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Investigating the solar energy potential for irrigation system and climate change adaptation in Rwanda.

The case study: Bugesera district Rurambi wetland

By

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Declaration

I hereby declare that this project contains my own original research work. I also declare that this project has not been submitted and will not be submitted to any other institution for a similar course.

Signature; ………… Date; ……………………...

Innocent SEBINEZA

Declaration by Supervisor

I confirm that the project work was carried out by the student under my supervision.

Name: Prof. Bonfils Safari

Signature: ……………. Date: ……………….

Supervisor

Name**:** Dr. innocent Nkurikiyimfura

Signature: ……………. Date…………………...

Dedication

I dedicate this project to my beloved family, my Supervisor and dear colleagues for their support during my study.

Acknowledgment

This project would not have been possible without the kind support and help of many individuals and organizations. I would like to extend my sincere thanks to all of them.

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Abstract

Climate change is a major challenge lead to low rainfall and Water scarcity especially during the dry season and small holder's farmers at Rurambi wetland struggle to find the alternative way to water their plants where traditional irrigation practices is the common strategy they use to face with that challenge yet tradition irrigation or hand irrigation is not efficient for them as the survey revealed , this study aim to investigate the solar energy potential as energy for irrigation system which can be a best solution to the crops for the small holders farmers at Rurambi wetland , average solar energy potential of Bugesera range 506w/m2 to 751 w/m2 which make a region feasible for irrigation system based on solar ,the minimum solar radiation occurred in rain season where no irrigation is needed and the summer show the highest peak of solar radiation in the time where the irrigation is highly needed,Bugesera is district which is characterized by low precification since the average annual rainfall for 40 yrs revealed that is below 1000m and is region of high temperature which is associated with higher solar radiation and the total number of sunshine hours is above 5 hours per day. due that is region of partly clouds which allow the incoming solar radiation to pass through. All these factors make Bugesera region a good area of using solar powered system for helping communities. solar irrigation system can't be only solution for increasing the crops production but also the solution for climate change adaptation since solar irrigation system use clean energy from the sun. The survey that was made revealed that most farmers use tradition irrigation for watering their crops Quantitatively, empirical data from interviews with farmers in the Bugesera district revealed that 90% of respondents, constituting 119 individuals, rely on manual irrigation practices, while the remaining 10%, comprising 13 farmers, employ alternative methods to fortify their climate change resilience. Almost farmers in this area cope with that challenge of water scarcity for their crops due to unreliable rainfall by using irrigation method which is hand irrigation although they reported that hand irrigation is not efficient for them and it is time consuming.

Keywords: Climate variability, Climate change, Adaptation measures, Irrigation system, Sustainable farming, and Time series analysis.

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List of abbreviations

CH_4	Methane
CO_2	Carbon Dioxide
EAC	East African Community
EACCCP	East African Community Climate Change Policy
EACCN	East African Climate Change Network
FAO	Food and Agriculture Organization
FONERWA	Rwanda Green Fund
GHGs	Green House Gases
GoK	Government of Kenya
IEA	International Energy Agency
IFAD	International Fund for Agricultural Development
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IWMI	International Water Management Institute
MARD	Ministry of Agriculture and Rural Development
MEMD	Ministry of Energy and Mineral Development
MINAGRI	Ministry of Agriculture and Animal Resources
MININFRA	Ministry of Infrastructure
MINIRENA	Ministry of National Resources of Rwanda
MoE	Ministry of Environment
N_2O	Nitrous Oxide
NCEF	National Climate and Environment Fund
NISR	National Institute of Statistics Rwanda
PV	Photovoltaic
REMA	Rwanda Environment Management Authority
REN21	Renewable Energy Policy Network for the 21st Century
RES	Renewable Energy Resources
UNEP	United Nations Environment Programme

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Solar energy has significant potential for smart irrigation and climate change adaptation on a global scale by harnessing the power of the sun, solar energy offers sustainable and renewable solutions for agricultural irrigation while mitigating climate change impacts [1]. Solar-powered irrigation systems have gained traction worldwide due to their numerous benefits, including reduced greenhouse gas emissions, increased energy efficiency, and enhanced water resource management [2,3]. For instance, Israel, a country known for its advanced agricultural practices in arid regions has pioneered the use of solar energy in agricultural applications, including smart irrigation systems. The combination of precision irrigation techniques and solar-powered systems has enabled farmers to optimize water usage, minimize evaporation losses, and adapt to water scarcity according to Israeli [4]. These technologies have resulted in increased crop yields, improved water efficiency, and reduced environmental impact.

Water scarcity and drought are critical global issues that have significant socio-economic impacts, particularly in developing countries [4]. For instance, Sub-Saharan Africa is known to have prolonged droughts that led to severe water shortages, affecting agricultural productivity and food security [4]. This, in turn, exacerbates poverty and hinders economic development, as agriculture is a primary source of livelihood for many people in the region. The impacts of water scarcity and drought underscore the urgent need for effective water management strategies and adaptation measures to mitigate their adverse effects on vulnerable communities. Climate change is a key driver of water scarcity and related hazards such as droughts and floods, impacting water resources in complex ways [5]. To illustrate this, in some parts of Bugesera, Kayonza and Nyagatare of the Eastern Province of Rwanda, climate change has resulted in decreased rainfall and increased temperatures, leading to prolonged dry spells and reduced water availability in rivers and reservoirs [6]. This has adversely affected agriculture, livestock, and human water needs, posing to sustainable development and livelihoods challenges in the region [7].

The African continent presents a huge amount of Renewable Energy Sources (RES) potential such as solar, wind, biomass, geothermal, and hydropower dispersed across regions and mostly are still untapped [8]. Similarly, Africa is often thought of and referred to as the "Sun

Continent" or the continent where the Sun's influence is the greatest where on average, sub-Saharan Africa receives approximately 2,000 to 3,000 hours of bright sunshine annually [9].

Rwanda, known as the "Land of a Thousand Hills," faces significant challenges related to agricultural productivity and climate change impacts [10] With a predominantly agrarian economy and a high reliance on rain-fed agriculture, smallholder farmers being the primary contributors are heavily relying on precipitation for their harvests, making them highly susceptible to droughts and water scarcity. Traditional irrigation methods employed by smallholder farmers prove ineffective during the dry season, making it difficult for them to irrigate their crops adequately and sustain production. the country's vulnerability to changing climatic conditions poses a threat to food security and livelihoods [11].

Among the various renewable energy sources, solar energy has emerged as a promising solution for powering irrigation systems in Rwanda [12,13] where its geographical location below the equator at 2° 0′ 0″ South and, 30° 0′ 0″ East makes it suitable enough for solar energy source potential, with the average daily global solar irradiation on the tilted surface being approximately 5.2 kWh/m^2 per day. Solar-powered irrigation offers a clean, cost-effective, and environmentally friendly alternative to traditional fossil fuel-based pumping systems [14]. By harnessing solar energy, farmers can overcome the limitations of erratic rainfall patterns and water scarcity, leading to increased agricultural productivity and adaptive capacity. Many institutions have started to see some potential of solar energy in Rwanda as a sustainable solution to water scarcity and climate-affected areas, FONERWA, in collaboration with the Ministry of Agriculture and Animal Resources, implemented the Solar Powered Irrigation Systems project in selected areas, including the Eastern Province [15]. The project aimed to enhance agricultural productivity, improve water management, and reduce greenhouse gas emissions using solar-powered irrigation technologies.

Bugesera district, located in the Eastern province of Rwanda, is particularly vulnerable to droughts due to its tropical savanna climate and semi-arid conditions characterized by low annual rainfall [16]. Despite having numerous lakes, Bugesera faces water scarcity and drought, posing significant challenges to the local population [17]. One area in this region that presents an interesting potential for solar energy for smart irrigation and climate change adaptation is the Rurambi wetland situated in the Eastern part of the country, the Rurambi wetland is a vital ecosystem supporting diverse flora and fauna, as well as local communities dependent on its resources for agriculture and livelihoods [17]. However, the wetland ecosystem is increasingly vulnerable to climate change-induced water stress and fluctuations in precipitation patterns.

1.2 Problem Statement

Globally, the agricultural sector faces significant challenges due to climate change impacts such as droughts, water scarcity and irregular precipitations, yet agriculture is the backbone of the economy of many countries especially developing countries, in developing countries smallholders farmers are Vulnerable to climate changes impacts because most of them rely on agriculture-fed. Climate change imposes a major threat on smallholder farmers which results in food insecurity, and poverty and hinder them to achieve sustainable development, some sub-Saharan countries experienced prolonged droughts which negatively impact agriculture practices. Smallholder farmers use inadequate irrigation methods in their agriculture practices to deal with droughts and the dry season which is ineffective making it difficult for them to irrigate their crops adequately and sustain production. the farmers' vulnerability to changing climatic conditions poses a threat to food security and livelihoods and international policies are set up to find a better solution for sustainable agriculture practices [19]. According to the International Renewable Energy Agency (IREA), solar photovoltaic (PV) systems have the potential to power irrigation for 8 million hectares of agricultural land worldwide and have the potential to power various agricultural processes, including water pumping, crop drying, and cold storage, leading to an overall reduction in greenhouse gas emissions by 0.4 gigatons of CO2eq annually by 2030 [20]. Also, The Food and Agriculture Organization (FAO) highlights that solar-powered irrigation can contribute to water savings of up to 40% compared to conventional irrigation methods, leading to more efficient water use in agriculture as well as contributing to climate resilience in providing decentralized and reliable energy sources for irrigation.

In sub-Saharan Africa, where agriculture is a key economic sector, these challenges are particularly pronounced [21]. Considering the solar energy sources potential existing on the African continent, solar energy sources could contribute largely to the sustainable development of the countries if it is well exploited [8]. Rwanda, located in Eastern Africa, experiences similar issues, with its agricultural productivity and food security vulnerable to changing climatic conditions [22]. The National Irrigation Master Plan of Rwanda states that solar-powered irrigation systems can contribute to increasing irrigation coverage by up to 30% in the country, enhancing food security and climate resilience [23]. In Rwanda's Eastern

Province, the Rurambi wetland is a critical agricultural area, providing livelihoods for local communities [24]. However, the Rurambi wetland faces constraints such as water scarcity, inadequate irrigation systems, and the impacts of climate change [25]. Conventional irrigation methods relying on fossil fuel-based pumping systems are insufficient and contribute to environmental degradation and greenhouse gas emissions [26].

The government of Rwanda has formulated policies, plans, and strategies to promote solar renewable energy, especially in agriculture to lift productivity and adapt to climate change [27]. The National Environment and Climate Policy of Rwanda acknowledges the importance of renewable energy in mitigating greenhouse gas emissions and adapting to climate change, it promotes the use of solar energy for irrigation and other agricultural activities to reduce reliance on fossil fuels, lower carbon emissions, and enhance climate resilience. Also, National Irrigation Master Plan aims to increase the adoption of solar energy technologies in irrigation schemes to improve water management, enhance agricultural productivity, and strengthen the resilience of farmers to climate change [23]. In terms of funding, the government has established different fund organizations such as Renewable Energy Fund (REF), The fund offers grants, loans, and other forms of financing to promote the adoption of solar-powered technologies, such as solar pumps for irrigation, to increase agricultural productivity and resilience according to the report of Rwanda Development Board, 2021. National Climate and Environment Fund (NCEF) as well as Rwanda Green Fund (FONERWA) all are endeavoring to support sustainable energy projects, including solar energy initiatives in the agricultural sector. These examples demonstrate the Rwandan government's commitment to promoting solar renewable energy in agriculture through various policies, plans, and funding mechanisms. However, the deep knowledge and feasibility analysis behind the capability of solar energy usage for smart irrigation to promote food security and adaptation to climate change are not demonstrated by many researchers.

Therefore, there is an urgent need to investigate the solar energy potential for smart irrigation and climate change adaptation in the Rurambi wetland. By harnessing solar energy for irrigation, it is possible to address water scarcity, enhance agricultural productivity, and improve climate resilience. [28]. Understanding the feasibility, benefits, and challenges of adopting solar-powered irrigation systems in the Rurambi wetland is crucial for sustainable agricultural development and climate change adaptation efforts.

This research aims to Investigate the solar energy potential for irrigation systems and climate change adaptation in the Rurambi wetland, Rwanda, to enhance agricultural productivity, water resource management, and climate resilience at the local level.

1.3 Objectives of the Study

1.3.1 Main Objective

The main objective of this research is to thoroughly investigate the solar energy potential within Rurambi wetland, Bugesera district as an alternative solution to address the challenges posed by climate change.

1.3.2 Specific Objectives

1. To evaluate the adaptive capacity of farmers in enhancing resilience against lack of water during a droughts period
2. To analyze the trend of rainfall and temperature in the Bugesera district
3. To examine solar energy potential in the Bugesera district.
4. To suggest possible mechanisms that can be implemented to promote smart irrigation and climate change adaptation in the Bugesera district

1.4 Research Questions

Table 1: Specific objectives and Research Questions

Specific Objectives	Research Questions
1. To evaluate the adaptive capacity of farmers during drought periods	How do farmers in Bugesera district show adaptive capacity in enhancing resilience against water scarcity during drought periods? What are the factors influencing the adaptive capacity of farmers in the Bugesera district, and how can these factors be leveraged to enhance resilience against water scarcity?
1. To assess temperature and rainfall trends in the Bugesera district	How have the temperature trends and rainfall in Bugesera district evolved over a specific period?
2. To examine solar	What is the solar energy potential in Bugesera district?

	energy potential in the Bugesera district.	What are the current practices and challenges in harnessing solar energy resources in Bugesera district, and how can their potential be maximized for sustainable energy development?
3.	To suggest possible mechanisms that can be implemented to promote smart irrigation and climate change adaptation in the Bugesera district	What are the key mechanisms and strategies that can be implemented to enhance smart irrigation practices and climate change adaptation in Bugesera district?

1.5. Research Hypothesis

Based on the research objectives, the research hypothesis is that there is a significant relationship between crop adaptive capacity and resilience against water scarcity during drought periods in Bugesera district. Also, the solar potential in the Bugesera district represents the potential capacity to serve as alternative solutions to address energy needs and promote sustainability. Secondly, the temperature of Bugesera district has been changing over a specific period, indicating the impact of climate change.

However, there are potential solutions that can be implemented to address above-mentioned issues. Firstly, enhancing the adaptive capacity of farmers can be achieved through the implementation of sustainable agricultural practices such as efficient irrigation techniques, crop diversification, and the use of drought-resistant crop varieties. This can help improve resilience against water scarcity during drought periods. Additionally, promoting renewable energy sources, particularly solar energy, can contribute to reducing reliance on fossil fuels and mitigating the effects of climate change. Also, implementing climate change adaptation and mitigation strategies at the local level, such as reforestation, water conservation measures, and education programs, can help build resilience to changing temperatures and rainfall patterns in Bugesera district.

1.6. Scope of the Study

The scope of the study will be focused on Rurambi Wetland, Bugesera district, Eastern province in Rwanda. The study aims to investigate the solar energy potential and its application in smart irrigation, as well as climate change adaptation measures in the context of Rurambi wetlands. The evaluation of the adaptive capacity of farmers, assessment of solar and wind energy potential, and analysis of temperature trends will be conducted within the geographic boundaries of the Bugesera district. The study will consider the agricultural and environmental aspects of the region, with a specific emphasis on water scarcity during drought periods and the potential of renewable energy sources.

1.7. Significance of the Study

The significance of the study lies in its contribution to the understanding and application of solar energy potential, smart irrigation, and climate change adaptation in the context of Bugesera district, Rwanda. By investigating the solar energy potential, the study will provide valuable insights into the feasibility and effectiveness of utilizing solar energy for irrigation purposes, which can enhance agricultural productivity and resilience against water scarcity during drought periods. This has significant implications for farmers, agricultural practitioners, and policymakers in Bugesera district, as it can contribute to sustainable agricultural practices, reduce reliance on traditional energy sources, and mitigate the effects of climate change.

Furthermore, the study's assessment of the adaptive capacity of farmers will provide valuable information on the ability of different crop species to withstand water scarcity conditions and their potential for enhancing resilience in agricultural systems. This knowledge can guide farmers in selecting suitable crops and implementing appropriate adaptive strategies, ultimately improving food security and livelihoods in the region.

Academically, this research will contribute to the existing body of knowledge on solar energy potential, smart irrigation, and climate change adaptation in agricultural systems. It will add to the understanding of the feasibility and effectiveness of utilizing solar energy for irrigation purposes, the adaptive capacity of farmers, and the impact of climate change on temperature trends. The findings and insights generated by this study can serve as a basis for future research in similar contexts. For instance, the exploration of new variables and indicators, and the identification of advanced approaches to address climate change challenges in agricultural settings.

1.8. Justification of the case study

The selection of the Bugesera district in the Eastern Province of Rwanda, and specifically the Rurambi wetland, as the case study area is justified by multiple factors. Firstly, the Eastern Province receives higher levels of solar radiation compared to other regions in Rwanda [29], making it an ideal location to explore the solar energy potential for various applications, including smart irrigation. Additionally, the Bugesera district is particularly vulnerable to drought and the impacts of climate change, highlighting the urgency to investigate alternative solutions to address water scarcity and enhance climate resilience. Rurambi wetland offers a promising setting for implementing smart irrigation techniques, as it provides opportunities for sustainable water management, mitigating the effects of climate change on agricultural productivity, promoting food security, conserving biodiversity, and improving the well-being of the local population. By conducting the case study in this region, the research can contribute valuable insights and practical solutions to address the pressing challenges of climate change, water scarcity, and food insecurity, ultimately benefiting Bugesera's local population in an environmentally friendly way.

1.9. Research project structure

These paragraphs summarize how the whole research project is structured:

Chapter 1: briefly explain the background of the topic and clearly state the research problem. It defines the research objectives and research questions that need to find solutions. Furthermore, it clearly explains the significance of this study.

Chapter2: discusses the background related to the topic by reviewing the literature to enhance the comprehension of the topic

Chapter3: describes the study area by indicating the location. Eventually, it describes the methods, procedures, equipment and tools applied in data collection, processing and analysis.

Chapter4: is composed of results that resulted from observations and counting, GIS technology and interview. These data were presented in the form of maps, tables and charts. It also discusses the results and reveals the relationships, trends and generalizations among them.

Chapter 5: refer to the research problem posed, and describe the conclusions reached by referring to the solutions from the research questions.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

On a global scale, climate change because of the escalating emissions of greenhouse gases (GHGs) from fuel combustion has become a pressing concern, posing a significant threat to the environment and ecosystems [30]. These emissions contribute to climate change, leading to a multitude of adverse effects, such as intensified extreme weather events including floods, droughts, and heatwaves [31]. Climate change is considered one of the most pressing global challenges of our time, and its impacts on weather patterns have led to an increased frequency and severity of droughts [32,33]. Reductions in rainfall and rising temperatures are key drivers of drought events worldwide [34]. As greenhouse gas emissions continue to rise, the Earth's climate system is being altered, leading to changes in precipitation patterns and evaporation rates [35]. These changes disrupt the delicate balance of water availability, exacerbating the risk of drought occurrence and intensification [36].

The East African Community (EAC) is grappling with the harsh realities and impacts of climate change, which have become increasingly evident in the region; where rising temperatures, changing rainfall patterns, and extreme weather events are among the key manifestations of climate change in the EAC countries [37]. These shifts in climate have led to a range of detrimental consequences, including reduced agricultural productivity, water scarcity, increased food insecurity, and heightened vulnerability to natural disasters [38,39]. One of the most pressing concerns is the impact on agriculture, which is the backbone of the region's economy and a vital source of livelihood for most of the population where climate change has disrupted traditional farming practices, resulting in reduced crop yields, loss of livestock, and decreased food production [40]. The increased frequency and intensity of droughts and floods have further exacerbated these challenges, pushing vulnerable communities into deeper poverty and food insecurity [43].

Furthermore, water resources are also under significant strain due to climate change at a global scale as well as in the EAC; hanging rainfall patterns and prolonged dry seasons have led to dwindling water supplies, affecting both domestic use and irrigation for agriculture [37,44]. The scarcity of water has far-reaching consequences for health, sanitation, and hygiene, as well as for industrial and energy production. It has also fueled conflicts over water resources, exacerbating existing tensions and hindering regional cooperation [45,46].

Extreme weather events, such as cyclones, heavy storms, and floods, have become more frequent and intense in the EAC region, posing significant threats to human lives, infrastructure, and ecosystems; these events lead to displacement, destruction of homes, schools, and hospitals, and disruption of critical services [47]. Furthermore, they contribute to the spread of waterborne diseases and vector-borne illnesses, amplifying the burden on already strained healthcare systems [48].

Droughts have far-reaching consequences, affecting not only agricultural productivity and water resources but also socioeconomic systems and ecosystems [49,50]. Understanding the linkages between climate change, reduced rainfall, increased temperature, and drought events is crucial for developing effective strategies to mitigate and adapt to the impacts of drought in a rapidly changing climate (IPCC, 2014). Addressing climate change in the EAC requires urgent action and collaborative efforts at various levels. One significant step is the implementation of national climate change policies and strategies. For instance, Kenya has developed the National Climate Change Action Plan and the National Climate Change Response Strategy to guide its efforts in addressing climate change impacts including the use of smart irrigation where solar panels are used to create energy that pumps water during the irrigation [51]. Similarly, Tanzania has launched the National Climate Change Strategy and Action Plan, outlining specific interventions to enhance resilience and reduce greenhouse gas emissions [52].

Moreover, another important measure is the promotion of renewable energy sources. Rwanda has made remarkable progress in this area, with the government aiming to achieve universal electricity access through off-grid and renewable energy solutions [53]. Uganda has also prioritized renewable energy development, particularly hydropower and solar energy, to reduce reliance on fossil fuels and promote sustainable energy alternatives [54]. Furthermore, the EAC countries have emphasized regional collaboration to address climate change collectively; they have established the East African Climate Change Network (EACCN) to enhance coordination, knowledge sharing, and capacity building among member states [55]. The EAC also actively participates in international climate change negotiations, advocating for the interests of its member states and contributing to global efforts in combating climate change whereas the use of solar energy in smart irrigation is a crucial solution to climate change to increase agricultural productivity.

Solar energy has emerged as a promising solution for smart irrigation systems in the East African Community (EAC), providing sustainable and efficient energy for agricultural practices whereas several countries in the EAC have recognized the potential of solar energy in enhancing irrigation systems [56]. In Kenya, for example, solar-powered irrigation systems have been widely adopted in various agricultural projects, enabling farmers to irrigate their fields using renewable energy sources [57]. Similarly, Tanzania has implemented solar-powered irrigation schemes in remote areas, where access to grid electricity is limited [58]. These systems harness the abundant solar resources in the region to power pumps and irrigation equipment, offering a reliable and cost-effective alternative to conventional energy sources. By utilizing solar energy in smart irrigation, the EAC countries are promoting sustainable agricultural practices while reducing reliance on fossil fuels and mitigating greenhouse gas emissions.

2.2. Definitions of Key Concepts

1. **Solar Energy**: Solar energy refers to the energy obtained from the sun's radiation, which can be harnessed and converted into useful forms of energy. This renewable energy source has the potential to provide electricity, heat, and power for various applications. Solar energy is captured using solar panels or photovoltaic (PV) cells, which convert sunlight directly into electricity through the photovoltaic effect [59].
2. **Solar Energy Potential:** This refers to the amount of energy that can be harnessed from sunlight in a specific area. It is typically measured in terms of solar irradiance, which is the power per unit area received from the Sun. The solar energy potential is influenced by factors such as geographical location, time of year, time of day, and weather conditions. By utilizing solar energy, smart irrigation systems can reduce their dependence on fossil fuels and contribute to climate change adaptation efforts by promoting sustainable agricultural practices [60,61].
3. **Smart Irrigation**: Smart irrigation involves the use of advanced technologies, such as sensors, data analytics, and automation, to optimize water usage in agricultural or landscaping irrigation systems. These systems can monitor various parameters, including soil moisture, weather conditions, and plant water requirements, to deliver water efficiently and precisely where and when it is needed. By integrating solar energy into smart irrigation systems, the reliance on conventional power sources can be reduced, making the systems more sustainable and environmentally friendly [59,61,62].

4. **Irrigation Efficiency**: Irrigation efficiency refers to the effectiveness and productivity of water use in agricultural or landscape irrigation systems. It measures the amount of water that is effectively used by plants for their growth and minimizes losses due to evaporation, runoff, or inefficient application [63,64].
5. **Energy Harvesting:** Energy harvesting involves capturing and converting ambient energy from the environment into usable electrical energy. In the context of smart irrigation, energy harvesting methods can be used to power sensors, data loggers, and other devices involved in the irrigation system [65].
6. **Climate Change:** This is defined as long-term shifts and alterations in global or regional climate patterns, primarily attributed to human activities, particularly the emission of greenhouse gases (GHGs) into the atmosphere [32]. It is primarily caused by the burning of fossil fuels (such as coal, oil, and natural gas), deforestation, industrial processes, and land-use changes. The increase in GHGs, such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), in the atmosphere, traps heat and leads to the phenomenon known as global warming. This warming effect alters Earth's climate system, resulting in a wide range of impacts, including rising temperatures, changing precipitation patterns, sea-level rise, melting ice caps and glaciers, extreme weather events, and shifts in ecosystems. The Intergovernmental Panel on Climate Change (IPCC), a scientific body established by the United Nations, has provided extensive assessments and reports on climate change, including its causes, impacts, and potential mitigation and adaptation strategies [66].
7. **Climate change Adaptation**: Climate change adaptation refers to the process of adjusting and responding to the impacts of climate change to minimize its adverse effects on human and natural systems. It involves identifying vulnerabilities, assessing risks, and implementing strategies to enhance resilience and reduce the negative impacts of climate change. By incorporating solar energy into smart irrigation systems, farmers and land managers can adapt to changing climatic conditions by optimizing water usage, mitigating water scarcity risks, and promoting sustainable agriculture practices [67].
8. **Climate Change Mitigation**: Climate change mitigation refers to efforts and strategies aimed at reducing greenhouse gas emissions and minimizing the drivers of climate change. It includes actions such as transitioning to renewable energy sources, improving energy efficiency, and implementing sustainable practices [68].

2.3 Agriculture in Rwanda

Rwanda's economy revolves primarily around agriculture, serving as the cornerstone of its economic activities. Approximately 69 % of Rwanda's private households, totaling around 2.3 million, are engaged in agricultural pursuits. Specifically, crop farming is practised by approximately 63 % of private households, equivalent to about 2.1 million households. The predominant crops cultivated within Rwanda encompass beans, with 80 percent of household farmers involved, maize at 56 percent, cassava at 49 percent, sweet potatoes at 44 percent, and bananas at 24 percent. Remarkably, nearly half of these households cultivate at least one variety of fruit. Furthermore, about 50 percent of private households, roughly 1.7 million, possess livestock. The primary livestock species reared and owned by private households in Rwanda consist of cows, representing 28 percent of households, succeeded by goats at 19 percent, pigs at 15 percent, chickens at 12 percent, and rabbits at 6 percent. With the recorded livestock numbers within private households, the overall livestock population is as follows: 1.4 million cattle, 1.5 million goats, 0.3 million sheep, 0.8 million pigs, 2.6 million chickens, and 0.4 million rabbits[2]. The agricultural calendar in Rwanda can be segmented into two distinct growing seasons. The initial season spans from September to January, allowing for the cultivation of various crops. Subsequently, the second season takes place from February to June, further contributing to the country's agricultural output. Notably, there exists a third growing season dedicated to the cultivation of rice and vegetables within the marshlands. These water-rich areas provide the necessary conditions for sustained agricultural production during this period. Remarkably, the agricultural sector holds a significant share in Rwanda's economic landscape, contributing as much as 33 percent to the nation's overall Gross Domestic Product (GDP). Over the years, Rwanda's GDP has displayed impressive growth, expanding annually at a commendable rate of 7% since 2014. Rwanda's agricultural prowess extends to international trade, with key commodities taking the lead. Notably, tea and coffee stand as prominent exports, showcasing the country's influence in the global market. On a domestic level, specific agricultural products carry substantial value. These include plantains, cassava, potatoes, sweet potatoes, maize, and beans, which collectively contribute to the nation's food security and economic stability. In the Eastern African context, Rwanda holds a notable position as an exporter. Among the goods that leave its borders are dry beans, potatoes, maize, rice, cassava flour, and maize flour. Additionally, the country contributes to the international market with exports of poultry and live animals, underscoring its diverse agricultural capabilities and significant role in the region's trade dynamics[69].

2.3.1 Agriculture Sector Profile

The Rwandan government's forward-looking development strategy, known as Vision 2050, places a strong emphasis on elevating the agricultural sector to new heights. By the year 2050, the government envisions a transformation where subsistence farming gives way to a thriving landscape of commercial agriculture and agro-processing, fueled by full-scale commercialization and innovative technological integration. Central to this agricultural evolution are key exports like coffee and tea, which have been the cornerstones of Rwanda's agricultural prowess. However, the nation is also venturing into an array of value-added agricultural products, showcasing its capability to produce and export a diverse range of goods. This assortment includes items such as canned tomatoes, honey, exquisite French beans, tantalizing passion fruit, rich macadamia nuts, and the earthy goodness of mushrooms. Notably, macadamia nuts stand out as a potential star in Rwanda's export repertoire. Journeying towards the eastern borders neighboring the Democratic Republic of the Congo, Rwanda engages in the export of live animals, unprocessed meat, and an array of dairy products. The expansion of flight routes facilitated by Rwanda Air and other carriers has broadened Rwanda's scope, linking it to far-flung markets in Europe, the Middle East, and Asia. This enhanced connectivity has propelled Rwanda's fresh agricultural products into these global regions[69].

Rwanda's geographical advantages, including its elevated terrain and temperate climate, provide the foundation for year-round agricultural production, setting the stage for success. Notably, a study conducted in 2018 under the aegis of the United States Agency for International Development (USAID) identified promising export prospects for fresh crops such as passion fruit, snow peas, zesty chilies, and earthy mushrooms. These findings underline the untapped potential in multiple avenues, spanning from the provision of vital inputs to the efficient aggregation of crops for export, and the intricacies of maintaining an unbroken cold chain. Yet, Rwanda's landlocked status coupled with the fragmentation of land into small parcels presents challenges to large-scale commercial agriculture. Nevertheless, the nation harbors the latent capability to cultivate distinctive speciality crops, which could carve out a unique niche in the global market. For Rwanda to manifest its aspirations in value-added agricultural development, a dual-pronged approach is imperative. This entails the expansion of irrigated farmland alongside the simultaneous importation of substantial quantities of essential inputs such as seeds, fertilizers, and appropriately scaled machinery. Such strategies are crucial in propelling Rwanda towards its ambitious agricultural goals, fostering growth and innovation in the sector, and ultimately ushering in a new era of prosperity.

2.3.2 Principal crops in Rwanda’s Agriculture

Rwanda boasts a diverse array of vital agricultural commodities that contribute significantly to its economy. Noteworthy among these are coffee, renowned for its exquisite flavor profile and global demand; pyrethrum, a natural insecticide derived from chrysanthemum flowers, playing a pivotal role in pest control; tea, cultivated across lush plantations and appreciated for its soothing properties; and a colorful assortment of flowers that add vibrancy to both local landscapes and international markets. Additionally, the country yields a variety of staple crops essential for sustenance and trade. Beans, a staple in Rwandan cuisine, provide a source of protein and sustenance for the population. Cassava, rich in carbohydrates, serves as a dependable food source, while bananas contribute essential nutrients to the diet. Irish potatoes thrive in Rwanda's favorable climate and are a key ingredient in various dishes. Moreover, rice and wheat cultivation play a crucial role in bolstering food security and reducing import dependence, enhancing self-sufficiency.

Capitalizing on the fertile soils, approximately 61% of Rwanda's land is dedicated to agricultural activities, illustrating the profound significance of this sector. The Rwandan government has demonstrated an unwavering dedication to propelling the growth of agriculture, evident through substantial investments in key areas. The creation of robust infrastructure, coupled with the establishment of citizen-responsive institutions, has facilitated a conducive environment for agricultural advancement. Emphasis on inclusive markets and pioneering approaches to innovation and extension services further underscore Rwanda's commitment. Parallel to government initiatives, the private sector is enticed by Rwanda's burgeoning agricultural landscape, offering a range of investment opportunities. Notable sectors with lucrative prospects include dairy production, where modernization and quality enhancement are sought after. Poultry and meat processing present avenues for value addition and export potential. Horticulture exploits Rwanda's diverse flora, tapping into global demand for fresh produce. Meanwhile, aquaculture harnesses the country's water resources for sustainable fish production.

Mechanization, another focal point, modernizes farming techniques for increased efficiency. Crop sourcing initiatives optimize supply chains, bridging the gap between farmers and consumers. The integration of blockchain technology ensures transparency and traceability in the agricultural market. Agrotourism, a burgeoning trend, merges agriculture and tourism, captivating visitors with authentic farm experiences. The production of irrigation equipment tackles water scarcity challenges, while cold chain logistics ensures the seamless preservation and transportation of perishable goods.

2.3.3 Importance of Agriculture to the farmers

Agriculture holds immense significance for the people of Rwanda due to a multitude of compelling reasons. Foremost among these is its role in guaranteeing a steady supply of nourishing food to the population, with an impressive 90 percent of the nation's dietary needs being met through agricultural activities. This ensures that a vast majority of Rwandans consistently have access to wholesome sustenance, promoting health and well-being across the nation. Furthermore, the livelihoods of approximately 75 percent of the global population, particularly those residing in rural areas, hinge upon agriculture as their primary source of both subsistence and income. This is notably true for Rwanda, where farming serves as the backbone of rural economies and provides the means for families to support themselves and thrive.

In the context of Rwanda's economic landscape, agriculture emerges as a pivotal contributor, constituting a substantial 63 percent of the total value attributed to the country's exports. The export portfolio is heavily reliant on key agricultural commodities, exemplified by products like coffee, tea, pyrethrum, macadamia nuts, flowers, and an array of fruits. These exports not only bolster the nation's economic health but also reinforce Rwanda's global standing within the agricultural trade domain. Beyond its economic prowess, agriculture assumes an indispensable role in propelling economic expansion and addressing poverty challenges. With its substantial contribution of 39 percent to the nation's Gross Domestic Product (GDP), agriculture serves as a driving force behind Rwanda's overall economic growth. This was notably demonstrated during the period between 2005 and 2010 when agricultural advancements played a pivotal role in reducing global poverty by a notable 12 percentage points. Furthermore, agriculture's potential extends beyond economic prosperity to encompass environmental sustainability and climatic resilience. The prospect of embracing sustainable agricultural practices, such as agroforestry, conservation agriculture, organic farming, and irrigation, holds promise for Rwanda. These practices can mitigate ecological impacts and enhance the nation's ability to withstand climatic challenges, marking agriculture as a vital avenue for promoting long-term environmental stability.

2.3.4 Climate change effects to agriculture in the Eastern Province

A significant portion of the farmers residing in the Eastern province of Rwanda heavily rely on rain-fed agriculture for their sustenance. This reliance on rainfall as a primary water source makes them particularly vulnerable to the far-reaching impacts of climate change, with drought emerging as a prominent concern that could severely undermine their ability to maintain their way of life. This predicament has led to a cascade of negative outcomes that threaten to disrupt their livelihoods in numerous ways. Here are a few illustrative examples of the repercussions they face:

1. **Diminished Agricultural Yields and Quality:** The intensification of heat stress, compounded by water scarcity resulting from altered precipitation patterns, has directly contributed to a substantial reduction in both the quantity and quality of crops. Maize and bean harvests, for instance, have dwindled due to prolonged dry spells, causing financial hardships for farmers who depend on these crops for income and sustenance.

2. **Escalating Pest and Disease Pressure:** The changing climate has ushered in an increase in pest infestations and disease outbreaks, with higher temperatures providing a conducive environment for the proliferation of harmful organisms. Coffee plantations, a vital source of income for many in the region, have been ravaged by the devastating coffee berry borer, causing significant economic losses for farmers who rely on coffee exports.

3. **Heightened Soil Erosion and Land Degradation:** The decline in plant cover due to water scarcity, coupled with more intense rainfall events when they do occur, has led to heightened rates of soil erosion and degradation. Terracing systems put in place to combat erosion are proving insufficient in the face of these changing conditions, resulting in the loss of arable land and reduced agricultural productivity.

4. **Decline in Animal Productivity and Health:** Livestock farming, a crucial component of many farmers' livelihoods, has been severely impacted by the reduced availability of pasture and inadequate water supplies. The Eastern province has witnessed a decline in milk and meat production, as well as increased susceptibility of animals to diseases due to weakened immune systems brought on by stress and poor nutrition.

5. **Increased Risk of Starvation and Poverty:** The combined effects of lowered agricultural output, reduced animal productivity, and falling incomes have exacerbated the risk of both starvation and poverty for farming households. Families are finding it increasingly challenging to secure enough food for sustenance, pushing them into a cycle of economic hardship that is difficult to break.

2.4. The use of solar energy in smart irrigation and climate change adaptation

Recognizing the urgent need to address this global challenge, researchers have diligently focused on identifying alternative, environmentally friendly energy sources [70]. One such alternative is renewable energy, which can be defined as any form of energy that can be harnessed and replenished by natural processes at a rate equal to or exceeding its rate of human consumption [71]. The pursuit of renewable mitigating climate change and its associated impacts on ecosystems, providing a sustainable solution for future energy needs [72].

In recent years, the adoption of alternative energy sources and hybridization strategies has witnessed significant advancements, with solar energy taking the forefront in renewable energy hybridization. The primary driving force behind this shift is the urgent need to reduce greenhouse gas emissions and combat climate change [73]. Solar energy offers compelling advantages in terms of its environmental sustainability and potential for large-scale electricity generation. Additionally, the dropping prices of renewable energy technologies have played a pivotal role in accelerating their penetration into the energy mix [72]. As the costs of solar panels continue to decline, renewable energy sources have become increasingly competitive with conventional fossil fuel-based power generation. This cost competitiveness, combined with the environmental benefits, has positioned solar energy as the central component of renewable energy hybridization efforts [74]. By harnessing the complementary attributes of solar power, hybrid systems can optimize energy production and storage, enhance grid stability, and contribute to the overall sustainability and decarbonization of the energy sector. The use of solar energy in hybrid systems not only offers a promising pathway towards achieving emission reduction targets but also signifies a significant transition towards a cleaner and more sustainable energy future.

Furthermore, there has been a growing interest in harnessing solar energy for various applications, including smart irrigation and climate change adaptation [75]. This investigation aims to explore the solar energy potential specifically for smart irrigation systems for increasing agricultural production and its role in enhancing climate resilience. Smart irrigation systems have emerged as a sustainable solution to optimize water usage in agricultural practices [76]. By integrating advanced technologies such as sensors, and weather data (such that rainfall and temperature data), these systems can provide precise irrigation schedules based on real-time environmental conditions; however, the energy requirements of such systems can be substantial, and traditional grid-based electricity may not always be a reliable or environmentally friendly option [77,78]. Solar energy offers a promising alternative for powering smart irrigation systems; the abundant availability of sunlight, especially in regions prone to water scarcity and climate variability, makes solar energy an attractive and renewable source of power [79]. By harnessing the sun's energy through photovoltaic (PV) panels, smart irrigation systems can operate independently, reducing the reliance on fossil fuels and minimizing greenhouse gas emissions [33].

Moreover, solar-powered smart irrigation systems can contribute to climate change adaptation strategies. As climate change continues to impact weather patterns, including prolonged droughts and heat waves, the ability to efficiently manage water resources becomes crucial for agricultural sustainability. Solar energy can help address this challenge by providing a reliable and sustainable power source for smart irrigation systems, enabling farmers to optimize water usage and adapt to changing climate conditions. However, to fully understand the solar energy potential for smart irrigation and its effectiveness in climate change adaptation, several factors need to be considered. These include solar irradiance levels, system efficiency, storage options, and the economic viability of implementing solar-powered solutions. Additionally, the integration of solar energy with other sustainable practices, such as water harvesting and precision agriculture techniques, can further enhance the effectiveness of smart irrigation systems in climate-resilient agriculture.

Numerous studies conducted in both developed and developing countries have focused on enhancing systems that harness solar and wind power to fulfil various energy needs, including powering irrigation pumps. For instance, a study by [80] explored the feasibility of using solar energy to power irrigation systems in India. The research demonstrated that solar-powered irrigation not only reduced dependence on fossil fuels but also increased the efficiency of water usage, leading to improved crop yields. Similarly, a study conducted by [81] in Zambia examined the viability of combining solar and wind energy to power irrigation pumps. The research highlighted the economic and environmental benefits of renewable energy-driven irrigation, including reduced operational costs and carbon emissions. These studies, along with many others, contribute valuable insights into the application of solar and wind power in irrigation systems, emphasizing their potential for sustainable agricultural practices.

2.5. Climate variation and the use of solar energy for smart irrigation in Rwanda

Rwanda experiences climate variation characterized by scarcity of rainfall and high temperatures, particularly in certain regions and these climatic conditions pose significant challenges, including water scarcity and increased risk of heat stress, which have direct implications for agriculture and water resources in the country [82]. Regions such as Bugesera District have been identified as areas with limited rainfall and elevated temperatures [83]. The scarcity of rainfall leads to reduced water availability for agricultural activities, affecting crop growth and productivity [84]. High temperatures exacerbate the situation by accelerating evaporation rates and increasing water requirements for irrigation, further straining water resources [85]. To address these challenges, climate change adaptation strategies are crucial. Implementing sustainable water management practices, such as rainwater harvesting, efficient irrigation techniques, and the use of solar-powered smart irrigation systems, can help mitigate the impacts of rainfall scarcity and high temperatures on agriculture [86].

Solar-powered smart irrigation systems, fueled by abundant solar energy resources in Rwanda, provide a sustainable and reliable solution for efficient water use in agriculture, ensuring optimized irrigation practices and reducing reliance on traditional water sources [87]. These systems integrate real-time data on weather patterns and soil moisture levels to enhance water delivery, minimize water wastage, and support climate change adaptation efforts in the face of rainfall scarcity and high temperatures [88].

Moreover, with its abundant solar resources, Rwanda has recognized the potential of solar energy in powering irrigation systems, improving water efficiency, and enhancing climate resilience [82,86,89]. Solar-powered smart irrigation systems utilize solar panels to generate electricity, which can be used to power sensors, pumps, and irrigation controllers [90,91]. These systems integrate real-time weather data, soil moisture sensors, and automated control mechanisms to optimize water delivery to crops, ensuring efficient water use and minimizing water wastage [89]. By harnessing solar energy, these systems offer a sustainable and cost-effective approach to irrigation while reducing reliance on fossil fuels and mitigating greenhouse gas emissions. In addition, solar energy can support climate change adaptation efforts by providing a reliable and decentralized power source for rural communities, enabling them to adapt to changing climate conditions and enhance their resilience in the face of water and energy challenges. Implementing solar-powered smart irrigation systems in Rwanda has the potential to enhance agricultural productivity, conserve water resources, and contribute to the country's sustainable development goals [92].

2.5. Policies, plans, and strategies adopted by Rwanda to tackle climate change issues

Rwanda, a landlocked country located in East Africa, has been actively addressing the challenges posed by climate change and has implemented a range of policies, plans, and strategies to mitigate its impacts. Identifying the importance of sustainable agriculture and water management, Rwanda has prioritized the adoption and promotion of irrigation systems to enhance agricultural productivity and resilience in the face of changing climatic conditions. Through these efforts, Rwanda aims to ensure food security, reduce vulnerability to climate change, and achieve sustainable economic development. These policies and strategies demonstrate Rwanda's commitment to addressing climate change challenges and promoting sustainable irrigation practices.

1. **National Climate and Environment Funds:** Rwanda established the National Climate and Environment Funds to finance climate change initiatives, including irrigation projects. These funds provide financial support for implementing climate-resilient strategies, such as water resource management and sustainable agriculture practices [93].
2. **National Irrigation Policy and Strategy:** In 2016, Rwanda launched the National Irrigation Policy and Strategy. The policy aims to enhance food security, increase agricultural productivity, and promote sustainable water management through irrigation. It sets targets for expanding irrigation coverage, improving water efficiency, and integrating climate change adaptation measures into irrigation practices [94].
3. **Sustainable Water Supply and Sanitation Master Plan**: The Sustainable Water Supply and Sanitation Master Plan, developed in 2019, focuses on ensuring access to safe water resources while considering climate change impacts. It emphasizes the importance of sustainable water management practices, including the use of irrigation to support agricultural productivity and resilience [95].
4. **Land and Water Management Program:** Rwanda's Land and Water Management Program, launched in 2015, promotes sustainable land and water management practices,

including irrigation. The program aims to reduce soil erosion, enhance water availability, and improve agricultural productivity through the implementation of climate-resilient irrigation systems [96,97].

5. **Climate-Resilient Green Economy Strategy:** Rwanda's Climate-Resilient Green Economy Strategy, adopted in 2011, focuses on promoting sustainable economic development while addressing climate change challenges. The strategy recognizes the role of irrigation in enhancing agricultural productivity and resilience to climate change impacts. It encourages the adoption of climate-smart irrigation technologies and practices [98].

2.6. The benefits of using solar energy in smart irrigation and climate change adaptation

The utilization of solar energy in smart irrigation systems brings about various benefits, both in terms of agricultural production and climate change adaptation. The use of solar-powered irrigation enables farmers to overcome challenges related to limited access to electricity in remote areas. For instance, in Tanzania, the implementation of solar-powered irrigation schemes has allowed farmers in off-grid regions to expand their agricultural activities and improve crop yields [50,99]. This increased productivity contributes to food security and economic development in these communities. Solar-powered irrigation systems offer a sustainable and environmentally friendly solution. By harnessing solar energy, farmers can reduce their dependence on fossil fuels and lower greenhouse gas emissions associated with conventional energy sources. This contributes to mitigating climate change and adapting to its impacts. For example, Kenya has seen notable advancements in solar-powered irrigation, with farmers transitioning from diesel-powered pumps to solar-powered systems. This shift has resulted in reduced carbon emissions, improved air quality, and minimized environmental degradation [100].

Moreover, the use of solar energy in smart irrigation helps to conserve water resources; by adopting precision irrigation techniques and integrating sensor technologies, farmers can optimize water usage and minimize wastage [101]. This is particularly crucial in regions facing water scarcity and drought conditions [102]. In Ethiopia, solar-powered drip irrigation systems have been implemented, allowing farmers to efficiently irrigate their crops while conserving water resources [103]. This efficient use of water contributes to climate change adaptation by enhancing agricultural resilience and reducing vulnerability to water stress. In summary, the adoption of solar energy in smart irrigation systems brings tangible benefits to both agricultural production and climate change adaptation. It enables farmers to overcome energy access challenges, increases productivity, promotes sustainability, reduces greenhouse gas emissions, and enhances water resource management [104]. Examples from countries like Tanzania, Kenya, and Ethiopia demonstrate the positive impacts of solar-powered irrigation on socioeconomic development and environmental sustainability [105].

Therefore, the utilization of solar energy in smart irrigation systems plays a pivotal role in climate change adaptation. By harnessing the power of the sun, these systems provide a sustainable and environmentally friendly solution to water management in agriculture. Solar energy not only reduces reliance on fossil fuels, but it also helps mitigate greenhouse gas emissions, contributing to global efforts in combating climate change. The integration of smart technologies enables efficient water usage and precise irrigation practices, promoting water conservation and resilience in the face of changing climatic conditions. By embracing solar energy and smart irrigation, we can achieve a more sustainable and adaptive approach to agriculture, ensuring food security while safeguarding the environment for future generations.

CHAPTER 3. METHODOLOGY

3.1 Introduction

Research methodology denotes a collection of principles and techniques that are used to examine and interpret concepts to address research questions and objectives This segment discusses the specific methodological approach that was used to translate theoretical concepts into measurable data to answer particular research questions. The section also covers various aspects of methodology, including materials, procedures, and the tools harnessed for data collection. Additionally, it outlines the methodologies employed for data analysis, including statistical procedures and the computation of solar radiation and wind energy potential through specialized formulas and distributions. By discussing these key elements of the method, readers gain a comprehensive understanding of how the research was conducted and how the results were obtained.

3.2. Case study description

Bugesera district, situated in the Eastern Province of Rwanda, is one of the country's thirty districts. It shares borders with the Republic of Burundi. The district consists of 15 sectors, 72 cells, and 581 villages, with a total population of 551,103 individuals, comprising 271,468 males and 279,635 females. Bugesera district covers an area of 1,288 km², with approximately 91,930.34 hectares of arable land and a population density of 427.7/km². Bugesera district accounts for around 13.9% of the Eastern Province's population and 3.4% of Rwanda's total population [106]. Geographically, it is located approximately 2° 8' 44" south of the equator and 30° 5' 29" east of the Greenwich Meridian, with an elevation of 1429 meters [17]. Rurambi Wetland, located within the Bugesera district in the Eastern Province of Rwanda, serves as the study area for this research. Rurambi Wetland is a significant ecological feature encompassing a diverse range of natural habitats, including marshes, swamps, and water bodies. It is situated near Lake Rurambi, near the border between Rwanda and Burundi. The wetland plays a crucial role in the local ecosystem, providing habitat for various plant and animal species, supporting biodiversity, and contributing to the overall environmental balance [107].

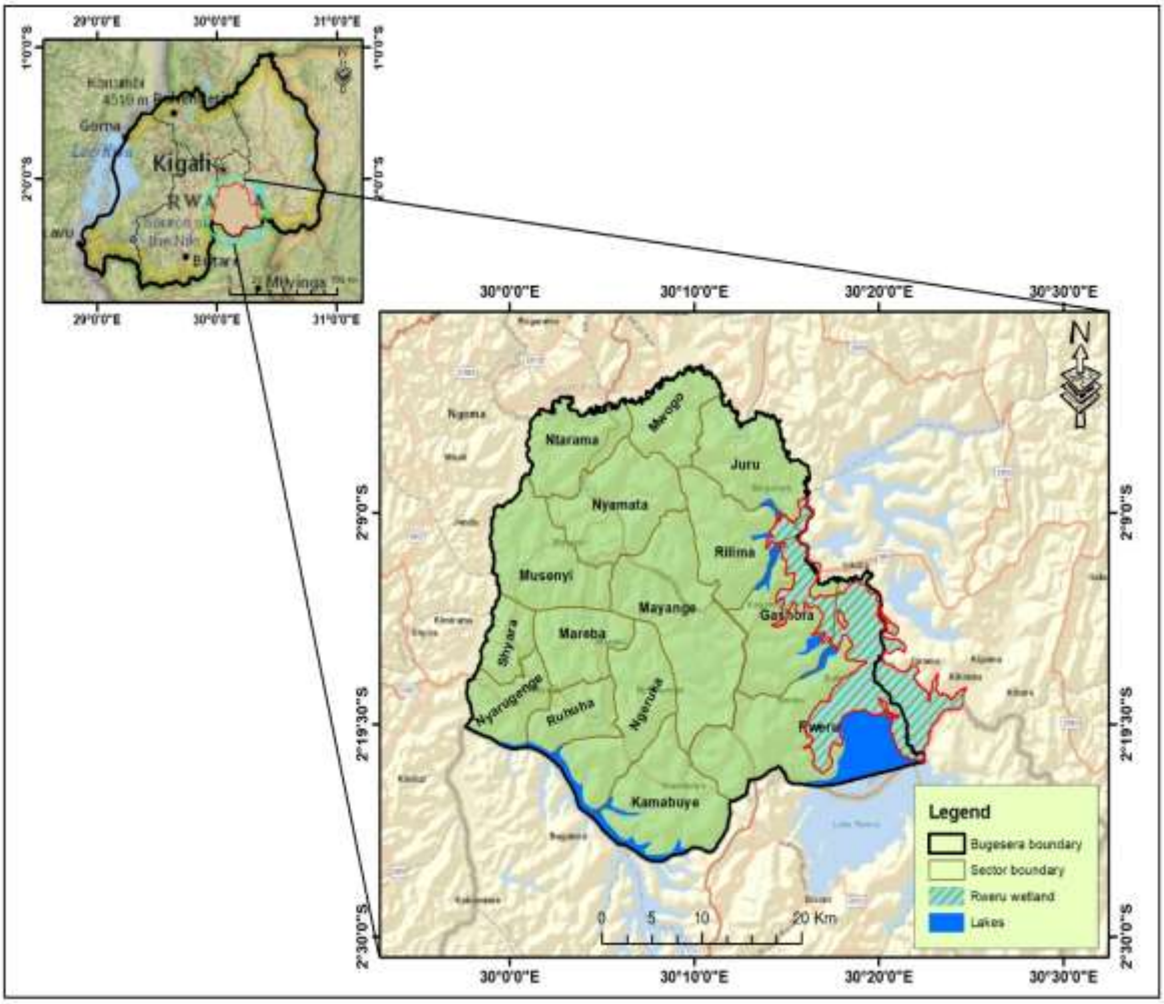


Figure 1Rurambi wetland, Bugesera district in Eastern province. Source:

3.3 Data Collection

This section provides a broad context of the various methods employed for collecting data, the sources from which the data is derived, and the tools and techniques harnessed to acquire the necessary information. Furthermore, this portion also covers the various types of sampling techniques utilized to ensure that the research objectives are met.

3.3.1. Data sources.

The primary data were acquired through a semi-structured interview, and questionnaire survey, systematically administered to engage farmers and stakeholders within operating in Rurambi wetland. The survey was meticulously crafted to capture quantitative insights into variables encompassing prevailing irrigation practices, water consumption trends, varieties of crops, and opinions pertaining to solar energy potential and the concept of smart irrigation.

In addition, to supplement the primary data, the research meticulously integrated secondary data collected from the prestigious Rwanda Meteorological Agency (RMA), which provided historical solar radiation data directly relevant to the study area. This strategic incorporation of supplemental information deepens the research's insights, allowing for a thorough and comprehensive assessment of the potential of solar energy in the context of smart irrigation and climate change adaptation within the Rurambi wetland.

The spatial data incorporated in this research are boundary of the wetland and district, lakes, wetland data and base map used to make the make very readable by non-mapping experts and were downloaded from official Rwanda Geospatial data portal named Rwanda Spatial data hub which was launched 2021 by the Ministry of ICT. Software like ArcGIS 10.8.2 was used in spatial manner whereas Microsoft Excel and Google Sheets were employed in non-spatial data analysis.

The following table highlights the nature of data, their sources and software used in processing.

Table 2: Data source and data processing software

Data	**Sources**	Data processing **Software**	**Link**
The shapefiles of administrative boundary	Rwanda Spatial Data Hub website	ArcGIS 10.8.2	https://geodata.rw/portal/apps/sites/#/nsdi
Temperature, rainfall and solar radiation data	Meteo-Rwanda	Microsoft Excel and Google Sheets	Data emailed to the researcher
Primary data (Qualitative and Quantitative)	Field work-Bugesera	Questionnaires	Archived

3.3.2. Sampling and target population

Sampling involves selecting a subset of units from a larger population of interest to conduct research, and the findings of the sample are then applied back to the entire population This particular research focuses on the Bugesera district as a specific region of interest known for its abundant solar potential and significant water resources. The study aims to gather data from farmers engaged in agricultural activities within the district who are facing challenges related to climate change and water scarcity. To efficiently manage time constraints and streamline the research process, a sampling method was utilized. This approach allowed the researcher to select a subset of respondents from the population, enabling the study to draw accurate conclusions and generalizations that represent the larger population.

In this case, among many farmers actively engaged in agricultural activities in the Rurambi wetland, one hundred thirty-twos were randomly selected to ensure an unbiased and well-balanced sample, particularly from sectors adjacent to the Rurambi wetland.

The research was done through questionnaire I randomly selected small holder's farmers to be interviewed about the impacts of the droughts and low rainfall on their agriculture practices and how they cope with the challenges arise due to those impacts, the sampling method used was based on the information on farmer's population in area of interest, I sampled 132 farmers who do agriculture practices and whom rely on rainfall

the wetland is mainly composed by 200 farmers who practice farming for different crops

this the formula of sample size I used $n = z^2 * \left(P\,\frac{1-P}{e^2}\right) + \left[z^2 * \left(P\,\frac{1-P}{e^2 N}\right)\right]$

Equation 1

n represents sample population

Z represent Z-score, for confidence level of 95 % Z-score would be 1.96

while p represents standard deviation which 50%

And *e* represents the margin error assumed to be 0.05

Structured questionnaire helped to find out the adaptive capacity of smallholder's farmers on how low rainfall or no rain in their agriculture practices. indicators I interviewed the farmers whose crops are cabbages, tomatoes, the survey was intended to know the impacts of climate change that farmers are facing and the adaptation strategies they had applied

3.3.3. Primary data collection

Primary data collection refers to the process of gathering original data directly from the source through methods such as surveys, interviews, focus groups, and field observations [106]. It involves the collection of data that is specifically tailored to answer the research questions at hand and is therefore unique to the study [107]. Within the framework of this research, the data collection process was carried out through two distinct approaches: semi-structured interviews with farmers engaged in activities within the Rurambi wetland, facilitating the gathering of primary data directly from the field. Additionally, questionnaire surveys were administered to a subset of research participants possessing relevant expertise and focused on the mechanics of ongoing irrigation practices, the envisioned smart irrigation system, and considerations for climate change adaptation. The information collected from these experts aimed to understand the effectiveness of solar radiation utilization in smart irrigation systems and climate change adaptation.

3.4.3.1. Interview

This study utilized a semi-structured interview approach to gather data from farmers who are currently engaged in agricultural operations in the Rurambi wetland. Through this approach, the farmers were able to provide detailed information about their experiences with the irrigation system, how it has impacted agricultural activities and challenges, and how smart irrigation systems can be the best alternative solution to sustainable agriculture and climate change adaptation in Bugesera district. The semi-structured interview technique allowed the interviewers to ask questions of each respondent, enabling them to provide more comprehensive information. This approach also made it easier for the researchers to record the respondents' responses. Generally, the semi-structured interview approach was effective in providing the necessary information for this study, and despite the challenges of the low literacy of the farmer respondents, the researcher was able to obtain valuable insights into the experiences of farmers operating in Rurambi wetland about their perceptions of using solar radiation for smart irrigation systems and climate change adaptation.

3.4.3.2. Questionnaire

A questionnaire survey is a data-collecting tool in which written questions are disseminated to a specific group to acquire information [108]. The technique offers a flexible framework that allows for a combination of predefined questions and open-ended responses, allowing respondents to provide detailed insights and perspectives while maintaining consistency across participants [109]. In this study, experts from varied domains took part in a questionnaire survey, offering their perspectives on a variety of focused issues. Agronomists, irrigation experts, water engineers, and administration members contributed data on topics such as current irrigation techniques, energy sources, climatic challenges, and potential remedies. The tailored survey generated a comprehensive dataset covering energy sources, the feasibility of solar solutions, benefits of solar-powered irrigation, regulations, and adaptation strategies, allowing for a comprehensive understanding of solar energy potential and climate change adaptation in the Bugesera district Rurambi wetland context.

3.4.3.3. Field observation

Field observations were vital for this study since they provided direct and first-hand insight into the subject area and its dynamics. The researchers carried out on-site observations in the Bugesera district, particularly in and around the Rurambi wetland, allowing them to collect thorough data on a variety of topics, including existing energy potential, irrigation techniques, and climate adaptability. The researchers observed and recorded the real conditions, practices, and behaviors in the study region using field observations. Through field observation, this study gathered insights into current information, such as the utilization of energy systems, irrigation techniques used by farmers, and the influence of climate change on agricultural operations. This qualitative technique yielded invaluable perspectives and contextual comprehension, thereby corroborating and supplementing findings derived from alternative data collection approaches. Ultimately, this comprehensive approach bolstered the overall dependability and inclusiveness of the study's outcomes.

3.5.2. Secondary data collection

Secondary data collection refers to the process of gathering information or data that has been previously collected by someone else for a different purpose [108]. It involves accessing existing sources of data, such as published literature, reports, databases, surveys, or any other form of recorded information from various organizations, institutions, government agencies, research studies, or other reliable sources [109]. Researchers utilize secondary data to address their research objectives without conducting new primary data collection.

3.5.2.1. Documentary review

The research employed a documentary review method to collect secondary data, encompassing an extensive range of documents and reports from various sources. These sources included governmental institutions such as the Rwanda Ministry of Agriculture and Animal Resources (MINAGRI), the Rwanda Meteorology Agency, and the Rwanda Agriculture Board (RAB), as well as international organizations, non-governmental organizations (NGOs), and public and private companies with a focus on solar energy and agriculture. Published books and journals also served as valuable sources of information. This comprehensive approach to the documentary review ensured the gathering of a wide range of reliable and relevant data.

3.5.2.2. Meteorological Data

To analyze the trends of solar radiation in the Bugesera region and facilitate effective planning for solar energy systems, monthly and annual solar radiation data were collected from 2012 through 2022. This extended time series dataset has provided a comprehensive understanding of the variability of solar radiation throughout different seasons and years. The data were obtained from the Rwanda Meteorology Agency, which is responsible for maintaining such records. The geographic coordinates of the Bugesera district, specified as approximately 30.112735° longitude, -2.231532° latitude, and an elevation of 1364 meters, served as the reference for analyzing the solar radiation potential in the study area. The collected data has played a crucial role in assessing the viability of solar energy systems and devising strategies for climate change adaptation in the region.

3.6 Data analysis

Data analysis is a meticulous process involving the thorough examination, refinement, transformation, and interpretation of raw data to reveal meaningful insights, support decision-making, and draw deductions. It utilizes a range of statistical and computational techniques to identify recurring patterns, evolving trends, and interconnections within the data, yielding valuable information that guides problem-solving and optimization efforts [112]. In the present study, this analytical approach played a vital role in assessing the solar energy potential of the region. By analyzing an extensive dataset of solar radiation data collected between 2012 and 2022 from the Rwanda Meteorology Agency, researchers aimed to uncover patterns and trends in solar radiation across different timeframes and seasons. Therefore, various data analysis techniques, including qualitative and quantitative ones like formulas and statistical distributions, were utilized to grasp the data's intricacies and unearth insightful details that could enhance the study's overall outcomes.

3.6.1. Qualitative data analysis

The qualitative data analysis technique supported in analyzing data collected using semi-structured interviews and questionnaire surveys included textual information provided by the research respondents, such as farmers and technical experts, including agronomists, water irrigation experts, and members of administrative staff. The qualitative data obtained from open-ended questions was analyzed to identify common patterns, themes, and key insights related to the research objectives. The integration of qualitative and quantitative analysis methods has provided a holistic understanding of the research data and facilitated the interpretation and discussion of the results.

3.6.2. Assessing the adaptive capacity of farmers to drought

To evaluate the adaptive capacity of farmers in enhancing resilience against water scarcity during drought periods, a mixed-methods approach was employed, incorporating literature reviews and case studies. The literature review involved a comprehensive search and analysis of relevant scientific studies, research papers, laboratory reports, and publications that have investigated the adaptive capacity of farmers' varieties to water scarcity. As a result, it provided a foundation of existing knowledge and findings in the field. Additionally, case studies were conducted in selected locations or farms within the Bugesera district. These case studies involve direct observation, surveys, and data collected from farmers and agricultural practitioners. The focus was on understanding the agricultural practices, crop choices, and management strategies employed by farmers to cope with water limitations and enhance resilience against droughts. The data collected from literature reviews and case studies were meticulously analyzed using qualitative analysis techniques to identify common patterns, key findings, and successful strategies employed by farmers. Consequently, it provided valuable insights into the adaptive capacity of farmers in the specific context of the Bugesera district.

3.6.3. Quantitative data analysis

Quantitative data analysis in research refers to the systematic examination and interpretation of numerical data collected from research studies or surveys and it involves applying statistical methods and techniques to quantify and summarize the data, allowing for objective and numerical insights [113]. Quantitative data analysis aims to uncover patterns, relationships, and trends within the data, and draw statistically supported conclusions to address research questions or test hypotheses [114]. In the present study, various mathematical techniques like formulas and distributions were employed to analyze the time series data like solar radiation data, rainfall and temperature from 2012-2022 to reveal patterns, relationships, and trends, thereby contributing to a statistically informed decision and met research objectives

3.6.4. Assessing Solar Energy Potential

For estimating solar energy potential, temporal variability analysis was used to find out how the solar radiation is varying over time, the graphic method was used to show how solar radiation is distributed in months for a specific period of time, statistical indicator such mean, standard deviation was used to evaluate the variation of solar radiation, since the solar radiation data is the most important component to estimate output of photovoltaic systems. Solar radiation is greater than 3 kWh/m2 indicates that the sky is clear, its intensity very high and very good for PV application

$$E = A * r * H * PR$$

Equation 2

E is the energy (kwh)

r is solar panel yield

H annual average solar radiation

A is the total area of the panel (m2)

PR performance ratio default value 0.75

Solar potential = (Average monthly solar radiation) * (Number of hours of sunlight per day) * (Efficiency of the solar panels)

In the conducted study, several key factors were considered. By integrating and analyzing these factors, the study estimated the solar energy potential in Bugesera district for solar-powered irrigation systems. Each factor contributed to the overall assessment by providing

critical information on the available solar radiation, climatic conditions, and geographical location. The findings aided in determining the feasibility and potential energy potential of solar-powered irrigation systems in the district, facilitating informed decision-making for sustainable agricultural practices and water resource management.

Solar Irradiance: Data on solar irradiance was obtained from meteorological stations. This data provided information on the amount of solar radiation available in the Bugesera district throughout the year, which was very critical for estimating solar energy potential.

Climate Data: Climate data, including temperature, and precipitation, were also collected from Meteo-Rwanda. This data helped the understanding of the climatic conditions in the area and their impact on solar radiation availability.

Latitude and Longitude: The geographical coordinates of the Bugesera district were determined to accurately calculate the angle and intensity of solar radiation based on the position of the sun. Latitude and longitude data were obtained from geographic information systems or online mapping tools.

3.6.5. Assessing rainfall and temperature Trends

For trend analysis for both temperature and rainfall, the temporal analysis approaches were used to assess their trend either annual and seasonal. The temporal analysis of rainfall consisted of determining the seasonal rainfall for specific period of time and subjected to a time series analysis. For this purpose, graphical method was used to assess the nature of trend in historical data by plotting observed rainfall against time. The benefits of this method is that it gives the overview of the trend quick visual observation of the presence of a trend in a given time series. Moreover, the use of the graphical approach for trend analysis is simple

Mann Kendell as statistical test was used to test the statistical significance of the trend observed in time series

Statistical methods were used to test the statistical significance of the observed trends in a time series

Positive values represent an increasing trend whereas negative values mean a downward slope

To estimate the degree of rainfall and temperature change, the Theil–Sen's slope estimator was applied. The statistical significance was reported based on level of significance (p-value or alpha) of 0.05

During the study, statistical analysis of temperature trends was conducted using various methods to assess the patterns and changes in temperature over time. One commonly used approach was the linear regression analysis, which helped determine if there was a significant upward or downward trend in temperature data. The formula for the linear regression equation was:

$$Y = a + bx$$

where Y represents the dependent variable (temperature), a is the intercept, b is the slope (indicating the rate of change in temperature per unit of time), and X is the independent variable (time). To determine the statistical significance of the trend, the coefficient of determination (R-squared) was calculated. R-squared measures the proportion of the variance in temperature that can be explained by the linear regression model. A high R-squared value suggests a strong relationship between time and temperature. Software particularly Microsoft Excel was used to perform linear regression analysis and calculate the R-squared value, produce graphs and other statistical measures regarding the published and common standards.

3.6.3.3 Assessing average monthly rainfall

The study was conducted by assessing historical rainfall data spanning 40 (1981-2021) years in the Bugesera region. Data was collected from the Rwanda Meteorological Agency, covering the specified analysis period. The collected data was then organized into a suitable format for subsequent analysis. Statistical methods were applied to calculate temporal rainfall analysis for Bugesera. This temporal analysis included determining the mean, standard deviation, and trends over time to evaluate rainfall variability. These calculations provided insights into Bugesera district's overall rainfall patterns during the specified period. Graphic methods were employed to visualize the findings.

3.6.6 Ethical Considerations

For this study, the researcher enlisted the participation of farmers, irrigation experts and local government leaders to obtain consent from respondents before gathering data. The researcher communicated the aims of the study to the participants and assured them of complete anonymity. Additionally, the participants were made aware of the expected duration of the discussion. Before initiating the conversation, permission to record the discussion was sought from the participants.

The researcher took several steps to ensure ethical and transparent data collection. Firstly, the study involved obtaining informed consent from participants. This was achieved by involving individuals who held influential positions in the community and who could assist in obtaining consent from participants. Secondly, the researcher provided a clear explanation of the study's objectives to the participants, ensuring that they understood the purpose of the research. Thirdly, researchers took steps to maintain the confidentiality and anonymity of the participants, which is crucial in gaining their trust. Lastly, researchers sought permission from the participants to record the discussion where there were needed, which is an essential step in ensuring accurate data collection.

data collection process took longer than anticipated. To overcome these challenges in future research, it may be helpful to consider conducting interviews with the agricultural workers during periods of low activity or when they are taking a break. Additionally, providing support to the respondents who have difficulties with reading and writing can be helpful in speeding up the data collection process

Chapter 4: Results and discussion

4.1 Introduction

This chapter presents the results of a study that evaluated historical rainfall, temperature, and solar radiation data spanning 40, 40, and 6 years, respectively. The researcher collected secondary data from the Rwanda Meteorological Agency, covering the relevant period for their analysis, in the Bugesera region. He also examined primary data to determine the extent to which farmers in the Rurambi wetland area can or cannot cultivate their crops successfully. The primary data was gathered through structured interviews with purposively selected farmers. The chapter further includes tables and graphs that illustrate the socio-economic characteristics of the interviewed individuals. Moreover, the challenges faced by farmers during recent farming seasons are also discussed in this chapter.

4.2 Results from field data collection

The results from the semi-structured interviews conducted with 132 individuals in the region revealed interesting patterns concerning the impact of temperature and precipitation on farming. Both temperature and precipitation play crucial roles in the challenges faced by the farmers in this area. Regarding temperature, it was observed that the region experiences high solar radiation due to its common association with high temperatures. This can be a double-edged sword for farming. On one hand, high solar radiation can be harnessed for the use of solar panels in irrigation systems, which could be an affordable and feasible solution for water scarcity. On the other hand, the high temperatures pose a significant challenge to crops, especially those that require more water, such as Cabbages and Tomatoes.

Precipitation, or rather the lack thereof, is a major concern in this region. The interviewees revealed that they face frequent droughts, affecting almost 90% of them. This scarcity of water forces farmers to resort to hand irrigation systems, which are laborious and time-consuming. Moreover, some individuals have to walk long distances, up to 300 meters, from their farms to their water sources, making the whole farming activity highly demanding and costly. The combination of high temperatures and limited water availability contributes to reduced productivity in farming, impacting the livelihoods of the people in the region. The cultivation of water-demanding crops like Cabbages and Tomatoes becomes even more challenging due to these climatic conditions. Therefore, to alleviate the suffering and negative impacts on the community, the findings stress the need for affordable and feasible irrigation systems, specifically those that can utilize solar panels. Such systems could help overcome water scarcity and reduce the burden on farmers. By tapping into the abundant solar radiation available in the region, a well-designed irrigation system could potentially improve agricultural productivity and alleviate the challenges posed by the prevailing climatic conditions.

Primary data collected from the field

Table 3: Characteristics of the respondents

N0	Name	Classes	Number per farmer	Percentage
1	**Respondents sex**	Male	88	66.7
		Female	44	33.3
2	**Age**	20-30	44	33.3
		31-40	31	23.4
		41-50	44	33.3
		51-60	13	10
3	**Changing Crops**	Mix of Cabbages & Tomatoes	75	56.7
		Tomatoes	57	43.3
4	**Farming scale**	Wide-scale	22	16.7
		Small scale	110	83.3
5	**Impact**	1: small impacted	9	6.7
		2: medium impacted	13	10
		3: highly impacted	106	80
		4: extremely impacted	4	3.3

6	**Irrigation type**	Hand irrigation	119	90
		Other	13	10
7	**Disadvantage**	Costly, time-consuming and less production	132	100
8	**Distance from the water source**	100m	26	20
		150m	26	20
		200m	48	36.7
		250m	14	10
		300m	18	13.3

4.2.1 Ages and Gender

The information that follows is the data that were acquired for the ages and genders of field work respondents.

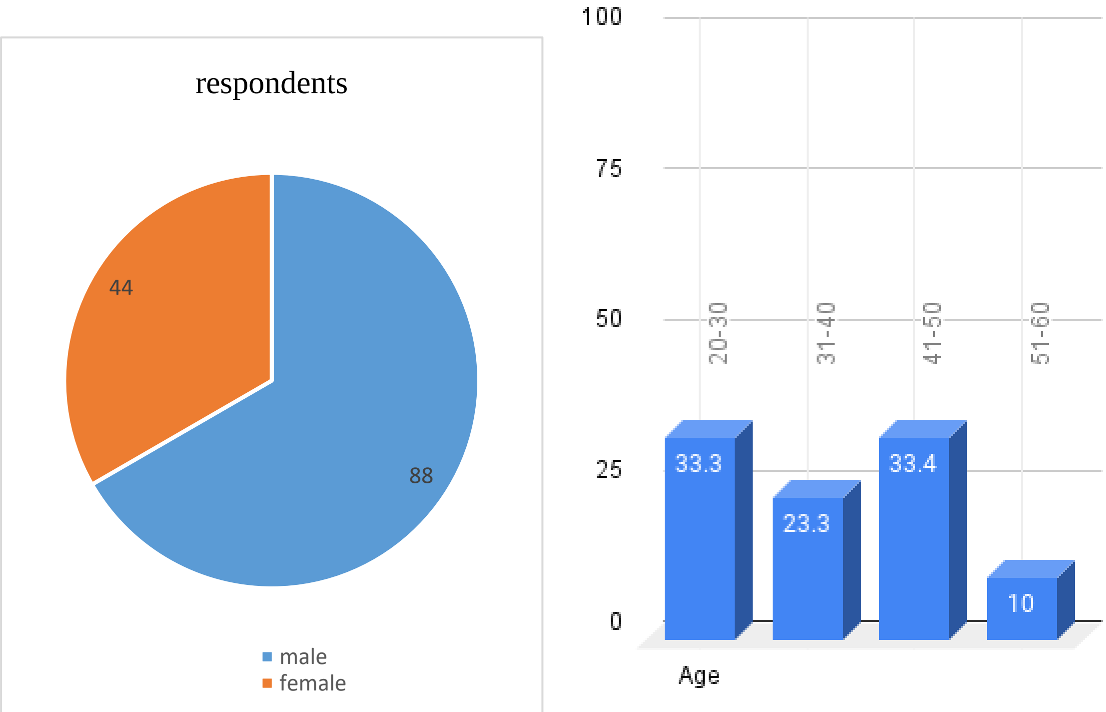


Figure 2 respondents gender and age

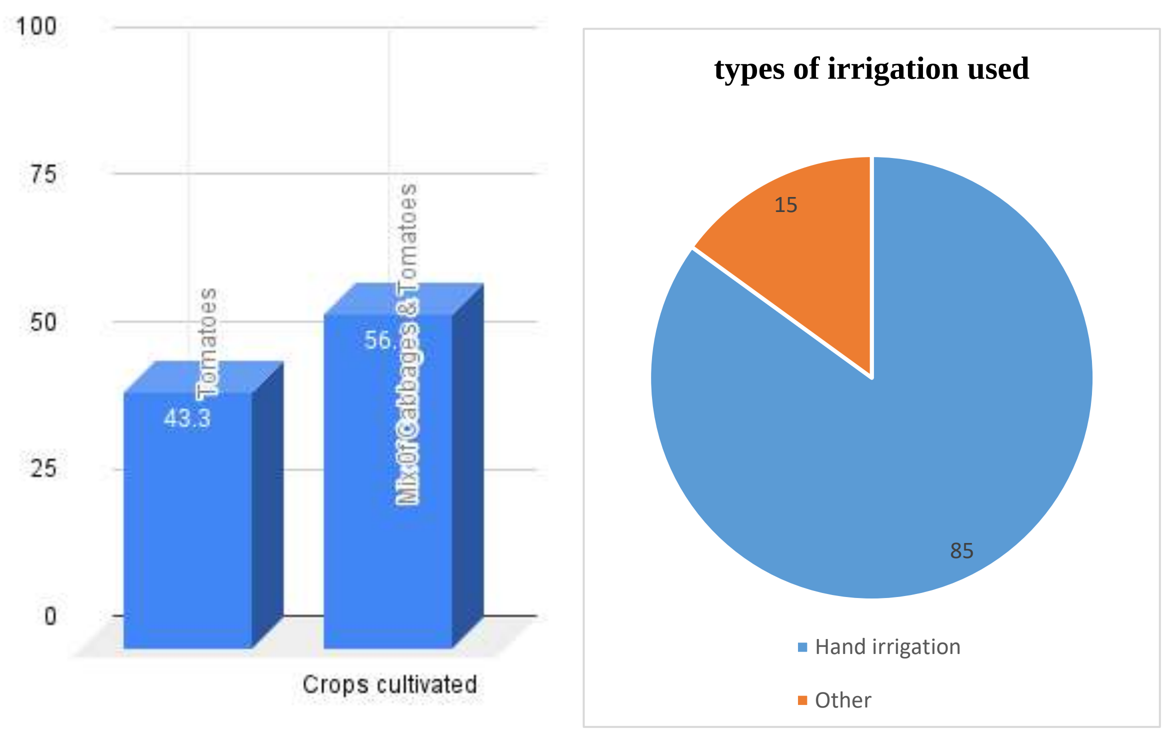
figure 2 represents displays the gender of respondents in number , while the second graph displays the ages of respondents, who were divided into four age groups, each of which was separated by ten years.

According to the findings that were uncovered through the analysis of the data gathered during the fieldwork, out of the total of 132 respondents who were interviewed, 33.3% were counted as female, which corresponds to 44 individuals. In contrast, male respondents accounted for 67.3% of the total respondents, which equals 88 individuals. Regarding the issue of ages, all of the people who responded were separated into various groups spanning as follows: the first category included respondents between the ages of 20 and 30 years, the second category included respondents between the ages of 31 and 40, the third category included respondents between the ages of 41 and 50, and the final category included respondents between the ages of 51 and 60. When it comes to their ages, the respondents are as follows: 44, 31, 44, and 13 correspondingly.

4.2.2 crops cultivated and current irrigation types

The information that follows is the data that were acquired for the changing crops and current irrigation types of field work respondents.

Figure 3 crops cultivated and irrigation type



The first graph, which can be found connected up top, depicts data on crops cultivated, which are defined as crops that are grown in a manner that is either diverse all at once or in rotation.

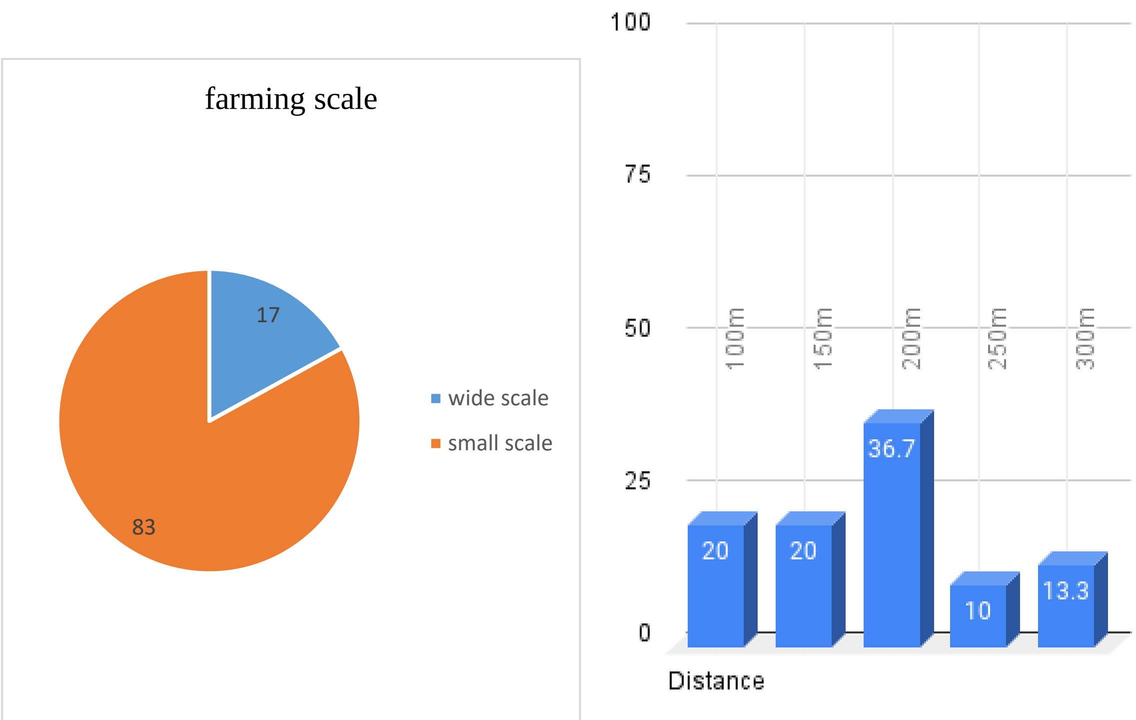
The current irrigation techniques used in the area that was surveyed are presented in the second graph.

The majority of the crops that are being grown within the marsh are cabbages and tomatoes, according to the calculations that have been done. It was observed that 43.3% of individuals solely grow tomatoes, while 56.7% of people prefer to grow a variety of plants in their gardens. The number of farmers who are now engaged in single or mixed farming is 57 and 75, respectively, according to the interviews. It was observed that the majority of the people who were interviewed use an irrigation type, while others use other traditional methods such as channelling water to the farming site. This method is considered to be very unfavorable because it has the potential to cause flooding to a certain extent. Mathematically, 90%, which is 199 of the farmers who were interviewed, utilize the method of hand irrigation, while the other 10%, which counts 13 farmers, use other methods.

4.2.3 Farming scale and Distance

The information that follows is the data that were acquired for the farming scale and walking distance from the field work respondents.

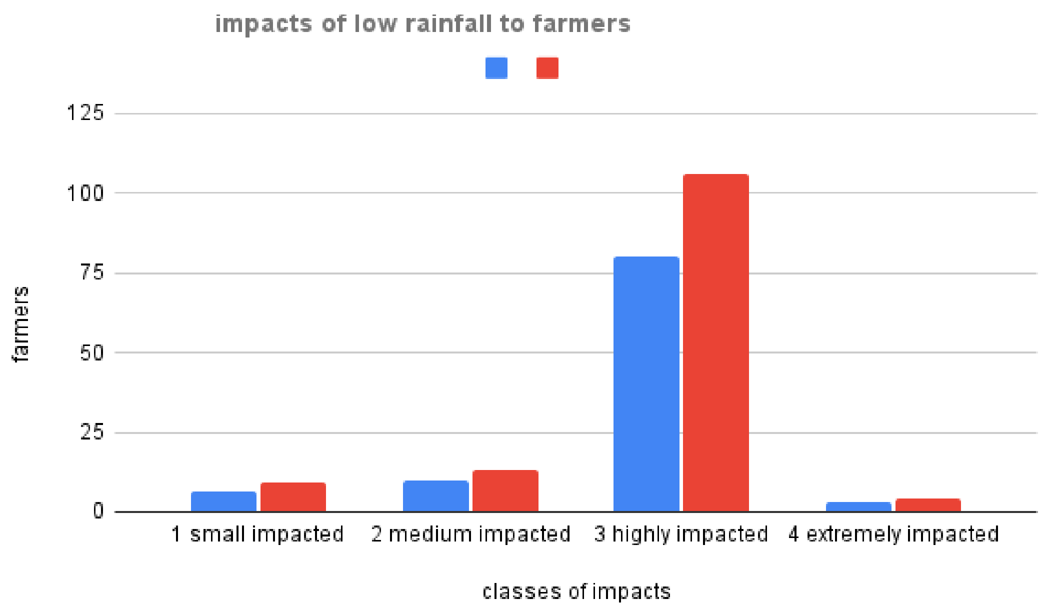
Figure 4 farming scale and distance



The first graph presents information regarding the number of farmers who were interviewed and the size of their operations. The second graph illustrates the distance that farmers had to go from their farmland to the source of the water that they utilized in the irrigation process. As was previously said, the majority of these farmers employed a manual form of irrigation.

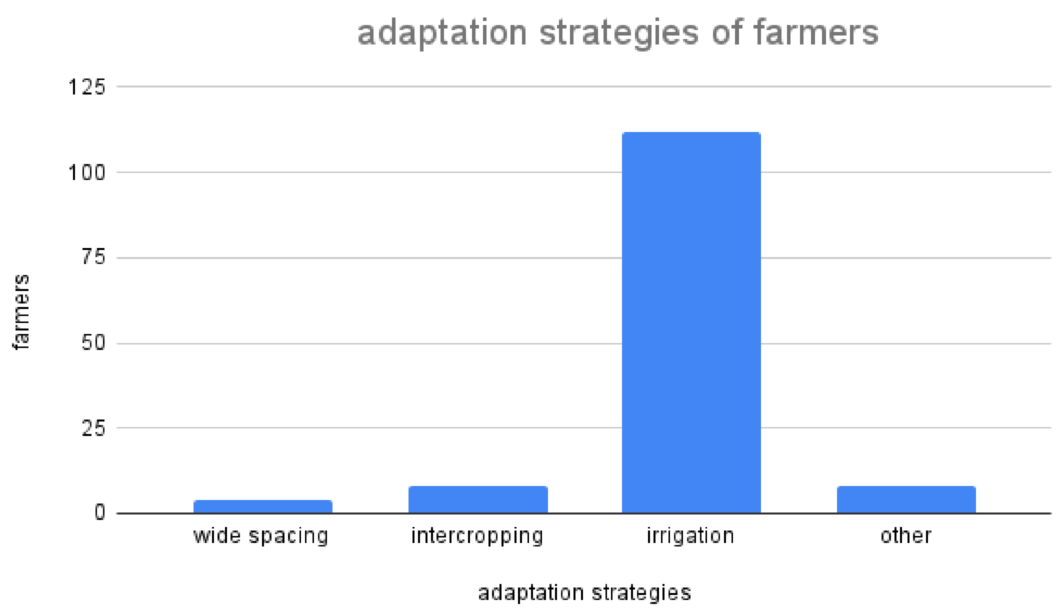
Surprisingly, among the 132 individuals who participated in the survey, a notable pattern emerged in their farming scale: 16.7%, or precisely 22 respondents, engage in large-scale farming activities encompassing at least 1 hectare, while the majority, constituting 83.3% or 110 participants, operate on a smaller scale, managing plots of land measuring less than 1 hectare. A prominent challenge that these individuals encounter in the region pertains to water accessibility for irrigation, especially given the prevailing drought conditions. This challenge will be thoroughly explored in subsequent subchapters. Notably, people in this area are compelled to cover significant distances in their quest for water, exacerbating their difficulties. The data collected regarding walking distances was segmented into five distinct classes, each class spanning a range of fifty meters. The initial category encompasses 26 respondents who walk 100 meters, followed by a group of 26 individuals covering 150 meters, a larger cohort of 48 people journeying 200 meters, a subset of 14 individuals travelling 250 meters, and finally, a group of 18 respondents undertaking the longest trek of 300 meters. While the impacts are widespread across various categories, a significant observation arises from the data: out of the 132 respondents, a substantial 106 individuals find themselves considerably affected by the dual challenges of high costs and meager yields resulting from their agricultural endeavors. In contrast, only a minor subset of 4 individuals is notably influenced by the exceptionally arduous task of cultivating crops amidst drought conditions in the Bugesera region. The consequence of this situation is multi-faceted, encompassing financial burdens, time constraints, and reduced overall productivity. In light of securing the long-term health and prosperity of these farms, it becomes imperative to address and ameliorate this predicament.

Figure 4 impacts of low rainfall to the farmers



most of the farmers interviewed said that are highly impacted by climate change impacts and irrigation is one of the adaptation strategies used by many farmers as shown by figure 5 most of the respondents said that nothing more special they do to adapt the challenge of low rainfall to retain water for their crops rather than using irrigation (hand irrigation)

Figure 5 adaptation strategies of farmers to low rainfall



4.3 Time series data

Time series data is a collection of information gathered over an extended period, enabling researchers to examine ongoing changes and patterns. When it comes to assessing climate change, time series data is a crucial tool for studying environmental trends over the long term and evaluating potential consequences. The research in question centers on exploring climate change and its impact on irrigation systems by analyzing Rainfall, Temperature, and Solar Radiation data in the Bugesera region of Rwanda.

The researcher acquired secondary data from Meteo Rwanda, a reliable source for meteorological information to ensure accuracy and comprehensive analysis. The data were collected from four different weather stations in Bugesera, namely Karama, Nyamata, Ruhuha, and Juru. Specifically, Rainfall and Temperature data spanning forty years (1981-2021) were used to observe climate trends in the region. Rainfall data provided insights into the changing precipitation patterns over the decades, which were crucial in understanding the impact of climate change on water resources. Temperature data allowed the researcher to analyze long-term temperature trends, which was essential for assessing global warming and its effects on local ecosystems. Additionally, Solar Radiation data ranging from 2016 to 2021 was incorporated into the study. Solar radiation data was vital for understanding the amount of solar energy available in the region, which was directly related to the potential for utilizing solar power for irrigation systems. The research objective revolved around investigating the solar energy potential for irrigation systems due to the impacts of climate change and droughts. As climate change intensified, the availability of water for irrigation became increasingly uncertain. Therefore, exploring alternative sources of energy like solar power for irrigation played a significant role in adapting to changing climate conditions. By analyzing the time series data from different weather stations over an extended period, the researcher identified long-term trends and fluctuations in rainfall, temperature, and solar radiation. These trends helped establish a clearer picture of climate change in the Bugesera region and provided insights into potential adaptations for sustainable agricultural practices.

4.2.1 Rainfall data of Bugesera

Rwanda, like many other equatorial countries, has historically experienced high amounts of rainfall due to its geographic location. However, over time, the climate conditions in Rwanda, as well as in other nearby nations, have been changing, impacting both rainfall patterns and temperatures. The observed trends indicate that the annual rainfall has been decreasing, while the temperatures have been on the rise. These changes can have significant implications for the environment, agriculture, and people's livelihoods. Between the years 1981 and 2021, data has shown a decline in the annual rainfall in Rwanda. This decrease in precipitation leads to water scarcity, affecting agriculture, water resources, and overall ecosystem health. It could result in reduced crop yields, affecting food security and livelihoods, especially for farmers who heavily depend on rainfed agriculture.

I conducted an extensive analysis using linear regression techniques, enabling me to extract the most appropriate trend lines. Through this approach, I was able to unravel the intricate patterns embedded within the total mean annual rainfall data spanning multiple years. The insights garnered from this analysis shed light on the fluctuations and tendencies within this climatic variable. To provide a comprehensive visual representation, I have graphically depicted the trends for each month of the year, spanning from January to December, in the figures presented below. In addition to the graphical illustrations, I have included the precise linear regression equations and coefficients of determination that correspond to these observed trends. These valuable insights can be readily observed in the accompanying visuals. Upon undertaking a meticulous examination of these linear regression trends and closely analyzing the associated equations, a conspicuous trend emerges.

It is evident that the overall mean annual rainfall has undergone a discernible reduction during the months of MAM (March, April, and May) as well as SOND (September, October, November, and December). This noteworthy revelation underscores a pervasive decrease in rainfall patterns across the Bugesera region. Unfortunately, this climatic shift carries with it

The annual average rainfall unfavorable implications, particularly affecting agricultural pursuits and farming practices within the area. The reduced rainfall poses challenges and considerations for sustainable land use and crop cultivation in the face of evolving climatic conditions.

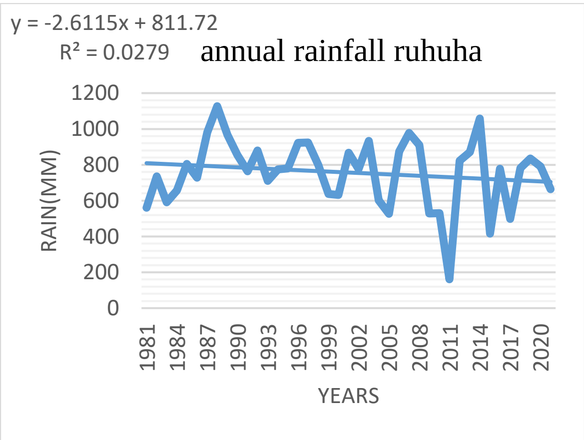
The annual mean rainfall ranges between 756 and 1267mm

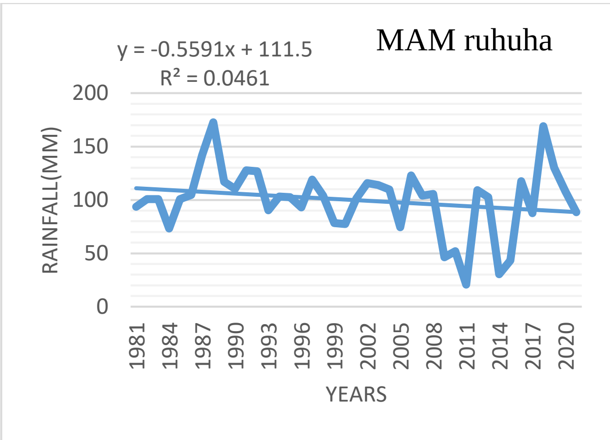
During high rain season of March to May season (MAM), the total rainfall observed vary between 299 and 363 while during short rain season known as September to December or SOND the total rainfall was revealed to be in range of 287 and 373mm.

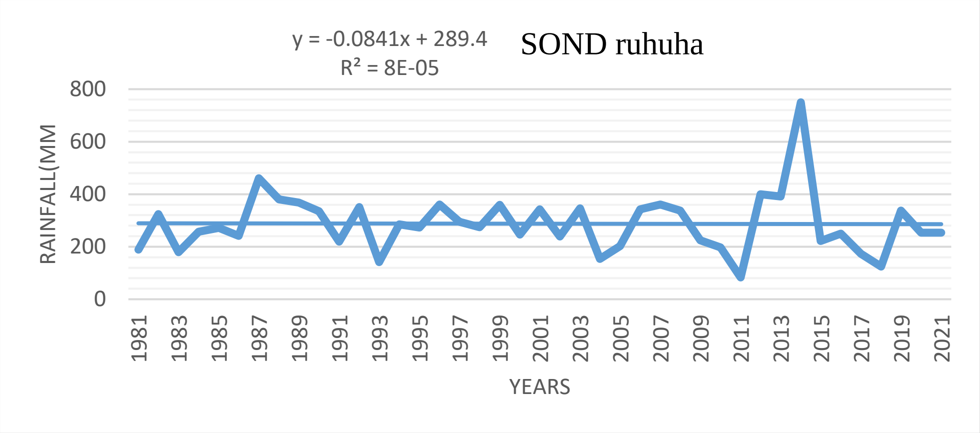
all stations as in figures below showed negative trend except Karama station that showed positive trend neither positive trend nor negative trend is significant as shown by table 4, the highest annual rainfall reported at Juru station which is 1829mm in 2003 while the lowest annual rainfall which is 161mm reported at Ruhuha station in 2011 ,2017 was the year where all stations reported the lowest average annual rainfall where the average mean at all stations is 548 mm

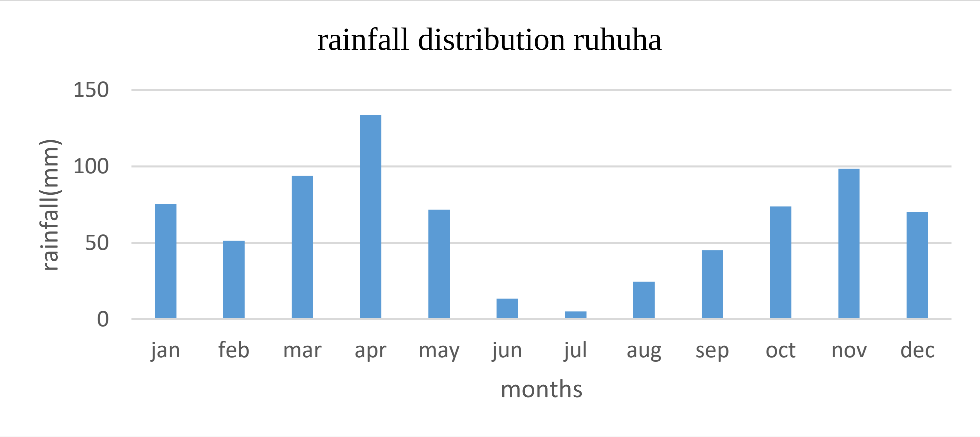
4.2.1.1 Ruhuha station

Figure 6 Annual average and season rainfall Ruhuha station



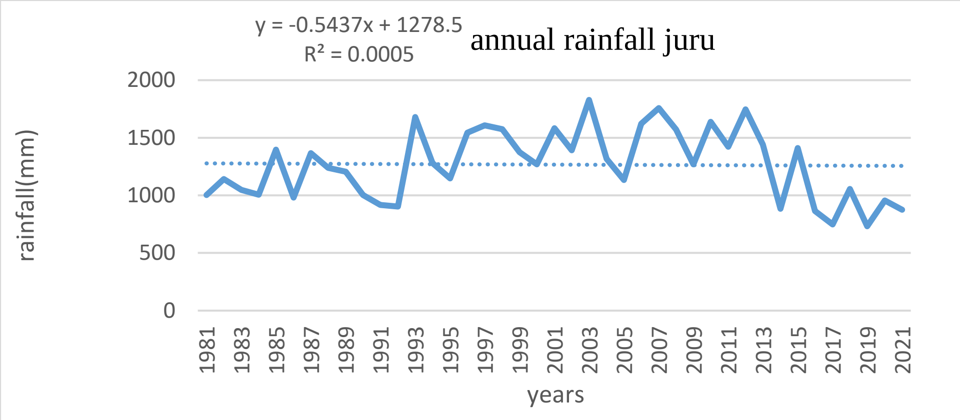


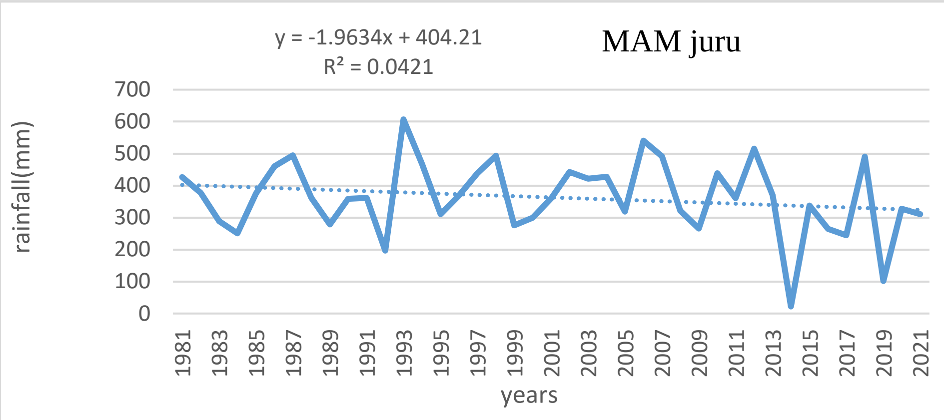


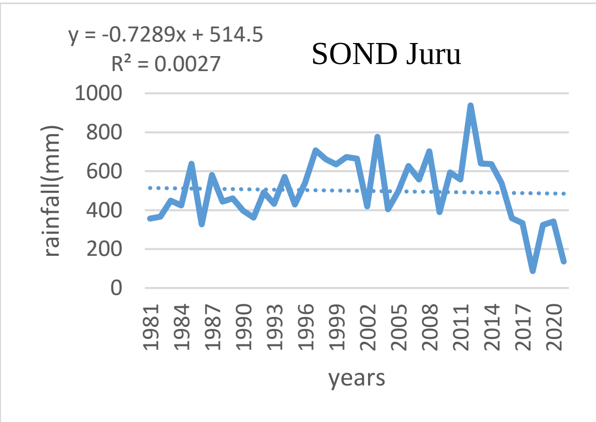


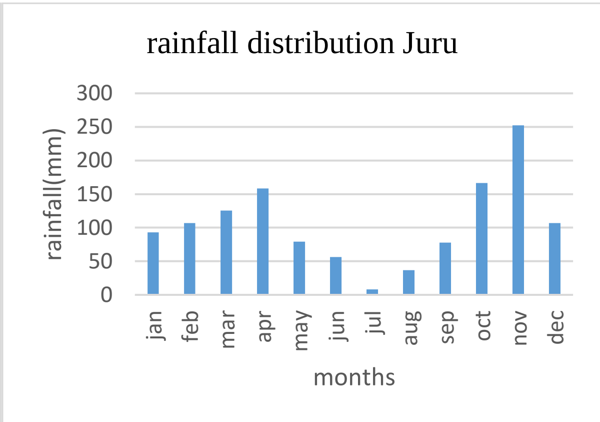
4.2.1.2 Juru station

Figure 7 average annual and season rainfall Juru station



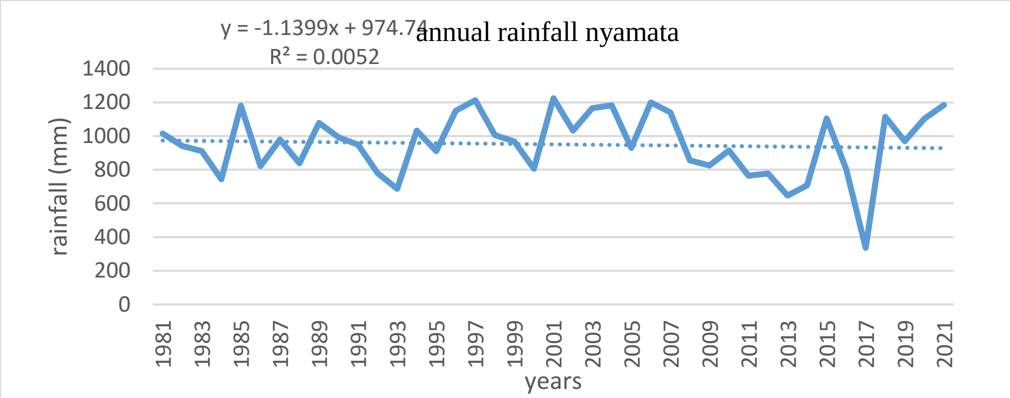


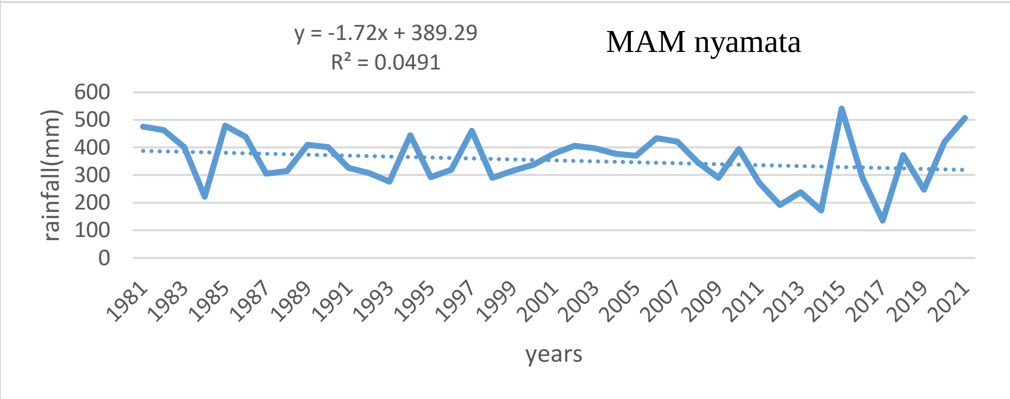


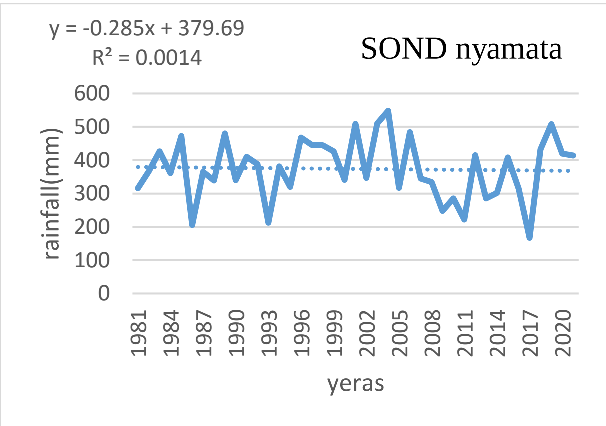


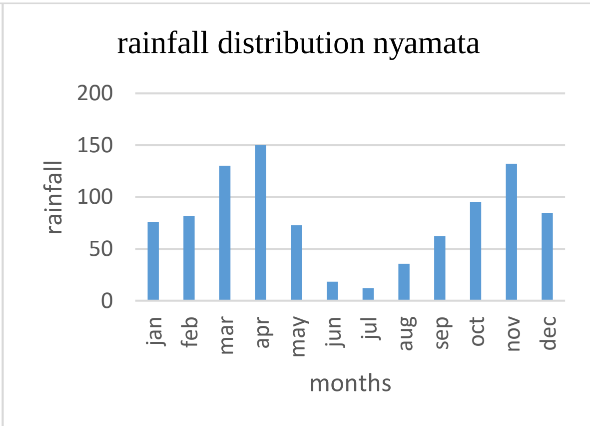
4.2.1.3 Nyamata Station

figure 8 average annual and season rainfall Nyamata station


y = -1.1399x + 974.74
R² = 0.0052
annual rainfall nyamata
rainfall (mm)
1400
1200
1000
800
600
400
200
0
1981 1983 1985 1987 1989 1991 1993 1995 1997 1999 2001 2003 2005 2007 2009 2011 2013 2015 2017 2019 2021
years

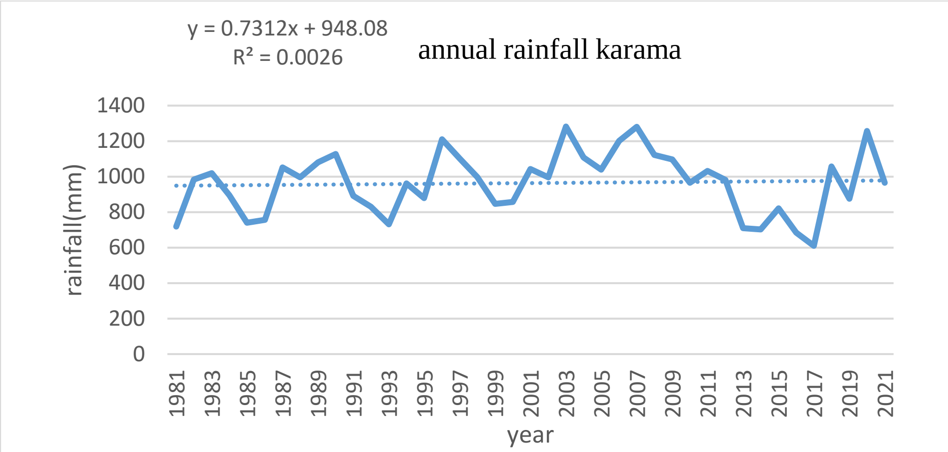

y = -1.72x + 389.29
R² = 0.0491
MAM nyamata
rainfall(mm)
600
500
400
300
200
100
0
1981 1983 1985 1987 1989 1991 1993 1995 1997 1999 2001 2003 2005 2007 2009 2011 2013 2015 2017 2019 2021
years

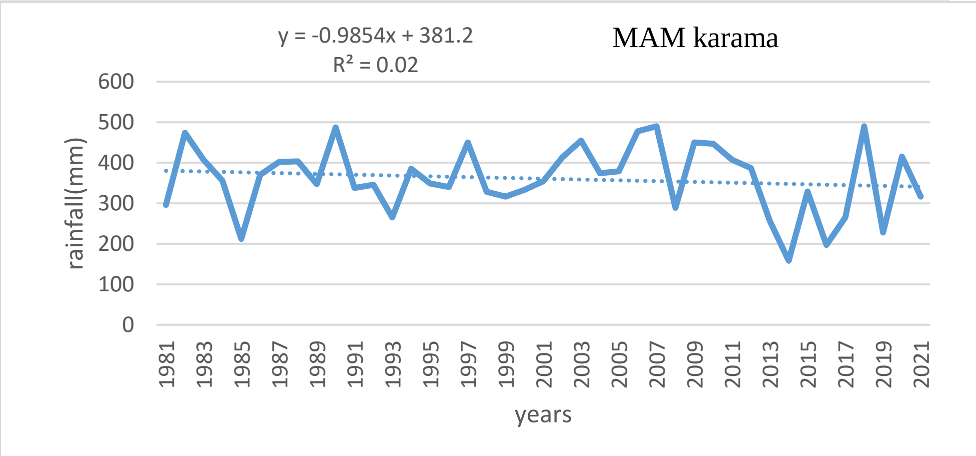

y = -0.285x + 379.69
R² = 0.0014
SOND nyamata
rainfall(mm)
600
500
400
300
200
100
0
1981 1984 1987 1990 1993 1996 1999 2002 2005 2008 2011 2014 2017 2020
yeras

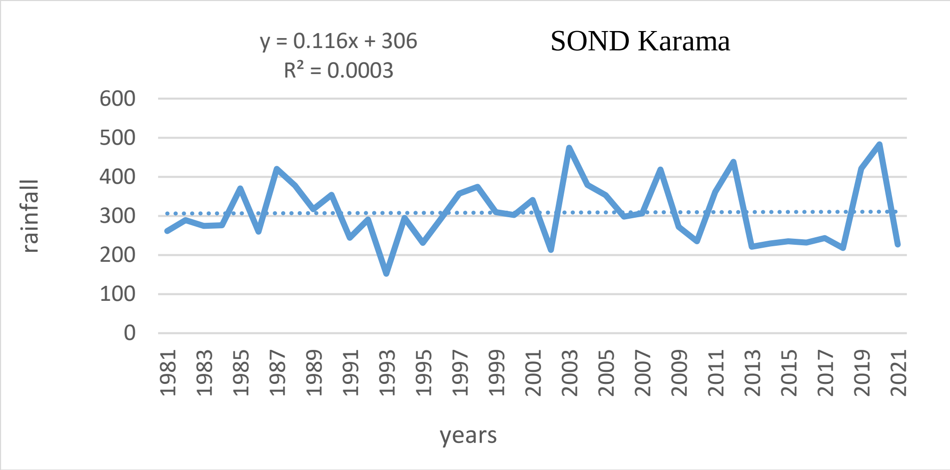

rainfall distribution nyamata
rainfall
200
150
100
50
0
jan feb mar apr may jun jul aug sep oct nov dec
months

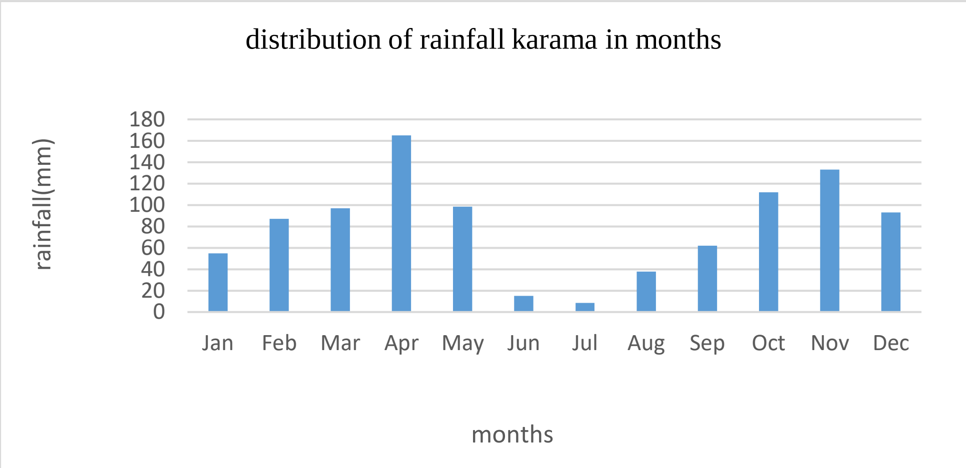
4.2.1.4 Karama station

figure 9 average annual and season rainfall Karama station









For test significance of the trend statistical test were used for 2 seasons and annual for all stations as shown in table below

Table 4 Statistical Test of significance of trend (5%) at all stations

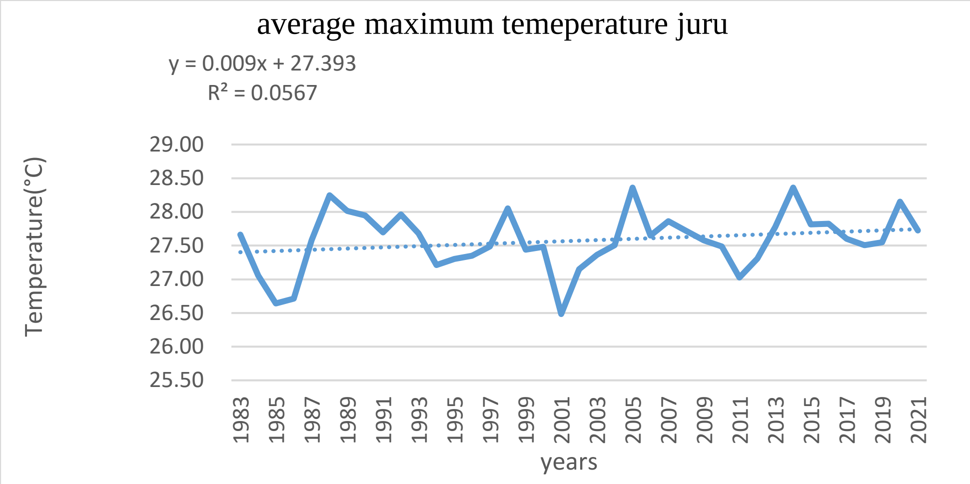
Time scale	station / test	Nyamata	Ruhuha	Juru	Karama
MAM	Kendall's tau	-0.175	-0.084	-0.122	-0.07
	p-value	0.111	0.445	0.266	0.529
	Sen's slope	-2	-0.902	-1.436	-0.88
SOND	Kendall's tau	-0.032	-0.059	-0.006	-0.033
	p-value	0.779	0.598	0.964	0.77
	Sen's slope	-0.308	-0.735	-0.121	-0.477
ANNUAL	Kendall's tau	-0.02	-0.061	0.009	0.023
	p-value	0.866	0.582	0.946	0.84
	Sen's slope	-0.633	-1.681	0.464	0.866

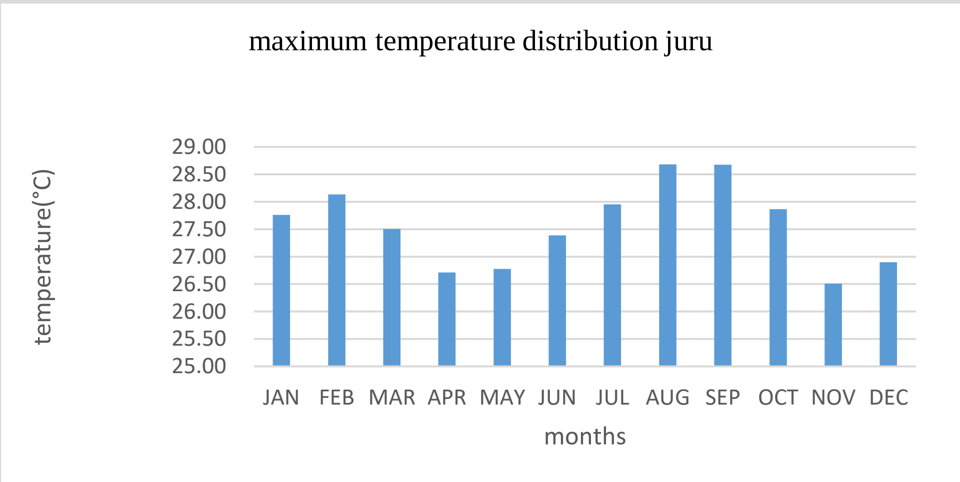
4.2.2 Temperature data of Bugesera

Conversely, the increase in temperature poses a different set of challenges. Rising temperatures lead to heatwaves and contribute to the intensification of weather events, such as droughts. Higher temperatures also impact human health, particularly vulnerable populations, and exacerbate existing health issues. One specific region in Rwanda, Bugesera, has likely experienced its own unique set of climate changes. The situation in Bugesera serves as an example that highlights the urgency for global cooperation and action to address these climate challenges. It becomes essential for countries worldwide to come together and implement various adaptation measures to mitigate the adverse effects of climate change and continue living as close to normalcy as possible. The data presented in the table provides an image of the average monthly precipitation and temperature patterns in the Bugesera district over the past 41 years. The graphs presented below depict the fluctuations in temperature at four stations situated in Bugesera.

4.2.2.2 Juru station

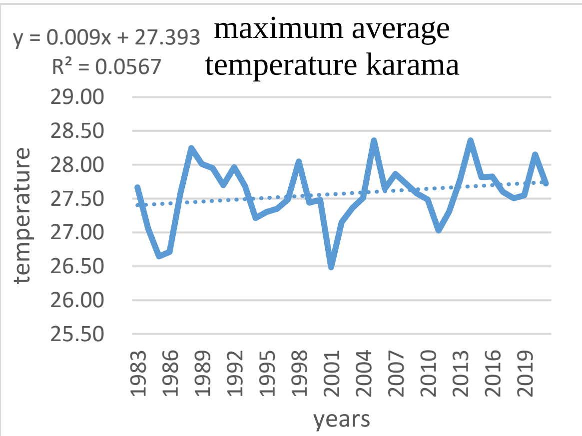
Figure 10 average maximum temperature Juru station

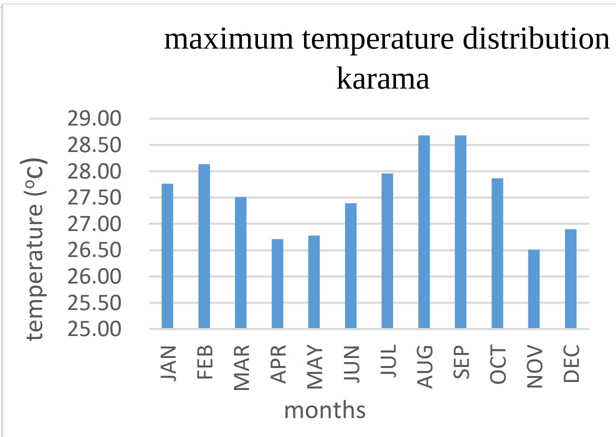




4.2.2.2 Karama station

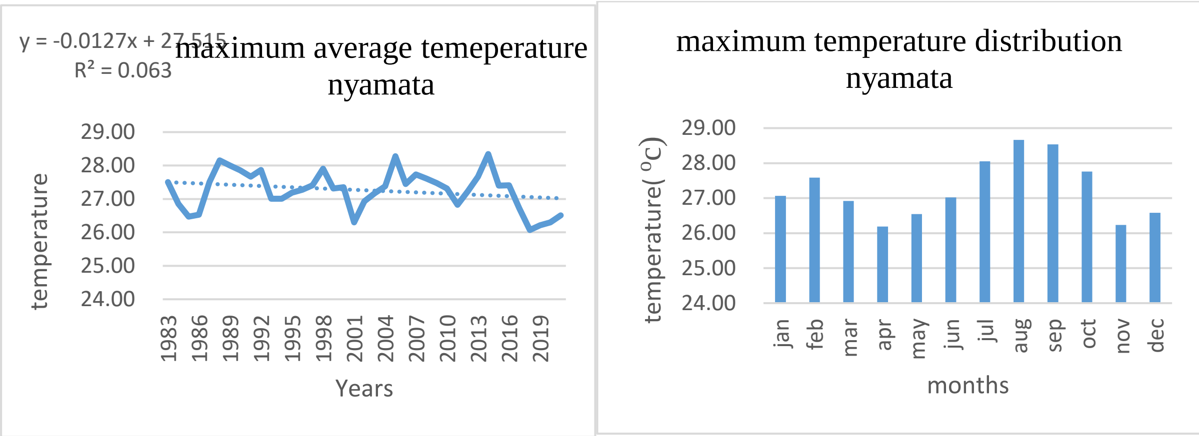
Figure 11average maximum temperature Karama station





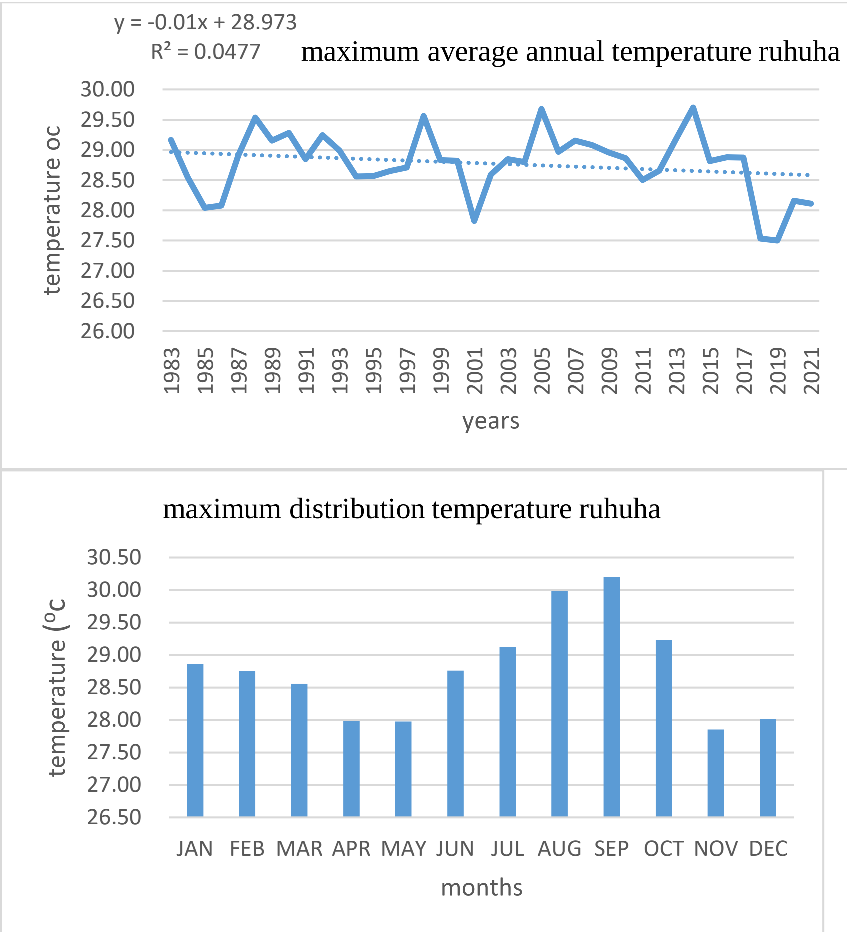
4.2.2.3 Nyamata Station

Figure 12 average maximum temperature Nyamata station



4.2.2.4 Ruhuha station

Figure 13 average maximum temperature Ruhuha station



Using a method called linear regression analysis, I delved into the data to uncover how temperatures have evolved for many years at four specific weather stations. The data I examined ranged from 1981 to 2021, encompassing a substantial 41-year timeframe. As I sifted through the data, a discernible pattern began to emerge, revealing intriguing insights into the changing climate. The pattern that emerged was quite consistent and noteworthy. Specifically, I observed that the months from January to March and from June to October consistently exhibited higher average temperatures when compared to the other months. This repeated occurrence of warmer temperatures during these periods underlines a consistent trend of warming that has persisted over time. Upon amalgamating and analyzing the various datasets, a compelling narrative materialized. Across all months, there was substantial growth in the average monthly temperature. This upward trajectory was particularly pronounced, except for April and November, where I noted a minor dip in the highest recorded temperature. This peculiar pattern leads me to a striking conclusion: the Bugesera district stands out as the epicenter of this climatic shift, experiencing the most significant rise in temperature across nearly all months. In essence, my analysis points to a noteworthy climate trend in the Bugesera district, where temperatures have been consistently climbing, save for a few exceptions. This understanding underscores the district's pivotal role in the larger context of climate change and its impact on local temperature variations.

Annually Rainfall and temperature data of Bugesera for the period of 1981-2021

Rwanda, like many other equatorial countries, has historically experienced high amounts of rainfall due to its geographic location. However, over time, the climate conditions in Rwanda, as well as in other nearby nations, have been changing, impacting both rainfall patterns and temperatures. The observed trends indicate that the annual rainfall has been decreasing, while the temperatures have been on the rise. These changes can have significant implications for the environment, agriculture, and people's livelihoods.

Between the years 1981and 2021, data has shown a decline in the annual rainfall in Rwanda. This decrease in precipitation leads to water scarcity, affecting agriculture, water resources, and overall ecosystem health. It could result in reduced crop yields, affecting food security and livelihoods, especially for farmers who heavily depend on rainfed agriculture. Conversely, the increase in temperature poses a different set of challenges. Rising temperatures lead to heatwaves and contribute to the intensification of weather events, such as droughts. Higher temperatures also impact human health, particularly vulnerable populations, and exacerbate existing health issues.

One specific region in Rwanda, Bugesera, has likely experienced its own unique set of climate changes. The situation in Bugesera serves as an example that highlights the urgency for global cooperation and action to address these climate challenges. It becomes essential for countries worldwide to come together and implement various adaptation measures to mitigate the adverse effects of climate change and continue living as close to normalcy as possible.

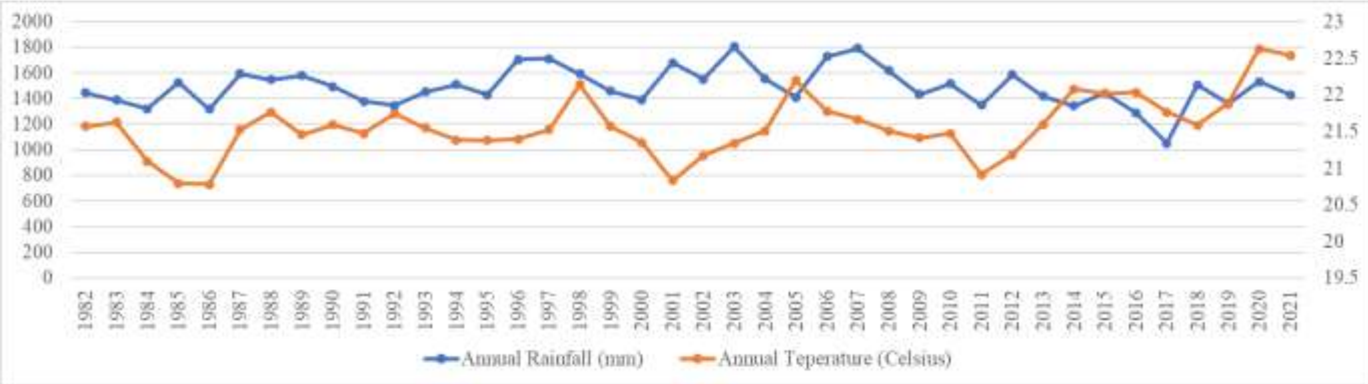
Table 5: Annual rainfall and Temperature

Years	1982	1983	1984	1985	1986	1987	1988	1989
Annual Rainfall (mm)	1446.25	1387.5	1321.5	1526.5	1318	1591.5	1547.25	1580.25
Annual Teperature (Celsius)	21.56707446	21.62416326	21.09254336	20.78855464	20.77587306	21.52382484	21.76403264	21.45612194
Years	1990	1991	1992	1993	1994	1995	1996	1997
Annual Rainfall (mm)	1491.75	1378.25	1346	1450.25	1510.5	1427.5	1705.75	1711.5
Annual Teperature (Celsius)	21.59059594	21.47483568	21.74129048	21.54572231	21.38244108	21.37637329	21.39587739	21.52139175
Years	1998	1999	2000	2001	2002	2003	2004	2005
Annual Rainfall (mm)	1593.75	1456.5	1391	1679.75	1549.5	1803.5	1553.25	1409
Annual Teperature (Celsius)	22.14082356	21.56707446	21.34800174	20.82628249	21.17212217	21.33858707	21.50763044	22.19826906
Years	2006	2007	2008	2009	2010	2011	2012	2013
Annual Rainfall (mm)	1726	1790.75	1617.25	1432.5	1514.75	1347.75	1585	1420
Annual Teperature (Celsius)	21.77704295	21.66473572	21.50860227	21.41343037	21.47300307	20.91338962	21.18418792	21.59960716
Years	2014	2015	2016	2017	2018	2019	2020	2021
Annual Rainfall (mm)	1341.75	1441.75	1287	1052.25	1506.5	1358	1532	1428
Annual Teperature (Celsius)	22.08070168	22.01533738	22.037104	21.76709229	21.58518601	21.88609415	22.62903836	22.54043499

The data in the table illustrates the distribution of average precipitation and temperature in Bugesera district from 1981 to 2021. Throughout this period, the annual precipitation fluctuated, reaching its peak (1879.5mm)), and hitting its lowest point (161mm), the annual precipitation was range between 756 and 1267mm

Regarding the temperature, the average was calculated by adding the minimum and maximum temperatures for each year and then dividing the sum by 2. The highest recorded temperatures were in 2021 (22.55°C) and 2020 (22.62°C), while the lowest was in 1986 (20.77°C) and 1985 (20.78°C). The average annual temperature over the 40 years was found to be 21.56°C.

Figure 14 average annual rainfall and temperature over Bugesera



These findings indicate that over time, although the changes may be slight, the temperature is increasing while rainfall is decreasing. Additionally, the rainfall in Bugesera is lower compared to other parts of the country, highlighting the drought challenges faced by the people in this region as they strive to boost their crop productivity.

Monthly Rainfall and Temperature data of Bugesera for the period of 1981-2021

The data presented in the table provides an image of the average monthly precipitation and temperature patterns in the Bugesera district over the past 40 years.

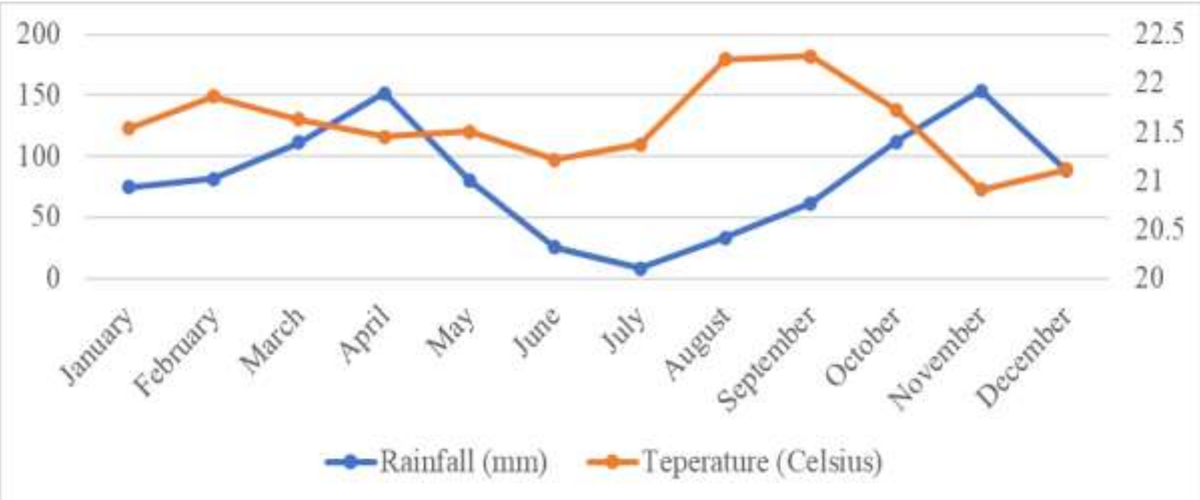
Table 6: Monthly rainfall and annual Temperature

months	**rainfall (mm)**	**Temperature (Celsius**
January	74.87	21.53
February	81.75	21.86
March	111.58	21.62
April	151.82	21.44
May	80.56	21.5
June	25.75	21.21
July	8.38	21.37
August	33.75	22.24
September	61.76	22.27
October	111.78	21.72
November	153.98	20.91

December	88.57	21.11

The table presents the analysis of average precipitation and temperature in Bugesera district from 1981 to 2021. Looking at the precipitation, we can observe that the monthly amounts varied significantly throughout the year. July and June had the lowest precipitation with 8.38mm and 25.75mm, respectively. On the other hand, April and November experienced the highest precipitation with 151.82mm and 153.98mm, respectively. On average, the monthly precipitation for the entire period was 82.04 mm. Regarding temperature, the study computed the average temperature by adding the minimum and maximum temperatures for each month and then dividing by 2. The analysis spanned 40 years, and it was found that November and December had the lowest average temperatures, ranging from 20.91°C to 21.11°C, respectively. In contrast, August and September recorded the highest average temperatures with 22.24°C and 22.27°C, respectively. The general annual average temperature for the entire period was 21.56°C.

Figure 15 distribution of rainfall and temperature in months over Bugesera



4.2.3 Solar radiation data of Bugesera

The incredible phenomenon of atomic fusion occurring on the sun's surface serves as the primary generator of solar radiation. This awe-inspiring process, where atoms merge and release energy, fuels the sun's brilliance. As we move outward to the chromosphere, the sun's outer layer, I encounter an intriguing contrast. Despite being significantly cooler than the sun's fiery core, the chromosphere still experiences a heating effect. This warmth is a direct result of some of the excess energy generated during the fusion process. The chromosphere, in turn, becomes a source of remarkable radiance. The radiation it emits is precisely what we recognize as solar radiation, an essential component of Earth's energy balance. Although the total irradiance reaching our planet's surface can surge to as high as 1000 watts per square meter (W/m^2), the portion of radiation accessible to us is often considerably less than this peak value. This variance arises from a medley of factors. The Earth's constant rotation causes varying exposure to the sun's rays, while dynamic weather conditions, notably cloud cover, further influence the amount of radiation we receive. Additionally, the composition of our atmosphere also plays a role in attenuating solar radiation. These combined factors culminate in a reduction of available radiation that reaches us. This nuanced interplay between the sun, Earth's rotation, atmospheric dynamics, and cloud formations is particularly relevant when considering the output of photovoltaic systems. Accurate estimation of solar radiation is crucial for optimizing the performance of these systems. Hence, data pertaining to solar radiation holds unparalleled significance, serving as a cornerstone in the precise calculation and projection of photovoltaic system efficiency[110].

The linear regression model can be used to estimate the solar radiation for the years 2016 through 2021 at Bugesera, as the same as done on the average difference between the highest and lowest air temperatures graphed above. This information was presented earlier in this section. The following chart illustrates the daily average solar radiation that have been received in Bugesera between the years 2016 and 2021.

In 2021 is the year that reported the highest amount of solar radiation as shown in figure below and the july month is the month that has the highest solar radiation amount

Figure 16 solar radiation distribution

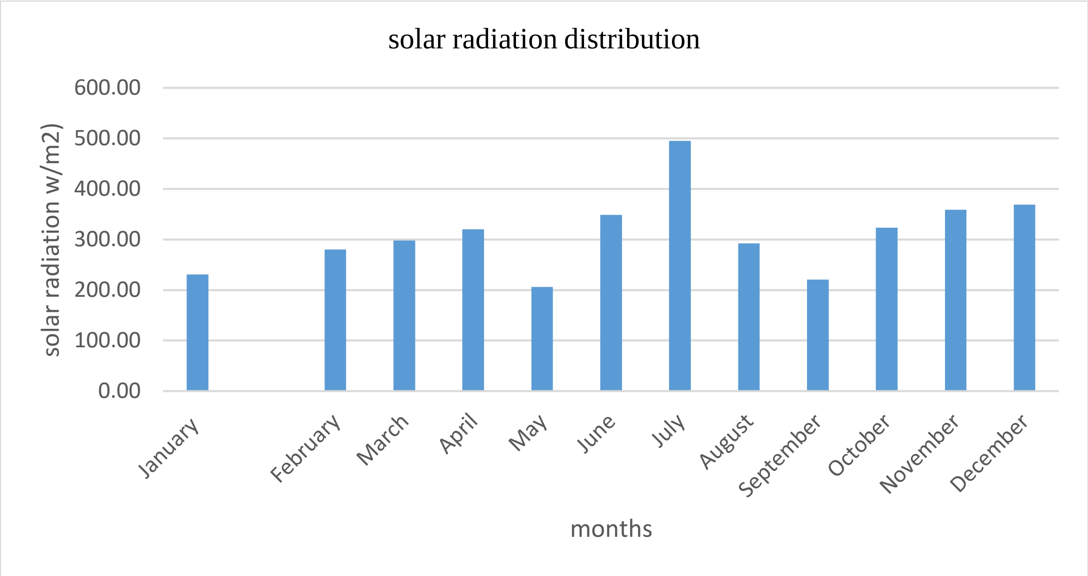


Figure 17 average annual solar radiation

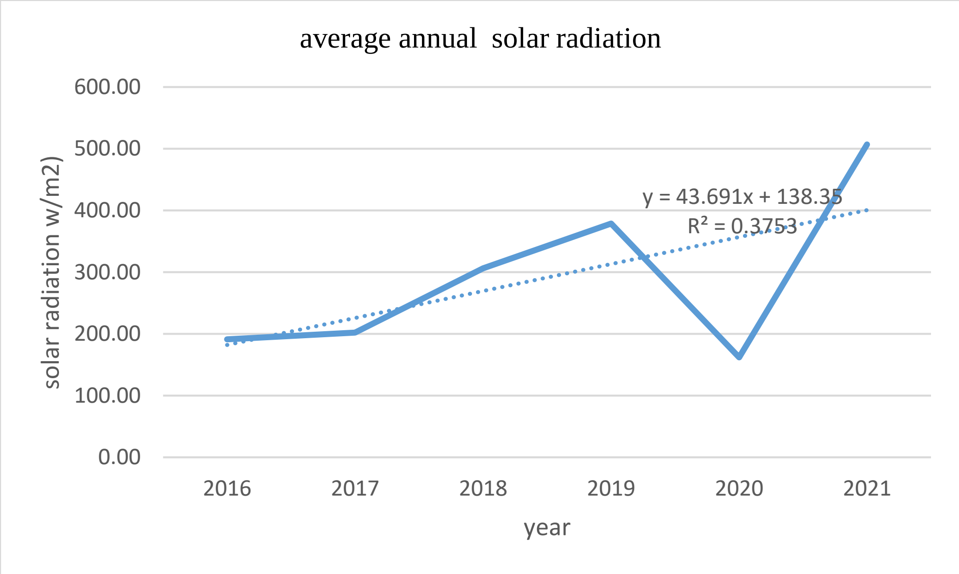
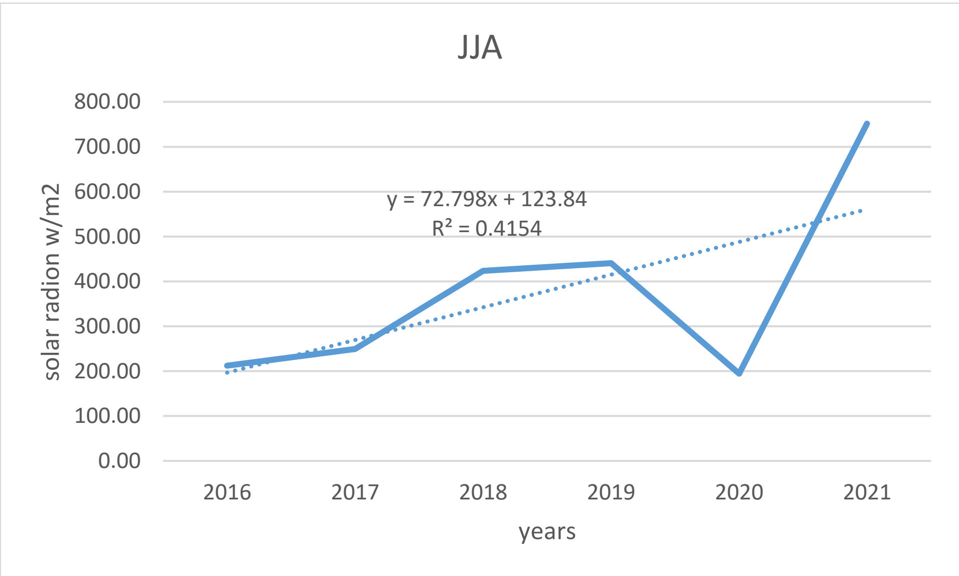


Figure 18 solar radiation in JJA season



In terms of the linear regression model and the analysis of variance, it has been found that the monthly mean maximum temperature has risen by a sizeable amount and that there is a significant positive linear correlation coefficient value between the air temperature and the solar radiation.

The mean montly solar radiation range from 230 to 495 w/m^2 ,during the summer is where we receive much radiation where the mean solar radiation during the JJA season rangefrom 212 to 751 w/m2 the average annual radition range from 506w/m2 to 751 w/m2 which shows a good potential for solar system .

The region experiences an average solar radiation of approximately 5.23 kWh/m2 per day, consistently maintained over the entire year. This measurement significantly surpasses the global mean of 3.85 kWh/m2 per day, thereby underlining the substantial untapped solar energy capacity inherent in the area. This empirical evidence substantiates the existence of fertile ground for the efficient harnessing of solar power.

CHAPTER 5: Conclusion and Recommendations

5.1 Conclusion

Climate change is a major challenge for farmers in Bugesera district. The district is experiencing increasing temperatures and declining rainfall, which is making it more difficult to grow crops. Farmers in that area are forcing to adapt these changes by switching to drought-tolerant crops, using more efficient irrigation methods, and diversifying their income sources.

Solar irrigation system can be the best solution to the small holders farmers to irrigate their crops since it can increase their production yet the study reveal that the Bugesera is the region that have good solar potential energy for solar irrigation since for better solar system solar radiation must be at least 0.5w/m2 but some advanced solar system can be even operate under that range ,Bugesera district receive the lowest rainfall which is also unreliable ,most the years between 1981 and 2021 reported average rainfall which is below 1000mm as the study revealed which make Bugesera vulnerable and considered like semi-arid region and make their soil dry which make agriculture practices very hard . compare to other regions and experience high temperatures yet in tropical regions high temperature are associated with high solar radiation , almost all farmers interviewed said that use hand irrigation which is not efficient for them because it is time consuming getting other alternative that make their work easy would be beneficial for them there are many reasons why Bugesera should focus on solar energy system since it is not only the source of energy but also the best way for climate change mitigation ,solar energy is the one of the clean energy which doesn't have emissions and can be the potential to modernize the agricultural sector in Bugesera by providing sustainable source of energy for crops irrigation

Therefore, from the findings I get from the research there are several key mechanisms and strategies that can be implemented to enhance smart irrigation practices and climate change adaptation in Bugesera district. These include:

1. Promoting the use of solar-powered irrigation systems.
2. Developing drought-tolerant crops.
3. Improving water conservation practices.
4. Increasing access to credit for farmers.
5. Providing training and education to farmers.

In addition to these mechanisms and strategies, there are several other things that can be done to enhance smart irrigation practices and climate change adaptation in Bugesera district. These include:

1. Supporting research and development of new irrigation technologies.
2. Strengthening extension services.
3. Building partnerships between farmers, government, and the private sector.

5.3 Recommendations

Based on the information presented, I would recommend the following 3 strategies for enhancing smart irrigation practices and climate change adaptation in Bugesera district:

Recommendations	**Assigned parties**
1. Promote the use of solar-powered irrigation systems. Solar-powered irrigation systems are a more sustainable and resilient alternative to traditional methods of	**Government:** The government can provide subsidies for solar-powered irrigation systems, and it can also create policies that make it easier for farmers to purchase and install these systems. **NGOs:** NGOs can provide training and education to farmers on the benefits of solar-powered irrigation

irrigation. They are also more affordable for farmers, as the cost of solar panels has come down in recent years.	systems. They can also help farmers to access financing for these systems. **Private sector companies:** Private sector companies can manufacture and distribute solar-powered irrigation systems to farmers. They can also provide financing for these systems.
2. Develop drought-tolerant crops. Drought-tolerant crops are crops that can withstand periods of drought without dying. Promoting the cultivation of drought-tolerant crops can help farmers to reduce their risk of crop failure during droughts.	**Government:** The government can provide funding for research on drought-tolerant crops. It can also create policies that encourage farmers to grow these crops. **Research institutions:** Research institutions can conduct research on drought-tolerant crops, and they can develop new varieties of these crops that are suitable for Bugesera district. **NGOs:** NGOs can provide training and education to farmers on the benefits of growing drought-tolerant crops. They can also help farmers to access seeds of these crops.
3. Improve water conservation practices. Farmers can improve water conservation practices by implementing water-saving irrigation methods, such as drip irrigation. They can also build water harvesting structures, such as dams and ponds, to collect rainwater for irrigation during the dry season.	**Farmers:** Farmers can implement water-saving irrigation methods, such as drip irrigation. They can also build water harvesting structures, such as dams and ponds, to collect rainwater for irrigation during the dry season. **Government:** The government can provide subsidies for water harvesting structures, and it can also create policies that encourage farmers to adopt water conservation practices. **NGOs:** NGOs can provide training and education to farmers on water conservation practices. They can also help farmers to access financing for water harvesting structures.

Here are some additional questions that could be explored in future research:

- ✓ What are the specific challenges and opportunities for implementing smart irrigation practices and climate change adaptation in Bugesera district?

- ✓ What are the most effective mechanisms and strategies for promoting smart irrigation practices and climate change adaptation in Bugesera district?
- ✓ What are the roles of different stakeholders, such as the government, NGOs, and farmers, in promoting smart irrigation practices and climate change adaptation in Bugesera district?
- ✓ How can the impact of smart irrigation practices and climate change adaptation be measured in Bugesera district?

Appendix

Questionnaire

1.farm information (farm size, soil type);

2. crop information (crop type)

3. adaptation to water scarcity (water source)

4.Did you have to change your cropping system during the drought period?

1 = Yes
2 = No

5. What type of cropping system did you employ during the drought period?

1 = Intercropping
2 = Wide spacing
3 = Shifting to quick maturing crops
4 = Cultivation of vast area in different directions
5 = Others

6. How did the low rainfall or no rain affect your crops?

1 = Little 2 = Very 3 = Very much 4 = Not at all

7. Did you have alternative source of water for your crops?

1 = Yes

2 = No

8. If yes, what are another sources of water?

1 = Hand irrigation

2= other irrigation systems

9**.** does tradition irrigation method or hand irrigation efficient for you?

1= efficient

2= not efficient

10. what are the disadvantages of using hand irrigation for crops

11. how long the distance from the farm to water sources.

12. what are coping strategies do you use to cope with low rainfall for your agriculture practices

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