterns are anticipated to shift. Consequently, a normal distribution with a single variance and a zero mean was fitted to the gamma distribution (Shiau, 2020). The precipitation amounts were recorded and matched to the standard normal distribution after a monthly accumulation period.

The study examined the SPEI time series using observed rainfall data from designated locations, identifying a drought from 1985 to 2020. Thus, using SPEI, the obtained forecast rainfall was evaluated for drought characteristics.

The monthly precipitation time series was modeled in the current study using several statistical distributions to initiate the SPEI computation (Lloyd-Hughes & Saunders, 2002). In the current investigation, the gamma distribution was employed. The SPEI was computed using monthly data for the specified time frames.

3.2.2 The Past Drought Features in terms of Length, Intensity, and Frequency

In the current study, the Bugesera District's SPEI indices' variability was calculated as a drought indicator. Patterns of interannual and seasonal SPEI variations were compared using the datasets (1985-2020). To determine the prior drought frequency, the number of each drought category for every year from the baseline era (1985–2020) was used.

Long-term precipitation over a specific time period served as the foundation for the SPEI computation. The cumulative gamma distribution was calculated as part of the SPEI value calculating process.

3.2.3 The Future Features of Drought in the affected Climate

This goal evaluated the principal drought-prone locations in Rwanda's Eastern Province, Bugesera District. The study made use of rainfall time series at several geographical, meteorological, and temporal resolutions from the CORDEX-Africa-0.22[^] output. For each 26-year period, individual model simulations from the CORDEX datasets were examined based on the years 2022–2099. It was assessed whether the rainfall over the Eastern province, Bugesera District could be replicated by the simulation. In order to comprehend the behavior of the future drought in relation to these historical drought characteristics, the future changes in SPI drought parameters throughout Eastern province were compared with historical drought characteristics.

The CORDEX over Africa dataset (van Vuuren et al., 2011) was used to aggregate the daily-simulated data to monthly rainfall from 2022 to 2099 using the low emission typical scenario of RCP2.6 and extreme RCP8.5. The study used the monthly data for forecasting SPEI for the future and compared CORDEX's performance over the eastern province of Rwanda in terms of drought length, severity, and frequency.

3.2.4. The evaluation of the CORDEX model's capability

The patterns of precipitation in Rwanda's Eastern Province, Bugesera District are complicated. Therefore, using climate models can help gain a solid understanding of the spatiotemporal variability of rainfall. In order to get climate projections with confidence that analyze global climate changes impacting precipitation and its related implications, model validation is necessary (Van Vooren et al., 2018). In this work, the model prediction for the Eastern Province of Rwanda from the CORDEX is compared with observational data sets (ENACTS) covering the period from 1985 to 2020.

3.2.5 The conceptual Framework

Climate change has an impact on the long-term increases in temperature, precipitation, drought, floods, and extreme occurrences. When analyzing droughts, ENACTS rainfall and temperature products are crucial. The ENACTS databases aid in the acquisition of relevant drought-related data for decision-making. Policies for adaptation at various levels can examine ways to help farmers and other affected parties deal with the effects of drought in order to reduce these risks.

3.3 The SPEI Method Utilization

Recent studies have applied SPEI to understand drought patterns in various African regions. For instance, Bolaños et al. (2018) used SPEI to analyze drought trends in East Africa and found that it provides a more accurate picture of drought severity compared to precipitation-based indices. This supports the relevance of using SPEI for a detailed analysis of drought trends in the Eastern Province of Rwanda.

SPEI is used to assess drought conditions by analyzing deviations from historical norms, considering both moisture availability and demand. It is particularly effective for identifying and monitoring drought trends over multiple time scales, which is crucial for understanding the severity and impacts of drought events.

Bugesera District in the Eastern Province of Rwanda experiences a semi-arid climate with distinct wet and dry seasons. The region is vulnerable to variability in precipitation and increasing temperatures, which affects both water resources and agriculture. Ntakiyiruta, G., & Mukamurera, J. (2018).

The procedure to calculate the SPEI is similar to that of calculating the Standard Precipitation Index (SPI); however, the advantage of the SPEI is that it takes into account temperature variability (Howard et al., 2014). SPEI was developed through a combination of the Palmer Drought Severity Index (PDSI) and the multi-temporal ability of the SPI (Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010))

By using the R package 'SPEI', we computed the annual Standardised Precipitation Evapotranspiration Index (SPEI), a drought indicator based on monthly PET and precipitation data (Vicente-Serrano et al., 2010), which is used to establish drought conditions related to

climate change (e.g., Haile et al., 2020;Li et al., 2015;Potop et al., 2014) and is considered a comprehensive measure of water availability (Stagge et al., 2014).

The Standardized Precipitation-Evapotranspiration Index (SPEI) used measure based on arguments in Vicente-Serrano et al. (2010). SPEI has positive and negative ranges where values greater than 2 are considered extremely wet and values below – 2 extremely dry. (Vicente-Serrano et al. 2010;Li et al. 2015;Yao et al. 2019;Zarei and Moghimi 2019).

3.4. The SPEI Datasets

Meteorological data used in this study, including mean monthly precipitation, mean monthly maximum and minimum temperature of stations in the study area for the period 1985 to 2020, were collected from the Rwanda Meteorological Agency.. Therefore, we fill the data gaps using another version of data, namely, gridded (4 km × 4 km) climate data obtained from Meteo Rwanda. These gridded data are the product of enhancing the national climate services (ENACTS) initiative, developing and implementing a tool for quality control of observations at national weather services. The complete data for the entire stations were then summarized for use in R-statistical package to calculate the index values for SPI/SPEI at 3- and 12-month timescales.

The following are several key steps for calculating the SPEI values, including the calculation of potential evapotranspiration (PET), the water balance, and fitting a probability distribution.

1. Hargreaves Method for PET Calculation

The **Hargreaves method** is simpler and can be used when only temperature data is available.

$$PET = 0.0023 (T_{mean} + 17.8) \sqrt{T_{max} - T_{min}} (T_{max} - T_{min})$$

Where:

T_{mean} =Mean monthly temperature (°C)

T_{max} = Maximum monthly temperature (°C)

T_{min} = Minimum monthly temperature (°C)

2. Calculate the water Balance

$$Water\ balance_t = Prespitation_t - PET_t$$

Where:

$Prespitation_t$ =The total precipitation for month t

PET_t =The PET for month t

$$\text{Cumulative water balance}_t = \sum_{i=0}^{N-1} (\text{Prespitation}_{t-i} - \text{PET}_{t-1})$$

Where N is the number of months in the period (e.g, 12 months for a 12-month SPEI).

3. Gamma Distribution for Standardization

To convert the cumulative water balance into a standardized form, fit a **Gamma distribution**. The Gamma distribution has two parameters: shape (α) and scale (β).

The probability density function (PDF) of the Gamma distribution is given by:

$$f(x, \alpha, \beta) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad \text{When } x \geq 0,$$

otherwise $f(x) = 0$ and assure $\beta > 0, \alpha > 0$

- $\alpha > 0$,shows the shape parameter
- $\beta > 0$,Indicate the scale parameter
- $x > 0$,shows the amount of the cumulative water balance.
- $\Gamma(\alpha)$ Indicate gamma factorial function i.e. $\Gamma(\alpha)! = \alpha - 1$

The cumulative distribution function CDF is:

$$F(x; \alpha, \beta) = CDF_{\text{gamma}}(x; \alpha, \beta) = \frac{\gamma\left(\alpha, \frac{x}{\beta}\right)}{\Gamma(\alpha)}$$

Where:

$$\gamma\left(\alpha, \frac{x}{\beta}\right) = \text{Lower incomplete gamma function}$$

$$\Gamma(\alpha) = \text{Gamma function with } \Gamma(\alpha)! = \alpha - 1$$

4. Standardization to Z-Score

To convert the CDF to a z-score, the inverse of the standard normal distribution (**z-table**) is needed to find the z-score corresponding to the CDF value.

$$SPEI = \Phi^{-1} (CDF_{\text{gamma}})$$

Where: Φ^{-1} is the inverse of the standard normal **CDF**

Interpretation of the SPEI values

MOSITURE CATEGORY	SPEI VALUE
Extremely wet	2.00 and above
Very wet	1.50 to 1.99
Moderately wet	1.00 to 1.49
Near normal	-0.99 to 0.99
Moderately dry	-1.00 to -1.49
Severely dry	-1.50 to -1.99
Extremely dry	-2.00 and less

By analyzing SPEI data, stakeholders can better understand historical drought trends and predict future drought scenarios. This information is crucial for developing effective water management strategies, agricultural planning, and mitigating the impacts of drought on local communities. **Kilonzo, M., & Gichuki, F. (2017).**

Drought in Rwanda

Understanding historical climate and drought trends in Rwanda involves examining changes in temperature, precipitation patterns, and the impact of these changes on drought conditions. Here's an overview of key studies and sources related to historical climate and drought trends in Rwanda: **Mimura, N., et al. (2014)**

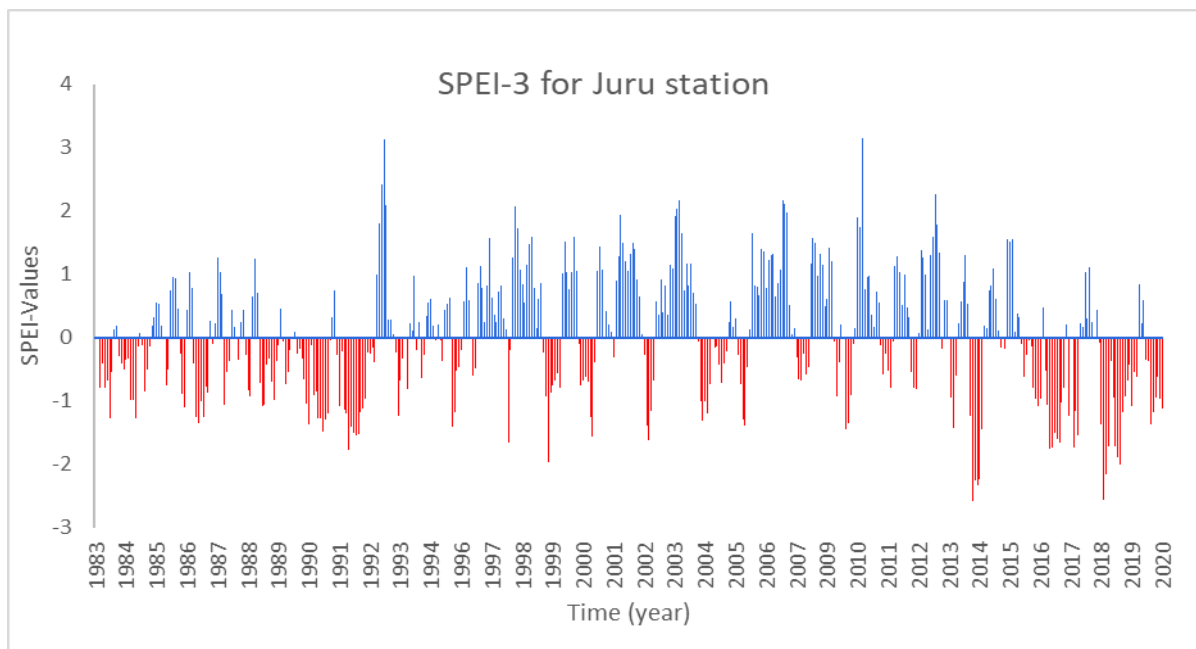
CHAPTER 4: FINDINGS AND DISCUSSIONS

4.0 Overview

This chapter includes analyses for every distinct goal, along with comments of the findings for each. The results are shown in the table and figures.

4.1. Temporal characteristics of Rainfall over BUGESERA District, Eastern Province of Rwanda

The following figures the trends which indicate the effects of climate change on Drought over Bugesera District in period from 1985 to 2020 and show the SPEI values.



The SPEI-3 graph for the Juru station (1983–2020) illustrates fluctuations in moisture conditions over time, using the Standardized Precipitation-Evapotranspiration Index (SPEI-3). The findings indicate that:

Positive SPEI values (Blue): Indicate wetter-than-average conditions, with higher values reflecting more intense wetness.

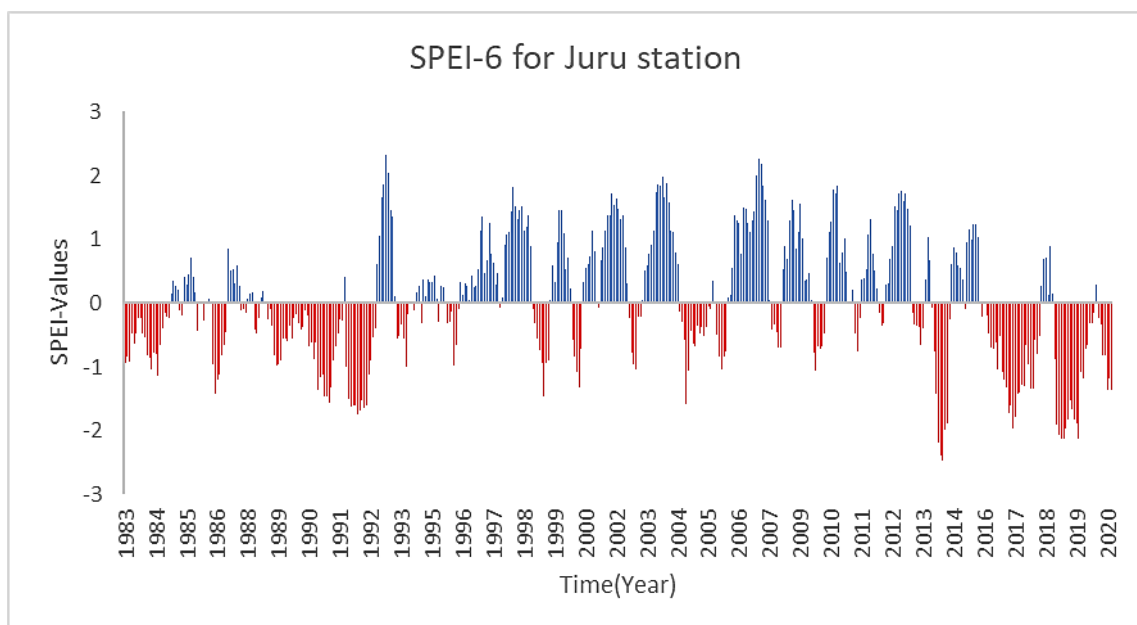
Negative SPEI values (Red): Indicate drier-than-average conditions, with lower values signaling more severe droughts.

Period Analysis

- **1983–1991:** This period is marked by frequent negative values, indicating moderate to severe droughts. Extreme droughts approached -2, with few wet occurrences.

- **1992–1993:** A dramatic peak in 1992, exceeding +3, indicates an extremely wet event, contrasting sharply with the previous drought years.
- **1994–2009:** This period shows variability with regular shifts between wet and dry spells. Notable wet conditions occurred around 1998, but there were also significant dry periods in the early 2000s.
- **2010–2020:** The graph predominantly features negative values, with frequent dips below -1.5, indicating severe and persistent droughts. Wet periods are rare.

The graph suggests that the Juru station region has been experiencing an increase in the frequency and intensity of droughts, particularly from 2010 onward. These results may have significant implications for agriculture, water resources, and climate resilience in the area. Wet periods are less frequent in the last decade, and the drying trend is more pronounced.



The Standardized Precipitation-Evapotranspiration Index (**SPEI-6**) evaluates moisture conditions over a six-month period, providing valuable insights into medium-term climate anomalies such as seasonal droughts and wet periods.

Decadal Interpretation

1983–1992:

- **1983 to 1985:** This period was predominantly dry, with negative SPEI values indicating moderate to moderately severe drought. Although 1985 showed some improvement with a few wet months, the overall conditions remained challenging.

- 1986 to 1988: Conditions fluctuated during this time. Years 1986 and 1987 experienced a mix of dryness (with values dropping to -1.4) and wetness, while 1988 showed near-normal to slightly wet conditions.
- 1989 to 1992: A trend towards increased dryness emerged, especially in 1991 and 1992, with consistently negative SPEI values indicating severe drought levels (ranging from -1.5 to -1.7).

1993–2002:

- 1993: Marked a sharp contrast with extremely wet conditions, peaking at an SPEI of 2.3, indicating an unusually wet period.
- 1994 to 1999: This decade saw a transition to drier conditions, particularly in 1999, which experienced severe to extreme drought, with values falling to -1.4.
- 2000 to 2002: Although there were some wet periods in 2000 and 2001, the trend towards drought re-emerged in 2002, with SPEI values dropping as low as -1.5.

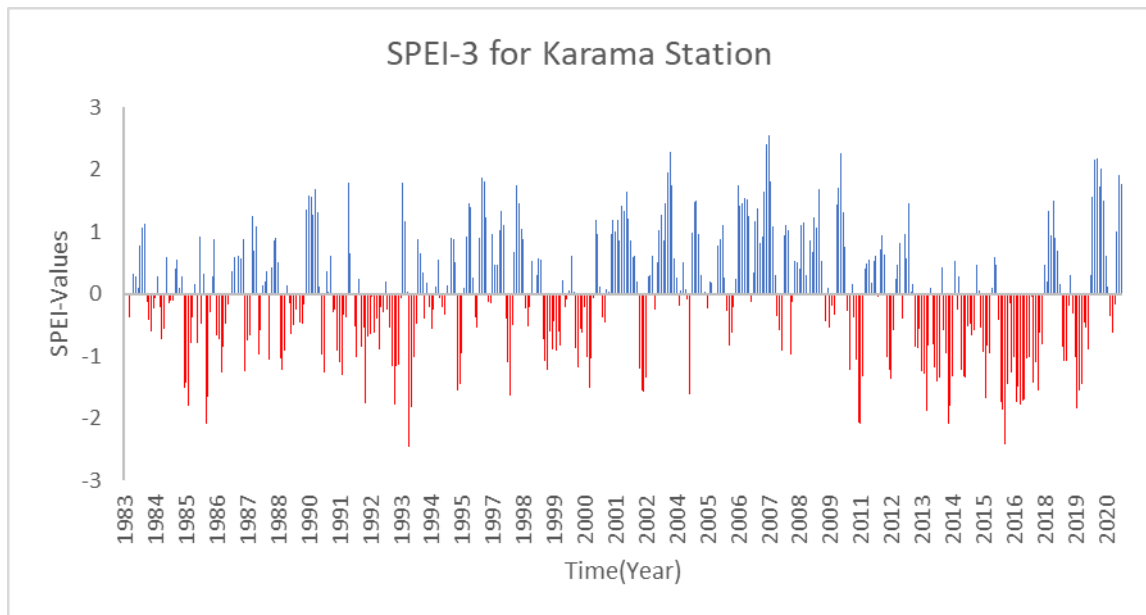
2003–2012:

- 2003 to 2007: This period experienced generally wet conditions, with notably extremely wet years in 2003 and 2007, achieving values above 2.
- 2008 to 2012: Continued the trend of wet conditions, particularly in 2011 and 2012, with SPEI values indicating moderate to severe wetness.

2013–2020:

- 2014: This year marked the return of severe to extreme drought, with SPEI values dropping to -2.4.
- 2015 to 2017: Conditions fluctuated, but there was an overall trend towards dryness, with multiple months indicating moderate drought.
- 2018 to 2020: Severe to extreme drought conditions dominated, especially in 2019, when values consistently fell below -2, indicating extreme drought.

Therefore, the SPEI-6 analysis underscores significant fluctuations in moisture conditions over the decades, highlighting periods of both abundance and drought, with increasing trends of severe drought particularly noted in recent years. If there are specific years or trends you wish to explore further, please let me know!



The presented values represent the Standardized Precipitation-Evapotranspiration Index (SPEI) on a 3-month scale (SPEI-3), a measure that quantifies droughts and wet periods by comparing precipitation and evapotranspiration data. Here's a detailed interpretation of the results:

1. Positive SPEI Values:

Positive values indicate wet periods, with higher values reflecting wetter conditions. For example, in 1990, there were consistently high positive SPEI values, reaching as high as 1.58, signifying significantly wetter conditions that year.

2. Negative SPEI Values:

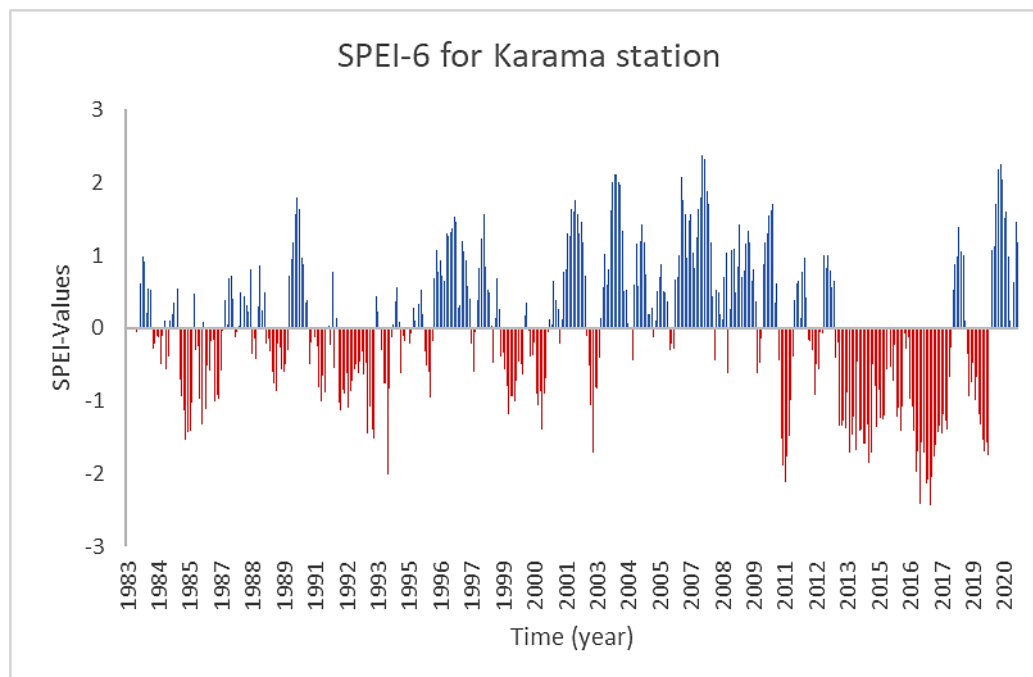
Negative values represent drought periods, with lower negative values indicating more intense drought. In 1986, SPEI values dropped to -2.08, reflecting severe drought conditions.

Interpretation

- **1983-1985:** This period shows mixed results, with some negative values indicating mild drought conditions, particularly in 1985, when SPEI dipped to -1.81.
- **1986:** A notably significant drought year, marked by some of the lowest SPEI values at -2.08.
- **1990:** An extremely wet year, characterized by numerous SPEI values well above 1, indicating robust wet conditions.
- **2003-2006:** These years experienced considerable wetness, particularly in 2003, which had values as high as 2.30, indicating an extremely wet period.

- **2010-2011:** This timeframe displayed a mix of conditions, predominantly severe drought, with SPEI values falling to -2.06 in both years.
- **2019-2020:** A recovery phase, with high positive values indicating very wet conditions, peaking around 2.17 in 2020.
- ✓ The dataset highlights significant variability in climate and moisture availability, with certain years experiencing severe drought or wet conditions.
- ✓ Some entries contain missing data, indicated as "NA," which may reflect gaps in the dataset collection for those specific months.

Therefore, this dataset illustrates the fluctuations between wet and dry periods over several decades, highlighting notable extremes in both droughts and floods during specific years. The analysis underscores the dynamic nature of climate conditions and moisture availability throughout the recorded years.



The data comprises Standardized Precipitation-Evapotranspiration Index (SPEI) values calculated over six-month intervals across various years, providing insights into drought conditions by comparing precipitation and potential evapotranspiration.

INTERPRETATION

- ✓ Positive values indicate wetter conditions (more precipitation or less evapotranspiration), while **negative values** signal drier conditions (less precipitation or more evapotranspiration).

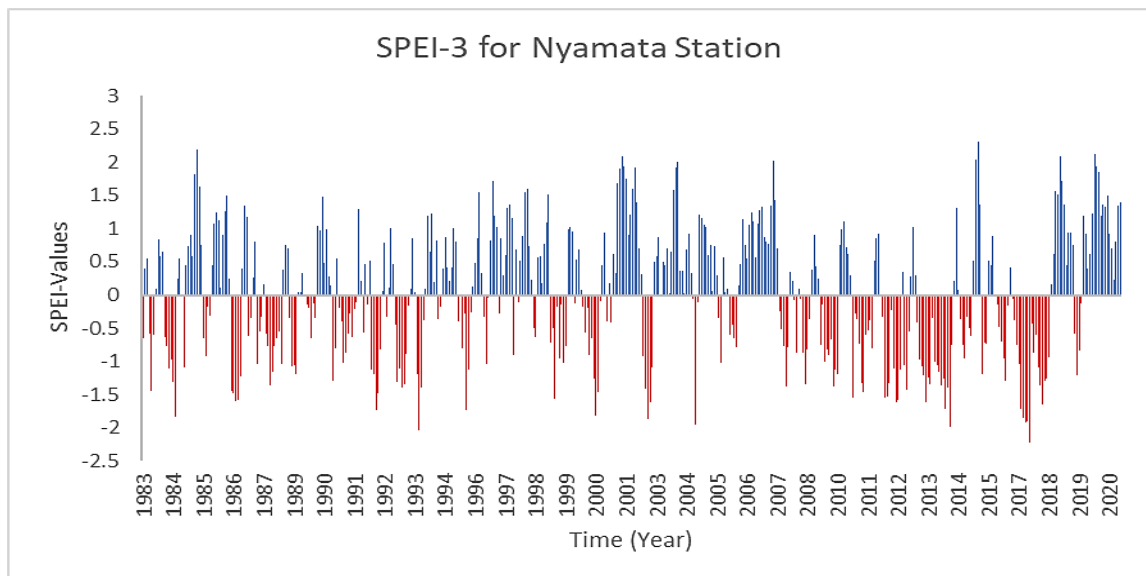
Trends in Data

- **1983-1984:** The data begins with a mix of missing values and a few recorded SPEI values. Fluctuations in 1984 suggest variable moisture conditions.
- **1985-1986:** Significant drops in SPEI values, particularly in 1985, indicate severe drought. Recovery begins in 1986 but values remain mostly negative.
- **1987-1992:** This period exhibits a mix of positive and negative values, reflecting fluctuating moisture conditions with some years better than others.
- **1993-1996:** Notable droughts occur in 1993 and 1994, with very low SPEI values. Improvement is seen in the latter part of this period as values become more positive.
- **1997-2000:** Generally positive SPEI values suggest wetter conditions, although fluctuations remain.
- **2001-2005:** Predominantly positive values indicate favorable moisture conditions, interspersed with some negative values.
- **2006-2009:** Mostly positive SPEI values indicate generally favorable moisture conditions with occasional dry spells.
- **2010-2014:** A mix of positive and negative values is observed, with significant drought in 2010 and some recovery in subsequent years, though 2014 ends with negative values.
- **2015-2019:** This period sees notable droughts, particularly in 2015 and 2019, with several consecutive negative values, though some recovery is indicated in other years.
- **2020:** A significant positive trend is noted, with consistently high SPEI values suggesting an exceptionally wet year.

Conclusion

- **Drought Periods:** Key drought years include 1985, 1993, 1994, 2010, and 2015, characterized by consistently negative SPEI values.
- **Wet Periods:** Wet conditions are prominent in the early 2000s and 2020, marked by consistently positive SPEI values.
- **Fluctuations:** The data reveals natural variability in moisture conditions over time.

Overall, the dataset highlights a dynamic pattern of moisture conditions, with alternating periods of drought and abundance. This information is valuable for assessing historical drought trends and understanding long-term patterns in precipitation and evaporation.



The data you've provided represents the Standardized Precipitation Evapotranspiration Index (SPEI) at a 3-month scale (SPEI-3) from 1983 to 2020. SPEI is a drought index that incorporates precipitation and potential evapotranspiration, allowing it to capture both wet and dry conditions over time.

Temporal Variability:

- ✓ **Droughts:** Periods with SPEI-3 values below -1 typically indicate drought conditions. Examples include significant drought years such as 1984, 1992, 1993, 1999, 2000, 2007, 2014, and 2017.
- ✓ **Wet Periods:** SPEI-3 values above 1 suggest unusually wet conditions. For instance, 1985, 1996, 2003, 2004, 2005, 2015, 2018, and 2019 show periods with above-average moisture.

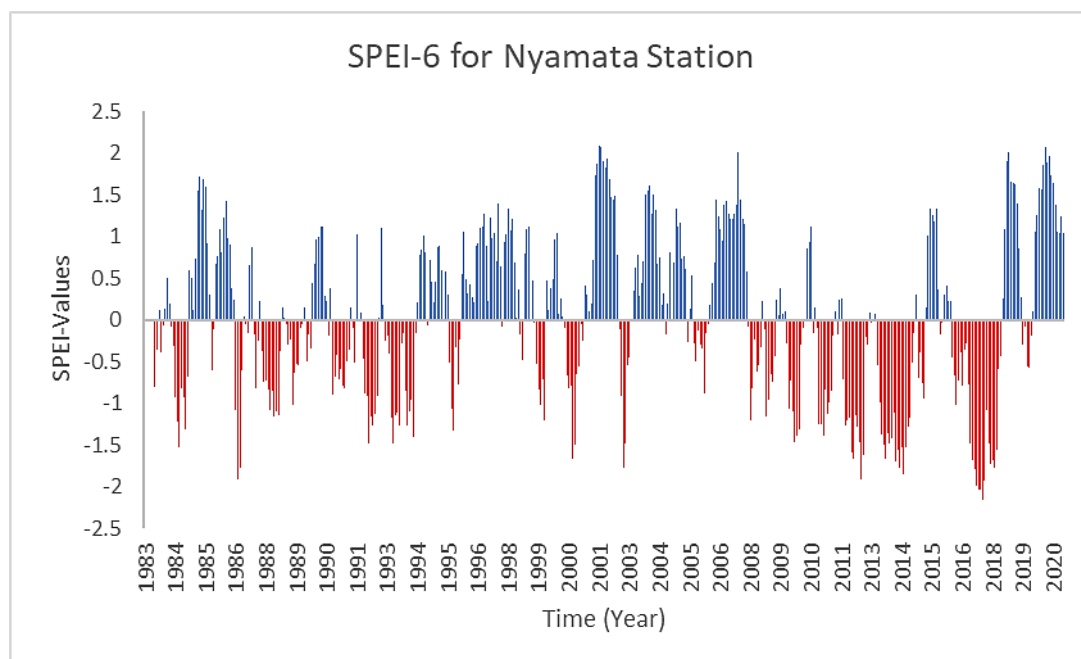
Recent Trends:

- ✓ **Increasing Dryness:** There's a noticeable trend of increasing drought severity in the late 2010s, with some of the lowest SPEI-3 values recorded in 2017.
- ✓ **Recent Wetness:** From 2018 onwards, there seems to be an increase in wet conditions, with high SPEI-3 values in 2018, 2019, and 2020.

Interpretation by Year

- **1983-1985:** This period shows a mix of wet and dry conditions. The years 1984 and 1985 are particularly notable for their extreme values.

- **1986-1991:** The mid-1980s to early 1990s experience fluctuating conditions with notable droughts in 1986 and 1990.
- **1992-1999:** A period with significant drought years, particularly 1992, 1993, and 1999. The late 1990s sees recovery with some wetter years.
- **2000-2007:** The early 2000s feature a mix of dry and wet conditions, with some recovery from the earlier drought periods.
- **2008-2015:** This period includes significant droughts in 2008 and 2014, with recovery and periods of wetness in between.
- **2016-2020:** Recent years show high variability with a noticeable trend towards wetter conditions towards the end of the decade.



The dataset you provided represents the Standardized Precipitation-Evapotranspiration Index over a 6-month period (SPEI-6) for each year from 1983 to 2020. Here's a general interpretation of the results:

Precipitation and Drought Variability:

- ✓ The SPEI values range from highly negative to positive. Negative values indicate drought conditions, while positive values suggest wet conditions.
- ✓ For several years, such as 1983 and 2014, there are extended periods with significantly negative values, indicating severe droughts.
- ✓ Conversely, some years like 2001, 2002, 2003, and 2020 show periods with consistently positive values, reflecting more favorable moisture conditions.

Decadal Variations:

- ✓ **1980s and 1990s:** This period includes several years with significant drought conditions, particularly in the mid-1980s and early 1990s. For instance, 1984 and 1992 have multiple months with very low SPEI values, indicating widespread drought.
- ✓ **2000s:** There is a noticeable increase in positive SPEI values in the early 2000s, suggesting a period of higher moisture and fewer drought events.
- ✓ **2010s:** The decade starts with a mix of positive and negative values, with a significant drop in SPEI values in the late 2010s, reflecting more severe drought conditions.

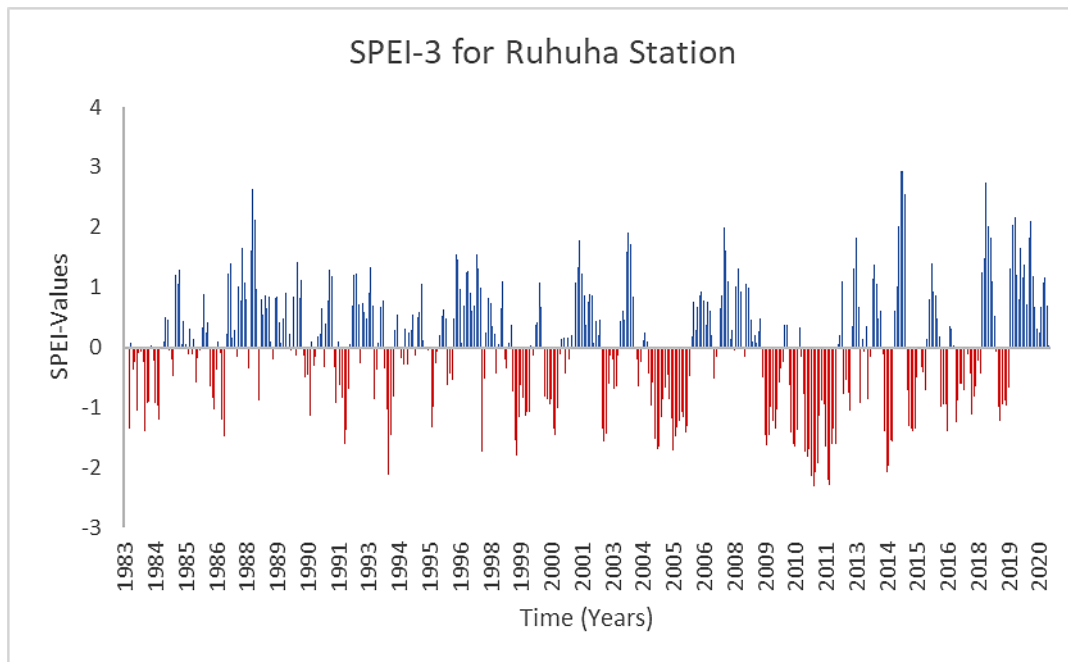
Recent Trends:

- ✓ **2018-2020:** This period shows a significant increase in SPEI values, particularly in 2019 and 2020, indicating a shift towards wetter conditions.

Detailed Observations:

- ✓ **1983:** Mostly missing data or very mixed values with a few positive and negative values, suggesting inconsistent moisture levels.
- ✓ **1984:** A year with severe drought conditions, with many months showing very low SPEI values.
- ✓ **1985-1986:** These years have a mix of positive and negative values, with some months showing high moisture levels.
- ✓ **2001:** Marked by very high positive values, indicating a particularly wet period.
- ✓ **2008-2011:** There are multiple years with severe droughts, with values dropping significantly in several months.
- ✓ **2017-2018:** Displays high positive values towards the end, indicating a return to wetter conditions.
- ✓ **2020:** Shows consistently high positive values, indicating a period of substantial moisture and less drought stress.

Therefore, the dataset highlights significant variability in moisture conditions over the decades. The 1980s and early 1990s experienced severe drought, while the early 2000s saw improved moisture levels. The trend in recent years, particularly from 2018 onwards, suggests a shift towards wetter conditions. This interpretation can help understand long-term climate patterns, water resource management, and agricultural planning.



To interpret the data provided, which appears to be values of the Standardized Precipitation-Evapotranspiration Index (SPEI) for various years, we should consider the following:

Values near Zero: Suggest normal conditions with neither surplus nor deficit.

Interpretation of Results

Trends Over Time:

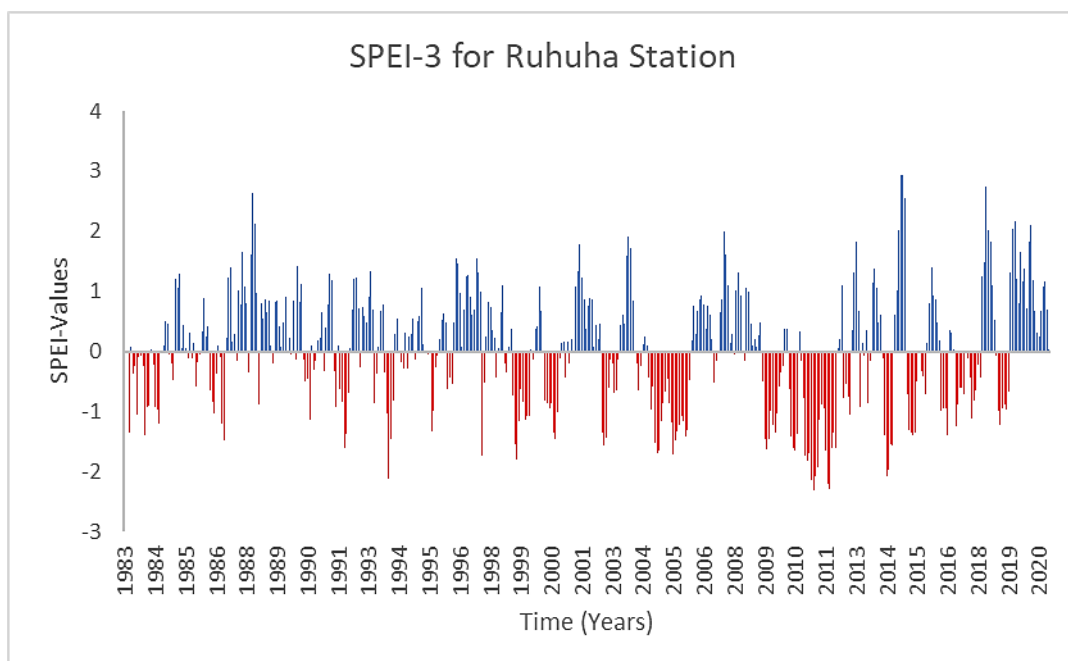
- ✓ **1983-1990:** The data shows a mix of positive and negative values. Notable dry years are seen in 1983 and 1984, while some years (like 1985) show relatively higher positive values indicating wetter conditions.
- ✓ **1991-2000:** This period also has a variety of SPEI values, with some years (e.g., 1991, 1994) showing positive values, indicating wet periods, and others (e.g., 1999, 2000) showing negative values, indicating dry conditions.
- ✓ **2001-2010:** There are fluctuations between wet and dry years, with some extreme negative values (e.g., 2010) indicating significant drought conditions, and some high positive values (e.g., 2001) indicating very wet conditions.
- ✓ **2011-2020:** This period shows a mix of extreme values. For instance, 2011 and 2014 have very negative values, indicating severe droughts. Conversely, 2018 and 2019 show strong positive values, suggesting very wet conditions.

Extreme Events:

- ✓ **Severe Droughts:** Years such as 1999, 2004, 2005, and 2011 exhibit very low (often negative) values, suggesting severe drought conditions.
- ✓ **Extreme Wet Conditions:** Years like 1988, 1993, 2018, and 2019 show very high positive values, indicating periods of excessive moisture or floods.

Recent Trends:

- ✓ The data from the last decade (2010-2020) suggests increased variability, with both extreme wet and dry conditions occurring, which might reflect changing climate patterns. The dataset shows considerable variability in moisture conditions over the years, with periods of both extreme wetness and drought. This variability can be indicative of changing climate patterns or shifts in precipitation and evapotranspiration dynamics. The most recent decade shows increased extremes, which could be a sign of more pronounced climate changes affecting the region.



The data you've provided appears to be a series of Standardized Precipitation-Evapotranspiration Index (SPEI) values over several years. The SPEI is a drought index that measures the difference between precipitation and evapotranspiration over a given period, and it's used to assess drought conditions.

General interpretation of these results:

Trend Analysis:

- ✓ The values vary widely from highly negative to positive. This suggests periods of both severe drought and wet conditions.

- ✓ Significant negative values indicate drought conditions, where the amount of evapotranspiration exceeds precipitation.
- ✓ Positive values represent wetter conditions where precipitation exceeds evapotranspiration.

Decadal Patterns:

- ✓ **1980s to Early 1990s:** The 1980s and early 1990s show a mix of positive and negative values, with several years of severe drought (e.g., 1983, 1992) followed by wetter conditions (e.g., 1988).
- ✓ **1990s:** This period includes more fluctuating values with noticeable drought years in the late 1990s (e.g., 1999).
- ✓ **2000s:** The early 2000s show a trend of increasing drought severity and recovery with some wetter years in the middle of the decade.
- ✓ **2010s:** This period shows severe drought conditions at the beginning of the decade (e.g., 2011), but also several years of wetter conditions towards the end (e.g., 2019).

Recent Years:

- ✓ The most recent years (2018-2020) show a mix of positive and negative values with some periods of significant drought followed by recovery and increased moisture. For example, 2018 had several positive values indicating wetter conditions, while 2019 and 2020 show both drought and wet conditions, with a general trend towards wetter conditions.

Extreme Values:

- ✓ The most extreme values in the dataset are from 2011, which shows some of the lowest (most negative) SPEI values, indicating severe drought conditions.

Recent Severe Drought:

- ✓ The end of the dataset (e.g., 2020) includes some negative values, suggesting that there were periods of drought even in recent years.

Therefore, the data suggests a fluctuating climate pattern with significant periods of both drought and wet conditions over the years. The interpretation of these values can be used for assessing water availability, agricultural planning, and understanding regional climate variability.

4.1 The Trend of Rainfall and Temperature in Bugesera District Rwanda's Eastern Province

The following figures illustrate the rainfall and Temperature variations over the Eastern province of Rwanda, Bugesera District based on the Standardized Precipitation Index (SPEI): Figures 5 through 14 utilize seasonal timescales (three months' SPEI) and annual (12 months' SPEI).

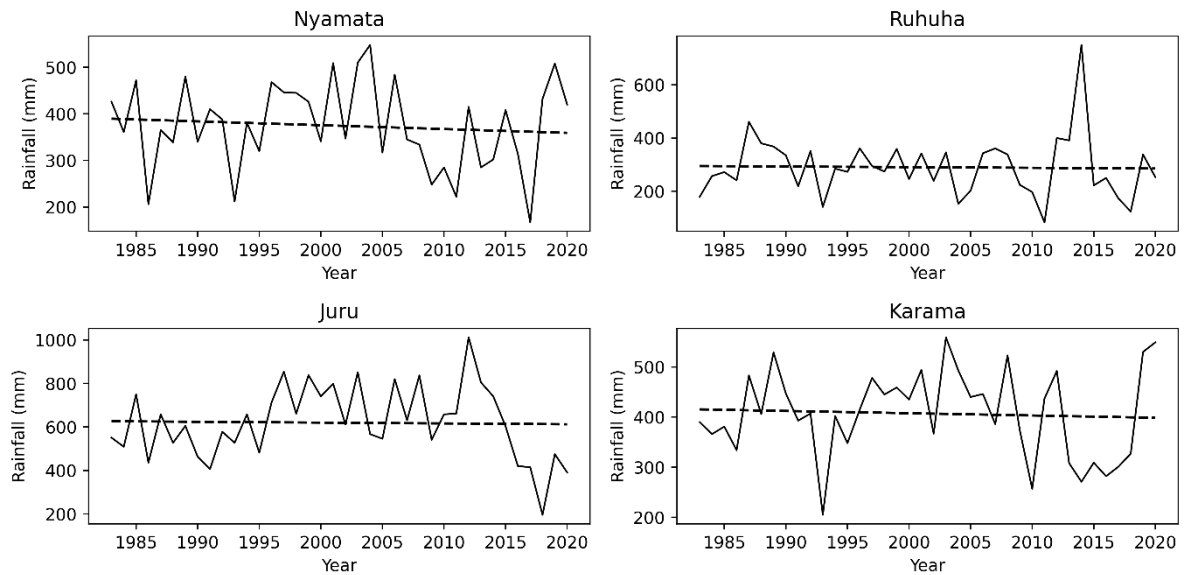


Figure 1: The rainfall trend in annual rainfall total

The annual rainfall totals (Figure 1) indicate a clear variability pattern over all stations used in this study with a different nature of variability. The results obtained using graphical method indicated a non-significant increasing trend at Nyamata, Karama and Juru stations while a decreasing trend was revealed at Ruhuha stations from 1985 to 2020

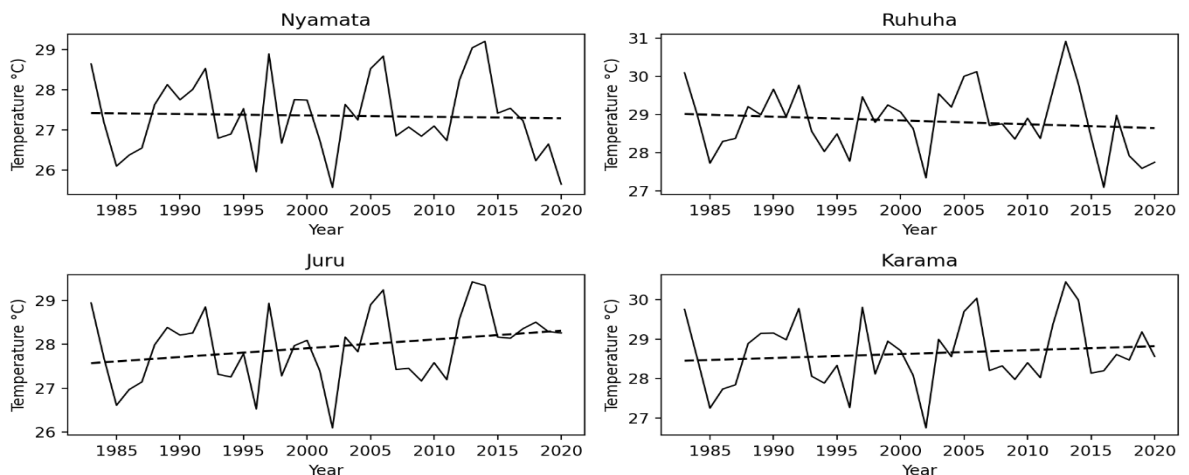


Figure 2: The temperature trend in annual maximum temperature total

The annual maximum temperature (Figure 2) indicate a clear variability pattern over all stations used in this study with a different nature of variability. The results obtained using graphical method indicated a significant increasing trend at all stations from 1985 to 2020

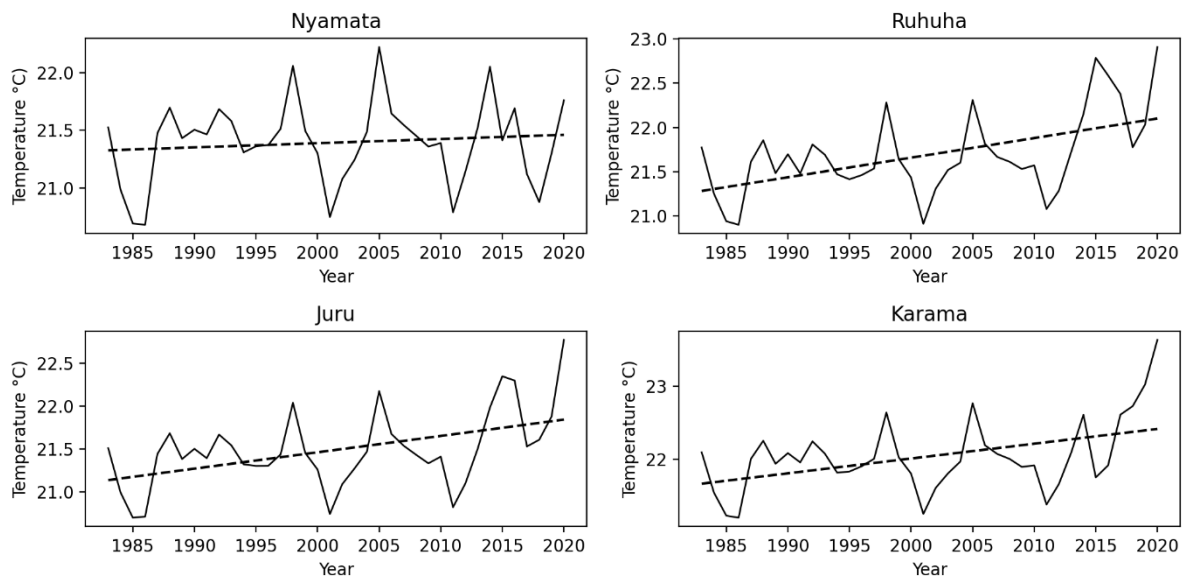


Figure 3: The temperature trend in annual mean temperature total

The annual mean temperature (Figure 3) indicate a clear variability pattern over all stations used in this study with a different nature of variability. The results obtained using graphical method indicated a significant increasing in tmean trend at all stations from 1985 to 2020.

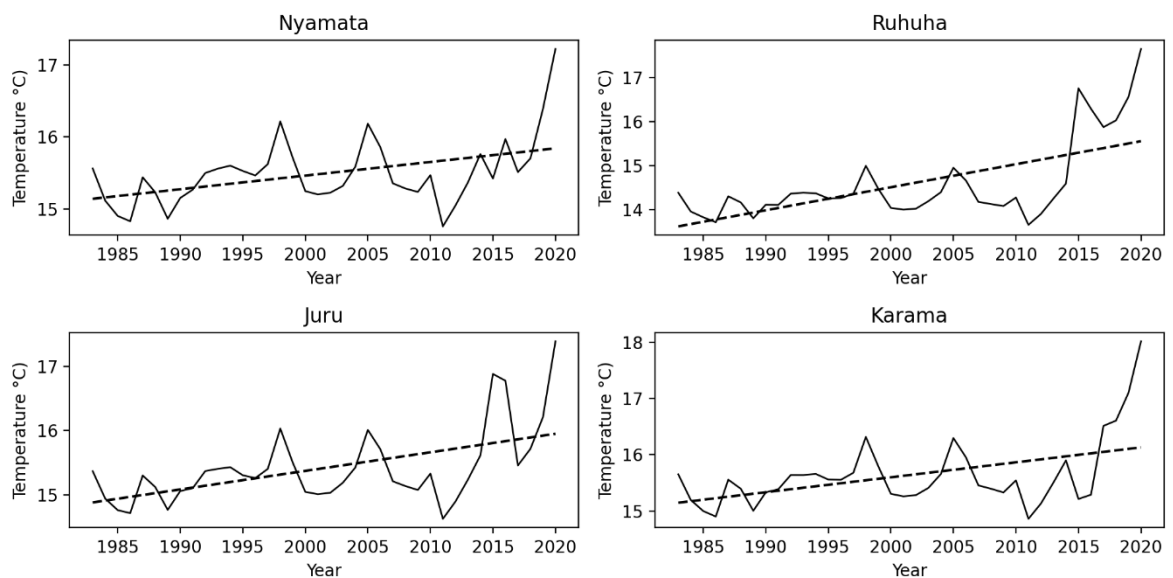


Figure 4: The temperature trend in annual minimum temperature total

The annual minimum temperature (Figure 4) indicate a clear variability pattern over all stations used in this study with a different nature of variability. The results obtained using graphical method indicated a significant increasing in tmin trend at all stations from 1985 to 2020.

method indicated a significant increasing in tmin trend at all stations from 1985 to 2020.

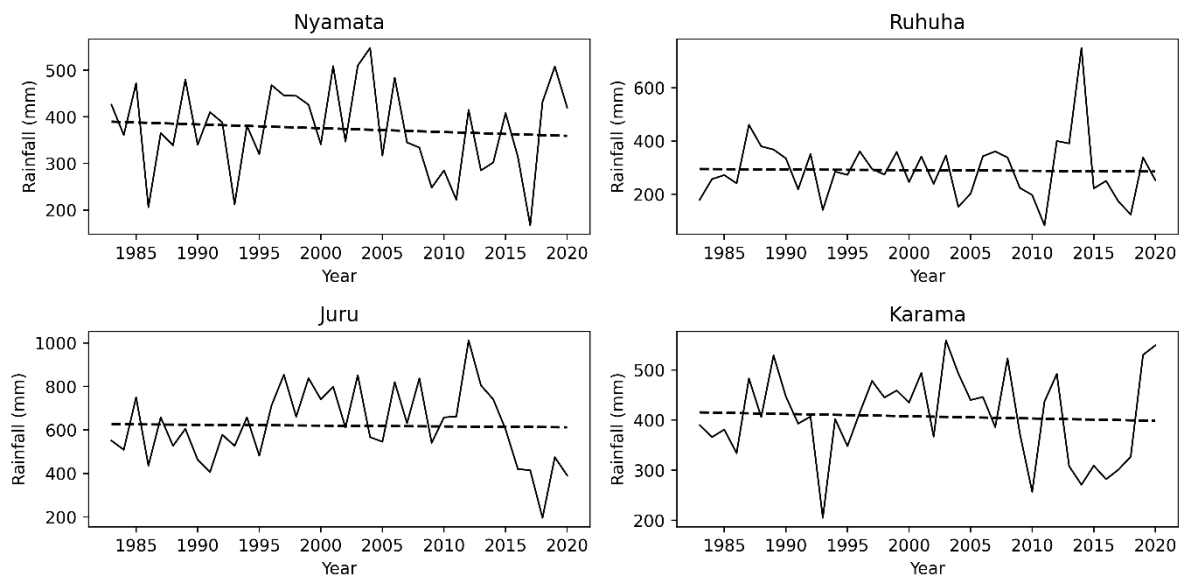


Figure 5: Rainfall trend in June to August seasonal rainfall total

June to August seasonal rainfall indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 5) obtained from graphical method indicated that all stations exhibited a decreasing trend.

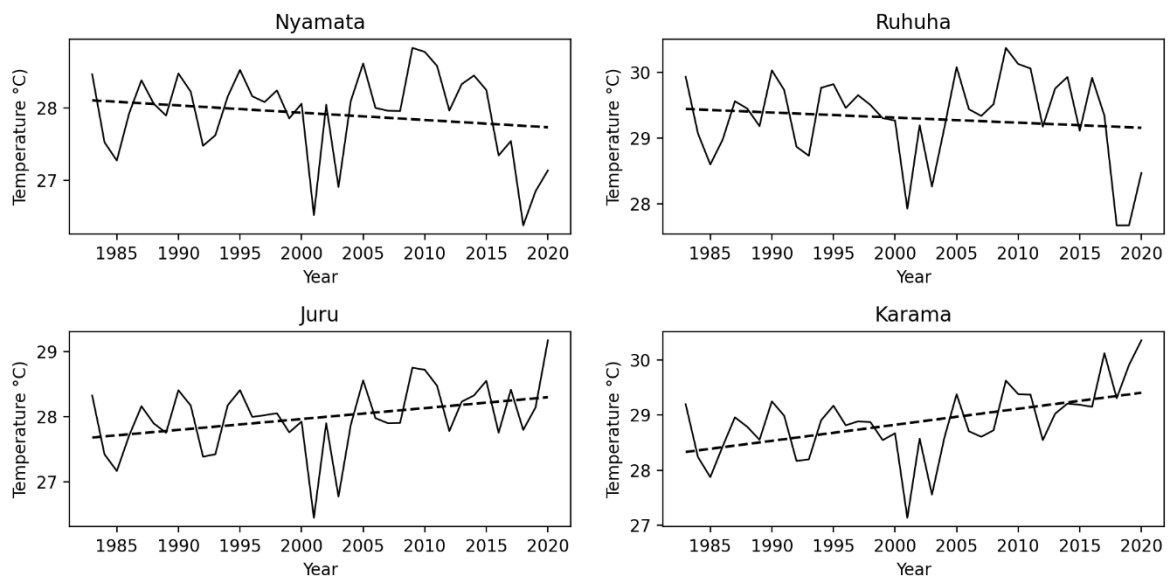


Figure 6: Maximum temperature trend in June to August seasonal temperature total

June to August seasonal Tmax indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 6) obtained from graphical method indicated that all stations exhibited an increasing trend.

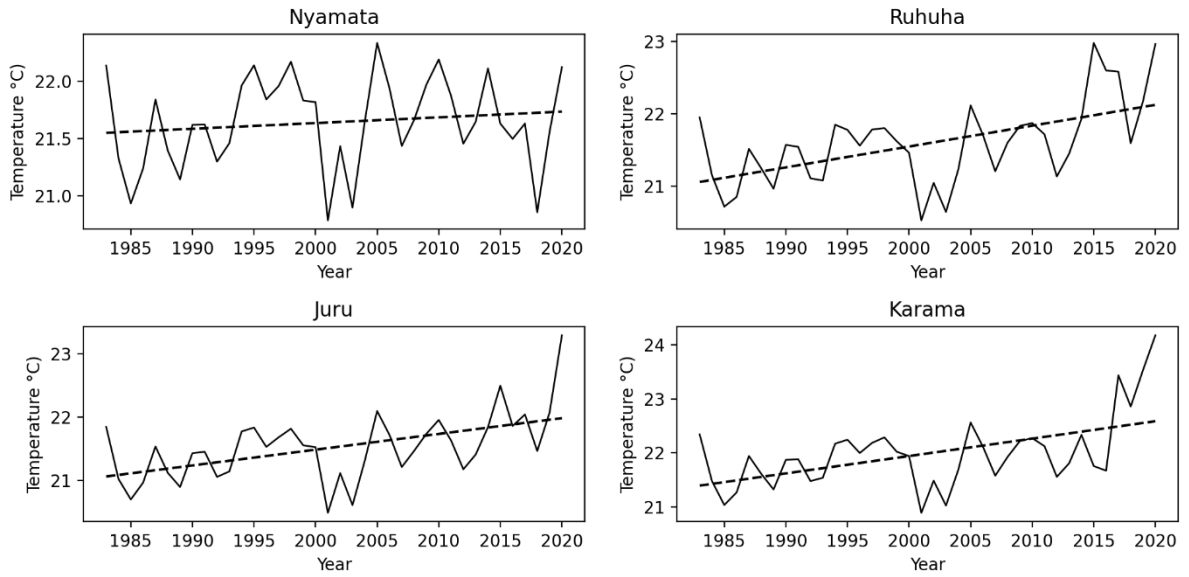


Figure 7: Mean temperature trend in June to August seasonal temperature total

June to August seasonal Tmean indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 7) obtained from graphical method indicated that all stations exhibited an increasing trend.

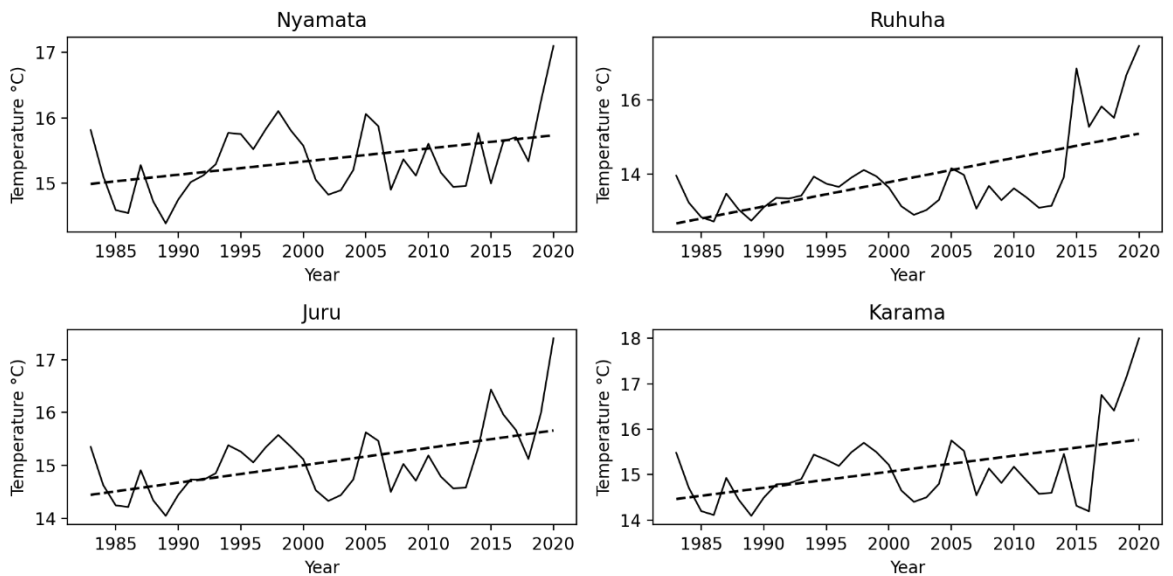


Figure 8: Minimum temperature trend in June to August seasonal temperature total

June to August seasonal Tmin indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 8) obtained from graphical method indicated that all stations exhibited an increasing trend.

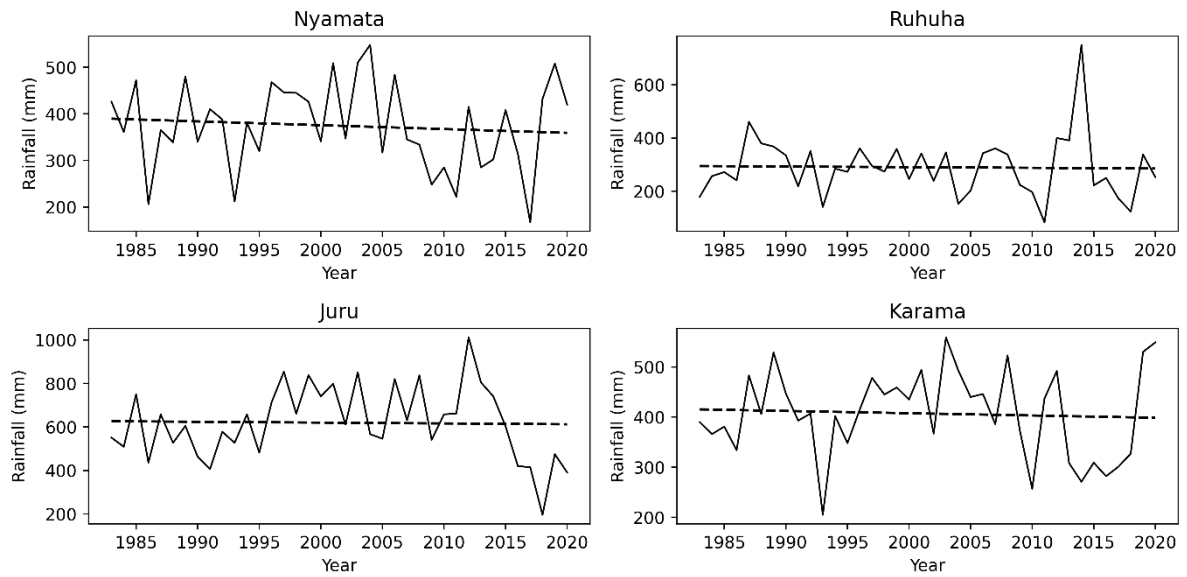


Figure 9: Rainfall trend in March to May seasonal rainfall total

March to May seasonal rainfall indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 9) obtained from graphical method indicated that all stations exhibited non significance increasing or decreasing trend.

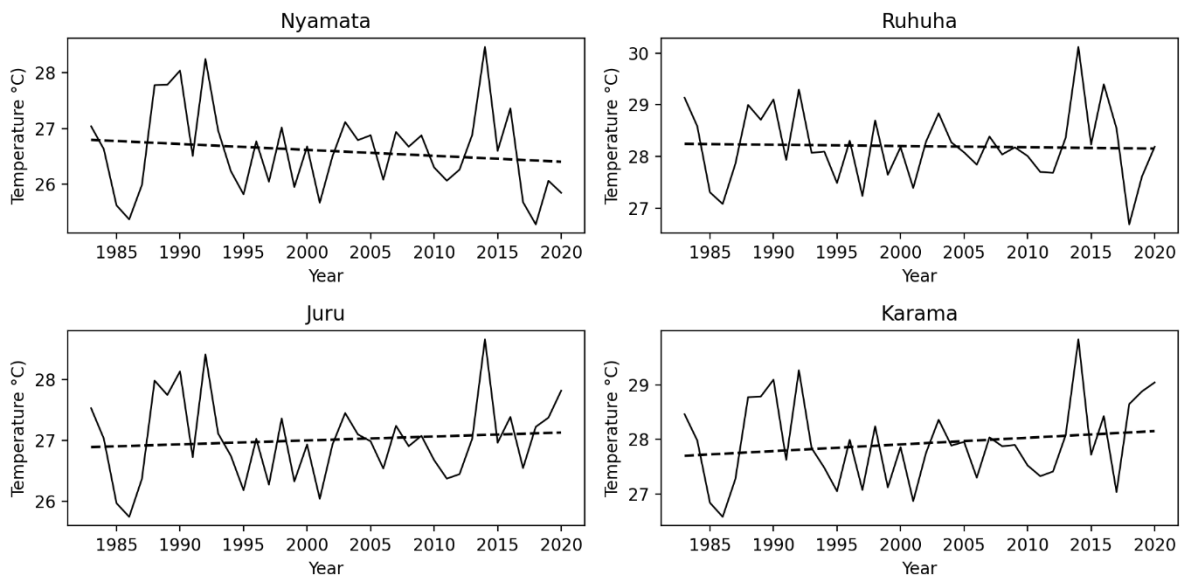


Figure 10: Maximum temperature trend in March to May seasonal temperature total

March to May seasonal temperature indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 9) obtained from graphical method indicated that all stations exhibited non significance increasing or decreasing trend.

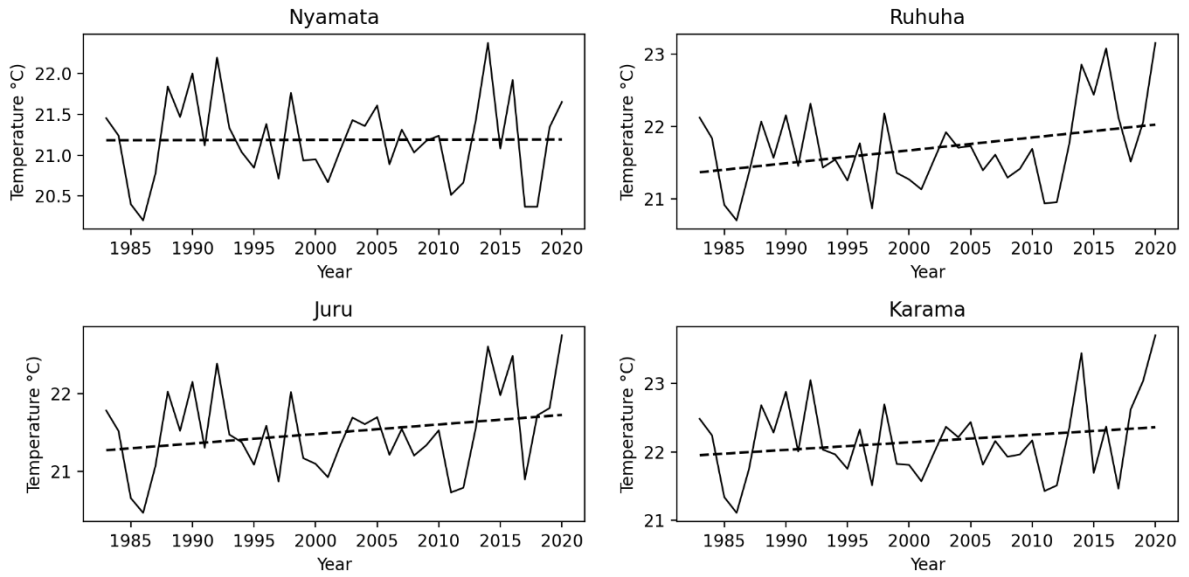


Figure 11: Mean temperature trend in March to May seasonal temperature total

March to May seasonal temperature indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 10) obtained from graphical method indicated that all stations exhibited significance increasing trend.

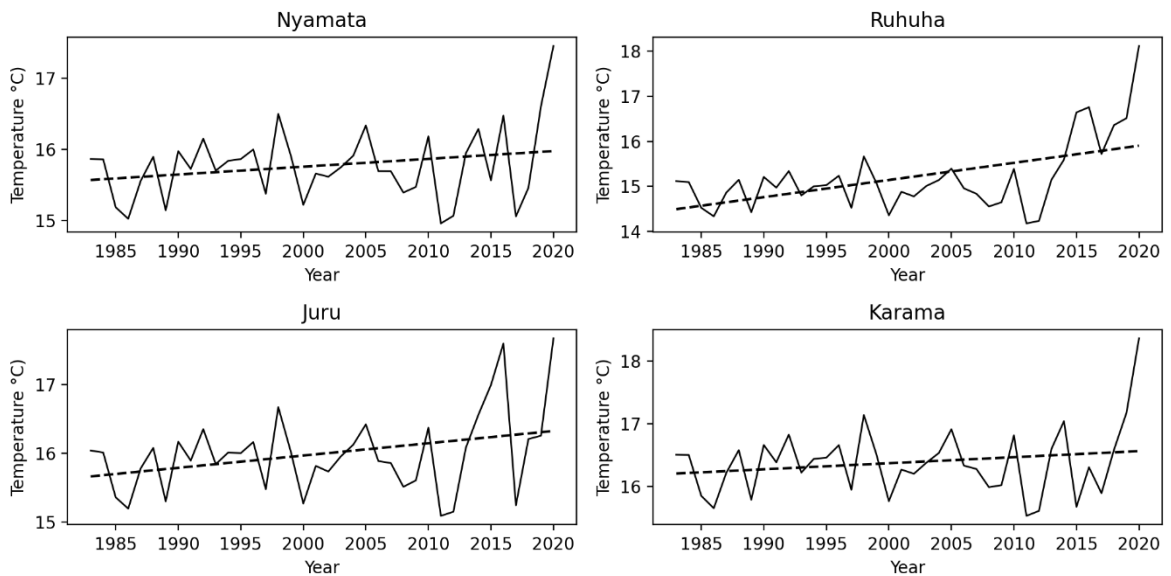


Figure 12: Minimum temperature trend in March to May seasonal temperature total

March to May seasonal minimum temperature indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 9) obtained from graphical method indicated that all stations exhibited significance increasing trend.

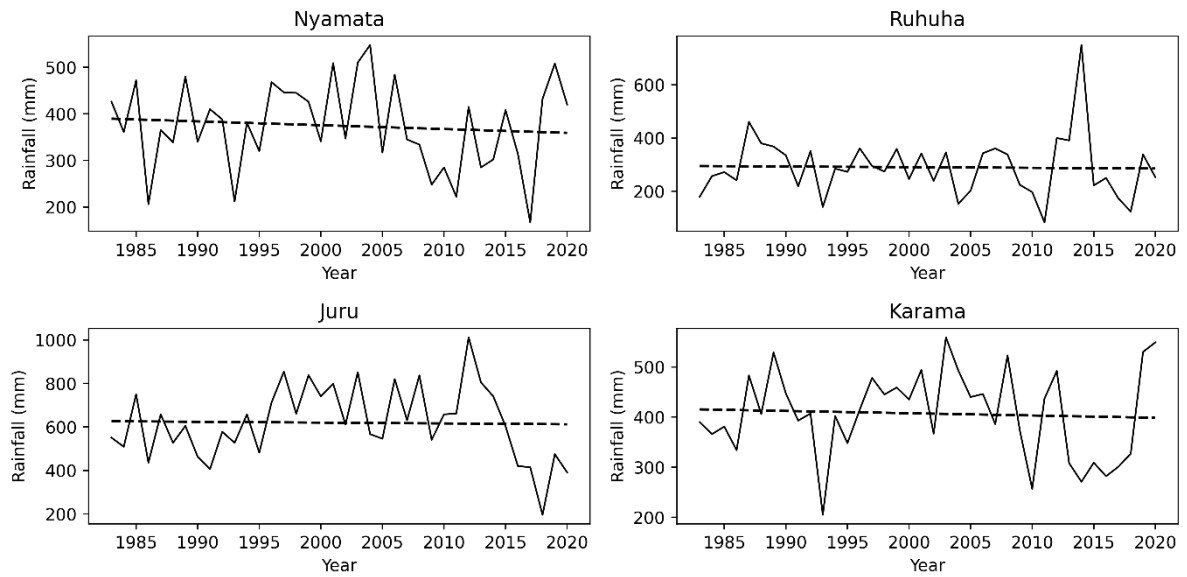


Figure 13: Rainfall trend in September to December seasonal rainfall total

September to December seasonal rainfall indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 12) obtained from graphical method indicated that all stations exhibited non significance increasing trend.

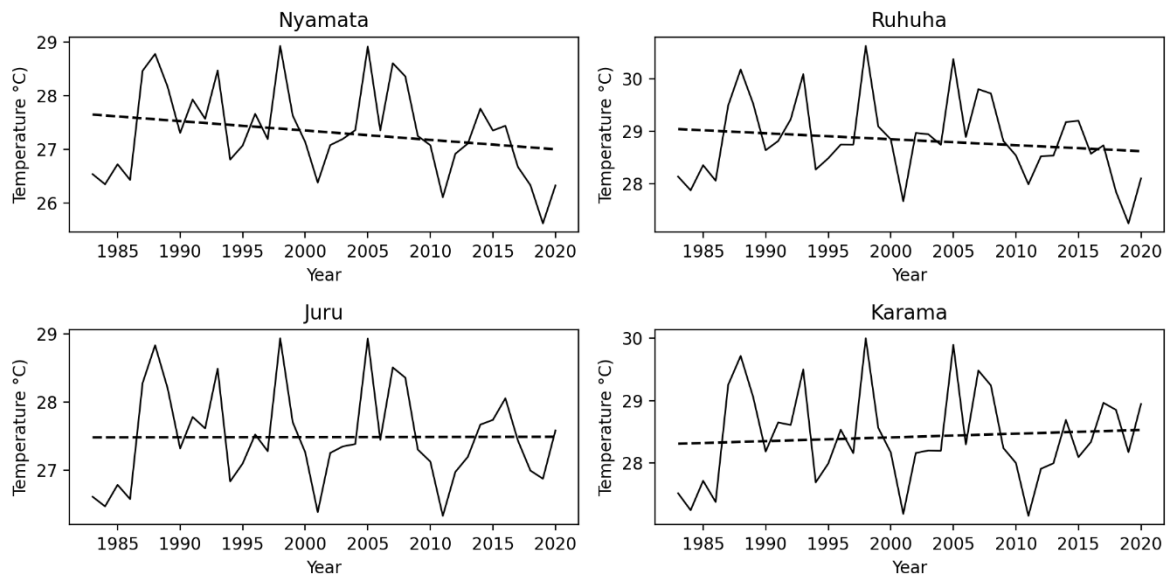


Figure 14: Maximum temperature trend in September to December seasonal temperature total

September to December seasonal Tmax indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 12) obtained from graphical method indicated that all stations exhibited non significance a decreasing trend.

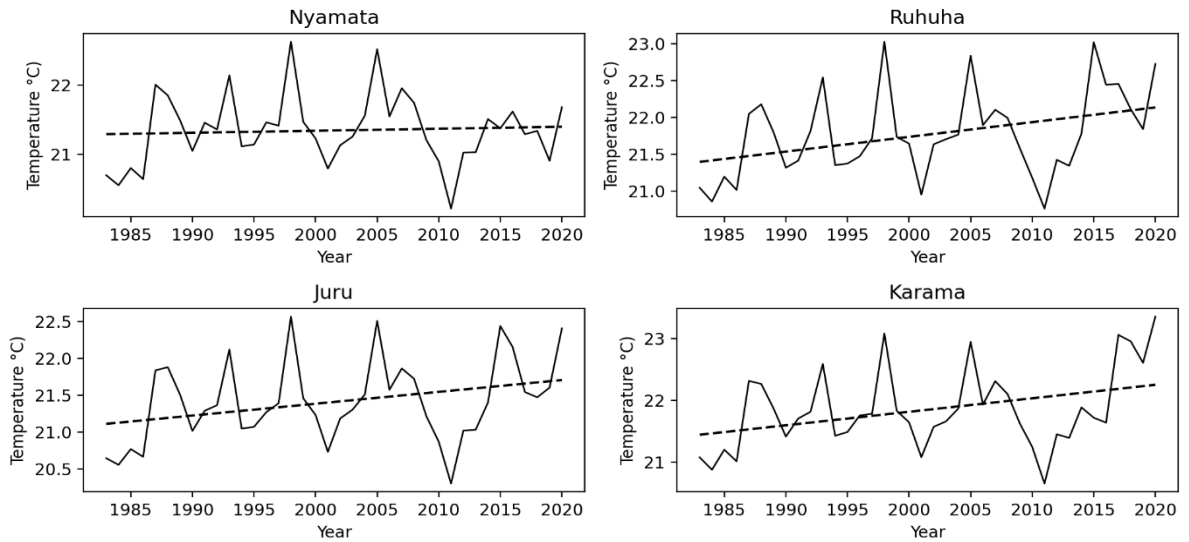


Figure 15: Mean temperature trend in September to December seasonal temperature total

September to December seasonal Tmean indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 13) obtained from graphical method indicated that all stations exhibited non significance an increasing trend.

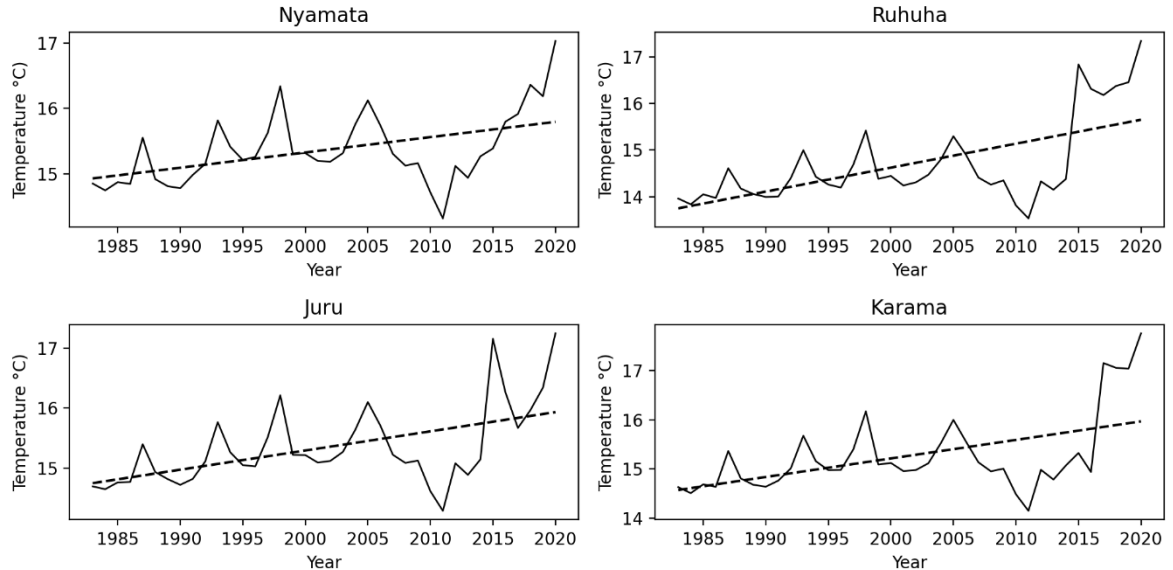


Figure 16: Minimum temperature trend in September to December seasonal temperature total

September to December seasonal Tmin indicate a clear variability pattern over all stations used in this study with a different nature of variability and the results (Figure 14) obtained from graphical method indicated that all stations exhibited non significance an increasing trend.

CHAPTER 5: RECOMMENDATIONS AND CONCLUSIONS

5.0 Overview

This chapter offers policy makers recommendations based on the research findings and conclusions drawn from the study.

4.1 The conclusion

The evaluation using the Standardized Precipitation-Evapotranspiration Index (SPEI) reveals that Bugesera District has experienced significant changes in drought patterns over recent decades. These trends indicate a notable increase in drought frequency and severity, correlating with broader climate change projections for the region.

Based on the length, severity, and frequency of past droughts over the Eastern province of Rwanda (1985-2020), the study concludes that Juru was the least droughty station, with 22 years without a drought, followed by Karama and Nyamata, which did not experience droughts in 21 of the 40 years that followed.

Under RCP8.5, Ruhuha which would experience mild to moderate droughts over the same period—will be the most severely affected stations.

According to the study, JURU received more rainfall each month than any other station. The stations' monthly rainfall peaks fell in April during the March–May season and in November during the September–December season. This has to do with how well CORDEX models replicate rainfall in Eastern Rwanda.

5.2 Recommendations

The stations' monthly rainfall maximum occurred in April during the March–May season and in November during the September–December season. This has to do with how well CORDEX models reproduce rainfall in Eastern Rwanda, Bugesera District.

The report recommends that Rwanda Meteorological Agency conduct further testing using mathematical model techniques like regression analysis and correlation analysis in order to establish the relationship between the independent and dependent variables for past and future droughts as well as for the rainfall analysis. The study concludes that because of the physical features of Rwanda's Eastern Province, the seven locations in the area are effectively networked.

In order to do this, there must be an adequate supply of both financial and human resources, as well as a greater emphasis on capacity building to support climate-related research and

empower the labor force. The study therefore suggests that in order to enhance the number of locations and ensuring that the stations are positioned strategically, approaches be taken by weather institutions and other policy makers working in the same field.

- ✓ Establish more localized and high-resolution climate monitoring stations to improve the accuracy of drought predictions.
- ✓ Develop and maintain comprehensive data on precipitation, temperature, and evapotranspiration to better understand and anticipate drought trends.
- ✓ Encourage the adoption of drought-resistant crop varieties and improve soil management techniques to enhance resilience.
- ✓ Promote water-saving irrigation techniques such as drip irrigation to optimize water use efficiency.
- ✓ Invest in water harvesting and storage infrastructure to buffer against periods of low rainfall.
- ✓ Implement sustainable water management practices to ensure equitable distribution and efficient use of available resources.
- ✓ Engage local communities in developing and implementing adaptation strategies tailored to their specific needs and conditions.
- ✓ Provide training and resources to farmers on climate-resilient practices and disaster preparedness.
- ✓ Integrate climate change projections into local development plans and policies to ensure that they address future challenges related to drought.
- ✓ Foster collaboration between government agencies, NGOs, and community groups to coordinate efforts and resources for drought management.
- ✓ Increase public awareness about climate change and its impacts on drought through educational programs and outreach initiatives.

The study suggests utilizing other satellites, like Tropical Application for Meteorology using Satellite data (TAMSAT), for the investigation of droughts in places where observable data are insufficient.

The current study used SPI and CORDEX to analyze rainfall and droughts, both past and prospective. The study suggests adopting remotely sensed drought indices, like NDVI, in the future to enhance the study's findings.

Additionally, the objective of the research was limited to evaluating the meteorological drought characteristics of the past and future in Rwanda's Eastern Province, Bugesera District in light

of climate change. The study suggests that rather than focusing solely on the Eastern province, a future study of a similar nature should cover all stations in Rwanda.

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