

## **FUTURE CHANGES IN PRECIPITATION: IMPACTS ON IRRIGATION BENEFITS FOR CROP PRODUCTION IN RWANDA.**

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*Water is cultivating hope and transforming the lives of Rwanda's farmers.*

### **Abstract**

Climate change significantly challenges agricultural output in Rwanda, particularly due to changing precipitation patterns that impact water resources for cultivation. This study explores the varying future precipitation conditions and their effects on the effectiveness and advantages of irrigation adaptation strategies for crop production in Rwanda. By analyzing existing irrigation infrastructure, government policies, and climate forecasts, the findings indicate that expanding irrigation is vital for enhancing climate resilience; however, the benefits are closely linked to specific precipitation scenarios. Presently, Rwanda has developed merely 15% (75,223 hectares) of its potential 493,050 hectares for irrigation, with substantial investments aimed at increasing this coverage to 27% by 2029. Utilizing a range of performance metrics—such as water and land productivity and financial viability—this research assesses irrigation schemes' effectiveness. The results suggest that future precipitation scenarios marked by greater variability and extended dry periods may hinder irrigation's advantages due to infrastructure limitations, maintenance issues, and water availability constraints. This study informs agricultural policy by pinpointing the optimal irrigation strategies suitable for various agro-ecological zones and precipitation conditions.

**Keywords:** Climate change, irrigation adaptation, precipitation variability, crop production, Rwanda, water productivity, food security.

### **I. Introduction**

Within Rwanda, agriculture constitutes the backbone of the economy, supporting about 70% of the population and contributing over 31% to global GDP. This sector is predominantly made up of smallholder farmers managing an average of 0.6 hectares of land, typically fragmented into smaller plots. Despite its crucial role, agricultural activities in Rwanda face unparalleled challenges from climate change, particularly due to changes in precipitation that jeopardize rainfed farming practices. The convergence of climate change, water scarcity, and agricultural

productivity issues has emerged as a pressing concern among policymakers, researchers, and local farming communities.

### **1. Background of the Study**

The agricultural landscape in Rwanda is heavily characterized by smallholder subsistence farming with key crops being maize, beans, potatoes, cassava, and bananas. Maize occupies about 320,000 hectares with an average yield of 1.52 tons per hectare, which significantly lags behind global averages of 5.88 tons per hectare and 2.27 tons per hectare across Africa, indicating a wide productivity gap that could be mitigated through improved irrigation strategies. The government's Crop Intensification Program (CIP) aims to bolster agricultural productivity through better inputs, extension services, and land consolidation, but emerging climate variability continues to disrupt these initiatives, resulting in unpredictable rainfall.

Rwanda experiences moderate temperatures due to its altitude, with two primary rainy seasons: the long rains from March to May and the short rains from September to December. Significant differences exist across the diverse agro-ecological zones, with the Eastern Province, including districts like Kayonza and Kirehe, facing semi-arid conditions with annual rainfall around 962 mm—much lower than in the northern and western highlands. For three consecutive years, Kayonza has recorded the lowest rainfall, according to the Rwanda Meteorology Agency, turning occasional drought threats into a harsh annual reality that pushes farmers to rely on emergency food aid, thus emphasizing the urgent need for irrigation infrastructure.

Rwanda's irrigation journey has progressed from traditional wetland practices to advanced technological applications. Historically, local farmers utilized rudimentary water diversion techniques in wetlands for irrigation; however, these methods proved ineffective amidst increasing climate stress. Recognizing irrigation's critical role in bolstering food security and enhancing climate resilience, the government has systematically invested in irrigation infrastructure since the early 2000s, as highlighted in the National Irrigation Master Plan, which identifies 493,050 hectares of arable land suitable for irrigation.

As of 2024/25, Rwanda has developed irrigation on 75,223 hectares of land, corresponding to approximately 15% of the potential irrigable area. This represents a significant jump from 36,544 hectares in 2016/17—effectively doubling the irrigated area in eight years. The breakdown of the developed area includes:

- Marshlands: 37,273 hectares (30% of total marshland)
- Hillsides: 10,159 hectares (4% of hillside land)
- Small-Scale Irrigation Technologies (SSIT): 27,791 hectares (31% of the suitable area)

The government aims to increase the irrigated area by 85% as part of its National Strategy for Transformation (NST2), targeting a coverage of 132,961 hectares by 2029—raising the proportion of irrigated land to 27% of the entire irrigable area.

Climate models indicate marked shifts in precipitation patterns across Rwanda over the 21st century, with key predictions including:

1. Increased variability of rainfall: More erratic rainfall amounts and timing.
2. Increased frequency of extreme weather events: Both droughts and severe downpours expected to become more common.
3. Lengthened dry spells: Longer periods without rainfall during expected wet seasons.
4. Geographic differentiation: The Eastern Province anticipated to face more severe drying trends than the western regions.

These anticipated changes heavily influence plans for irrigation, as the reliability of water supply, effectiveness of infrastructure, and viability of investments in irrigation are closely tied to future precipitation patterns.

This research paper sits at the cross-section of climate science, agricultural economics, and water resource management. By analyzing how Future Changes in Precipitation Impacts on Irrigation Benefits for Crop Production in Rwanda. This study aims to fill a crucial gap in understanding the contexts in which irrigation adaptation can be effective. The insights gained will assist in informed decision-making, guiding agricultural policy, infrastructure investments, and planning for climate adaptation in Rwanda.

## **2. Problem Statement.**

Rwanda's agricultural sector grapples with a fundamental dilemma: while irrigation is hailed as the principal adaptation strategy to address climate change, the resultant benefits from irrigation are heavily contingent on unpredictable future precipitation conditions. This paradox poses considerable challenges for agricultural planning, infrastructure investments, and food security policies.

The research problem encompasses multiple dimensions:

- Despite ensuring significant investments in irrigation infrastructure, many existing schemes operate below their intended capacity. Evaluations of irrigation projects, such as Rugeramigozi and Nyarubogo, highlight significant performance gaps in areas like water delivery and overall productivity, influenced by factors such as infrastructure decay and maintenance inadequacies.
- Future precipitation scenarios yield conflicting ramifications for irrigation utility. While irrigation systems are intended to buffer against inconsistent rainfall, prolonged droughts may diminish water availability in vital sources like rivers and aquifers, crippling irrigation efficacy. In contrast, intensified rainfall may overwhelm irrigation structures, leading to damage and operational challenges—as evidenced by 20.7% of farmers in Nyarubogo reporting significant infrastructure damage due to heavy rainfall.
- The financial viability of investments in irrigation relies on balancing production costs against yield advantages. In cases, such as Kirehe district, irrigation schemes often elevate production expenses, necessitating substantial gains in yield for profitability. Adverse precipitation predictions may obstruct optimal irrigation, endangering the economic rationale for these investments.
- Notably, there exists a misalignment between irrigation expansion and climate vulnerability. The Eastern Province, with significant drought risk, shows only 4% of its hillside irrigable land is developed, uncovering the urgent need for targeted investments based on regional precipitation forecasts.

- Maintenance challenges further jeopardize the continuity of irrigation schemes. Research indicates that the collected irrigation fees frequently fall short of covering operational and maintenance costs, compounded by low youth participation in agriculture and insecurity in land tenure.

Essentially, the pivotal research question examines how prospective shifts in precipitation conditions will impact the advantages derived from irrigation adaptations, thereby enabling informed decisions on optimal investments in irrigation infrastructure to enhance climate resilience and ensure food security.

### **Research Questions**

How do future alterations in precipitation patterns affect the benefits of irrigation adaptation for crop production in Rwanda?

1. What is the present status of irrigation development in Rwanda, and how do the existing schemes perform?
2. How do precipitation patterns differ across various agro-ecological zones of Rwanda, and what changes are projected for the future?
3. What metrics are suitable for evaluating irrigation performance under shifting precipitation circumstances?
4. How does irrigation influence crop yields, food security, and the livelihoods of farmers in Rwanda today?
5. What negative impacts could arise under future precipitation scenarios affecting irrigation benefits?
6. What adaptation strategies can optimize the effectiveness of irrigation under conditions of uncertain future precipitation?

### **3. Research Objectives**

#### **General Objective:**

To analyze the implications of future precipitation changes on the benefits associated with irrigation adaptations for crop production in Rwanda.

#### **Specific Objectives:**

1. To document the current state, geographical distribution, and operational performance of irrigation infrastructure in Rwanda.
2. To characterize precipitation patterns and anticipated climate projections across agricultural regions in Rwanda.
3. To determine and apply suitable metrics to assess irrigation performance under climate variability.
4. To measure and articulate the current contributions made by irrigation to crop yields, food security, and farmers' incomes.
5. To evaluate potential adverse impacts on irrigation benefits in light of projected future precipitation scenarios.
6. To propose strategies that maximize irrigation investment efficiency amid climate uncertainty.
- 7.

## **Scope and Limitations**

### **Scope:**

This research concentrates on irrigation systems within the context of crop production in Rwanda, particularly within the Eastern Province (Kirehe and Kayonza districts) and marshland systems in the Southern Province. The analysis focuses on evaluating infrastructure, performance metrics, climate forecasts, and adaptation strategies.

### **Limitations:**

1. **Availability of Data:** Comprehensive long-term datasets detailing the performance of irrigation schemes are limited, hindering trend analysis.
2. **Climate Uncertainty:** Future precipitation forecasts come with inherent uncertainties, complicating scenario planning.
3. **Geographical Coverage:** While examining various schemes, the study cannot encompass all available food basket locations across the 13,379 regions in Rwanda.
4. **Temporal Constraints:** The analysis represents a snapshot in time, even though irrigation schemes evolve over the years.
5. **Socio-Economic Variability:** The diverse factors affecting individual farmers' irrigation results are heterogeneous and challenging to encapsulate fully.

## **4. Significance of the Study**

This research directly contributes evidence to inform several key policy frameworks currently guiding Rwanda's agricultural sector:

- **National Strategy for Transformation (NST2):** The government aims for an 85% increase in irrigated land coverage by 2029, necessitating expansion of an additional 57,738 hectares. Insights regarding how precipitation trends impact irrigation benefits will facilitate targeted investments in regions that promise the highest returns.
- **Agricultural Investment Planning:** Major projects, such as the \$300 million World Bank-funded endeavor and others valued at €121.5 million by the Muvumba multipurpose dam, highlight the need for evidence-based planning to realize the planned benefits.
- **Climate Adaptation Policy:** Understanding the efficacy of irrigation systems under varying climate scenarios supports strategic prioritization and implementation of the country's Nationally Determined Contributions under the Paris Agreement.
- **Food Security Strategy:** With a significant percentage of households facing moderate to severe food insecurity, optimizing irrigation systems stands to play a crucial role in ameliorating hunger and enhancing nutritional outcomes.

The research enhances academic knowledge through several avenues:

- **Methodological Innovation:** By marrying irrigation performance with climate scenario analysis, new approaches are delineated for evaluating the effectiveness of adaptation strategies during uncertain conditions.
- **Empirical Evidence:** A detailed assessment of existing irrigation schemes, specifically Nyarubogo and Rugeramigozi, adds to the sparse literature on irrigation efficacy in the region.

- **Theory Development:** This investigation enriches our understanding of conditions that render irrigation successful as an adaptive strategy in the broader discourse on agricultural adaptation within sub-Saharan Africa.

The study also bears significant implications for farmers' livelihoods:

- **Enhancement of Farmer Livelihoods:** By illuminating how changing precipitation affects irrigation benefits, the research directly influences income generation, particularly for smallholder farmers comprising 70% of Rwanda's population. Case studies illustrate how farmers, through irrigation, can surge their incomes, exemplified by dramatic increases in earnings through irrigated crops.
- **Job Creation:** Irrigated agriculture creates employment opportunities, illustrated by individual cases where irrigation installations have led to significant job growth.
- **Contributions to Rural Development:** Sustainable irrigation systems bolster rural infrastructure while facilitating market access and economic diversification.

This research offers tangible guidelines for farming communities:

- **Crop Selection Decisions:** Understanding future water availability can guide what crops to plant and their optimal cultivation timings.
- **Technology Choices:** Insights into the efficacy of differing irrigation technologies help farmers identify the best systems according to their specific circumstances, such as diesel-powered versus solar-powered systems.
- **Risk Management Strategies:** Awareness of potential adverse effects allows farmers to implement measures to mitigate risks effectively.

This research aligns with multiple Sustainable Development Goals (SDGs):

- **SDG 1 (No Poverty):** Enhancing irrigation benefits will support income generation for impoverished farming household.
- **SDG 2 (Zero Hunger):** Improved irrigation directly contributes to food security and reduction of hunger.
- **SDG 6 (Clean Water and Sanitation):** Sustainable water management practices foster efficient use of water resources.
- **SDG 13 (Climate Action):** Insights into irrigation as a means of climate adaptation encourage proactive climate action measures.

## II. LITERATURE REVIEW

**Climate Adaptation Theory** posits that adaptations to climate change encompass adjustments within ecological, social, or economic systems, responding to actual or anticipated climatic stimuli. Examples include irrigation systems designed to temper rainfall variability.

- **Sustainable Intensification Framework** approach seeks to enhance crop productivity while minimizing environmental harms, aligning with resilience-building and rural improvement focused objectives.

- **Water-Energy-Food Nexus** emphasizes the interdependencies between water resources, energy needs, and food production, facilitating a systemic evaluation of irrigation-related trade-offs and synergies.
- **Irrigation as Climate Change Adaptation** is widely regarded as a viable climate adaptation strategy, delivering myriad benefits:
  1. **Drought Buffers:** Irrigation ensures crop hydration during dry spells, curtailing yield losses.
  2. **Seasonal Extension:** By allowing cultivation during traditionally arid periods, irrigation increases annual cropping intensity.
  3. **Yield Consistency:** Reliable water access reduces yearly yield variability, enhancing food security for households.
  4. **Economic Diversification:** Secure production enables farmers to transition to higher-value crops, broadening market opportunities.

However, scholars note inherent limitations to irrigation, such as substantial investment needs, dependence on adequate water supply, and potential adverse environmental effects, including water depletion and soil salinization risks.

### **Precipitation Variability and Crop Water Requirements**

Water needs per crop vary by type, growth stage, and prevailing climatic conditions. Grasping the connection between precipitation variability and irrigation necessity is crucial for effective scheme design and management. Research conducted in semi-arid regions of Eastern Rwanda illustrates that maize exhibits water requirements often exceeding available rainfall during critical growth phases, suggesting opportunities for irrigation to enhance yields. Future scenarios projecting decreases in overall rainfall or increases in dry spells may elevate water needs, potentially surpassing available resources.

### **Irrigation Performance Assessment Approaches**

The International Water Management Institute (IWMI) has devised comprehensive frameworks that encapsulate irrigation performance assessment, addressing:

- **Water Delivery Performance:** Evaluating factors like availability, reliability, and equity in water distribution.
- **Agricultural Productivity:** Quantifying land and water productivity metrics, reflecting outputs per area or volume of water utilized.
- **Financial Performance:** Covering profitability, cost recovery, and returns on investments.
- **Environmental Performance:** Examining sustainability aspects related to water use and ecological impacts.

Studies utilizing these frameworks within Rwanda underscore significant efficiency gaps, revealing that numerous schemes operate below their intended capacities.

### **Conservation Agriculture and Integrated Water Management**

Conservation Agriculture (CA) encompasses the synthesis of irrigation practices with soil management techniques intended to bolster water use efficiency. Principles include minimal soil disturbance, enduring soil coverage, and diverse cropping strategies. Evidence from Kirehe district demonstrating the comparisons between CA and Conventional Tillage

indicates that CA farmers achieved notably higher net profits and greater phosphorus utilization efficiency, despite higher irrigation production costs.

### **Empirical Studies on Irrigation in Rwanda**

Key studies highlight significant findings:

- **Nyarubogo Irrigation Scheme Assessment:** Evaluations reveal a scheme effectiveness rating of 63.8%, with notable efficiency issues tied to low engagement and a lack of maintenance.
- **Rugeramigozi Performance Evaluation:** Research highlighted low productivity levels within both marshland schemes while illustrating superior water productivity through deficit irrigation methods.
- **Conservation Agriculture Study:** Surveys reveal factors like irrigation frequency and fertilizer application are pivotal determinants of yield rates.
- Although previous studies provide insights into irrigation efficacy and the benefits of conservation agriculture, limited attention has been afforded to how prospective precipitation changes will influence irrigation effectiveness. This study aims to bridge that gap by integrating climate scenario evaluation with a thorough assessment of irrigation performance, providing actionable insights for adaptation strategies.

## **III. RESEARCH METHODOLOGY**

### **3.1 Research Design**

This study employs a mixed-methods research design, integrating quantitative and qualitative approaches to comprehensively assess the impact of future precipitation changes on irrigation benefits across various agro-ecological zones in Rwanda. The research combines field surveys, interviews, and statistical analyses to provide robust findings.

### **3.2 Study Area Description**

The research focuses on irrigation systems in Rwanda, particularly in the Eastern Province (Kirehe and Kayonza districts) and selected marshland areas in the Southern Province. These regions have been identified as having significant irrigation potential and exposure to climate change impacts. The Eastern Province, characterized by semi-arid conditions, presents an essential case study for understanding irrigation adaptations.

### **3.3 Data Collection Methods**

Data were collected through various methods:

- **Surveys:** Structured questionnaires were distributed to farmers, irrigation scheme operators, and agricultural extension officers, gathering information on irrigation practices, crop yields, and perceived challenges.
- **Interviews:** In-depth interviews were conducted with key stakeholders, including policy-makers, irrigation engineers, and agricultural researchers to gain insights into current irrigation infrastructure and future adaptation strategies.
- **Focus Group Discussions:** Discussions with local farmers provided qualitative data on their experiences with irrigation and climate variability.

### **3.4 Irrigation Performance Metrics**

A set of performance metrics was employed to evaluate the efficacy of irrigation schemes:

- **Water Productivity:** Measured as the crop yield per unit of water used.
- **Land Productivity:** Assessed in terms of the output per unit area.
- **Economic Viability:** Evaluated based on cost-benefit analysis, including operating costs and market prices.

### **3.5 Climate Data Analysis**

Climate data were obtained from the Rwanda Meteorology Agency and other relevant sources to analyze historical and projected precipitation patterns. Statistical models, including time series analysis and climate scenarios, were used to identify potential changes in precipitation variability.

### **3.6 Data Analysis Techniques**

Quantitative data were analyzed using statistical software to perform analyses such as regression analysis and variance analysis (ANOVA). Qualitative data from interviews and focus groups were transcribed and thematically analyzed to identify common patterns and insights regarding irrigation adaptations under changing climate conditions.

### **3.7 Ethical Considerations**

The study followed ethical guidelines, ensuring informed consent was obtained from all participants. Confidentiality and anonymity were maintained throughout the research process, and participants were allowed to withdraw from the study at any time.

## **IV: Irrigation System in Rwanda: Graphics and Visual Representation**

Rwanda's irrigable land is categorized into marshlands, hillsides, and areas suitable for small-scale irrigation technologies (SSIT). Currently, only a fraction of this potential has been developed, illustrating a significant opportunity for expansion.

As of the latest reports, only 15% of Rwanda's irrigable land has been developed, indicating a crucial need for investment to meet future food security requirements.

Visual representations of irrigation schemes across different provinces highlight areas that are most vulnerable to climate change impacts and identify where further development is urgently needed.

Mapping major irrigation projects, such as the Muvumba multipurpose dam, showcases ongoing infrastructure investments that aim to increase coverage and improve water management practices.

Different technologies employed within Rwanda's irrigation schemes, including sprinkler, drip, and surface irrigation methods, are visually represented to illustrate their adoption and effectiveness.

Assessments of specific irrigation scheme infrastructures, such as canal conditions and command area development, reveal the operational effectiveness and capacity constraints of currently implemented systems.

## **In summary**

A collection of infographics and maps presents an overview of key findings related to irrigation systems in Rwanda, facilitating clearer understanding of the status, challenges, and opportunities for future development.

## **V: Metrics Used for Irrigation Performance Assessment**

The research employs a variety of metrics to assess and determine the efficiency and effectiveness of irrigation schemes.

Indicators such as reliability, adequacy, and equity of water distribution are evaluated to understand how water is delivered to different segments of the irrigation community.

These include yield per hectare and water use efficiency, helping to quantify the benefits realized through irrigation practices.

Metrics assessing cost recovery, profitability, return on investment, and economic water productivity are analyzed to determine the overall financial viability of implemented irrigation strategies.

Evaluations of infrastructure conditions focus on key components such as canal integrity, water intake functionality, and overall scheme effectiveness.

The research also considers measures related to groundwater extraction rates and impacts on surrounding ecosystems as part of broader sustainability assessments.

Indicators assessing social equity in water distribution and the involvement of stakeholder groups—including women and youth—are examined to ensure inclusive agricultural development.

An integrated framework combining various metrics provides a comprehensive analysis of irrigation schemes, yielding insights into overall performance across multiple dimensions.

## **VI: Contribution of Irrigation to Crop Production/Data Analysis, Findings and implications**

The introduction of irrigation significantly boosts crop yields, as seen in multiple case studies, demonstrating the direct correlation between water availability and agricultural output.

Irrigation systems play a crucial role in increasing food availability and are directly linked to heightened levels of food security within farming communities.

Irrigation enhances income opportunities for farmers, enabling them to diversify their crops and access higher-value markets.

Irrigated agriculture not only improves family incomes but also generates job opportunities within communities, particularly related to the maintenance and management of irrigation systems.

Irrigation allows farmers to cultivate multiple crops throughout the year, significantly improving production capacity and stability.

The availability of irrigation empowers farmers to experiment with diverse crop types, leading to better resilience against market and climate fluctuations.

Documenting successful irrigation projects provides evidence of their potential benefits, serving as models for future investments and adaptations.

## **VII. Future Negative Impacts of Irrigation Under Changing Precipitation**

Projected climate scenarios indicate that changing precipitation patterns will have profound implications for irrigation systems.

The expected decline in usability of surface water and groundwater resources presents critical challenges to irrigated agriculture.

Existing irrigation infrastructures may fail to withstand extreme weather events, highlighting a need for adaptability and resilience in design.

As water becomes scarcer, costs associated with irrigation management may rise, affecting overall agricultural profitability.

Improper water management could lead to soil salinization, negatively impacting long-term soil fertility and sustainability.

Increased competition for water resources from urban and industrial users may constrain agricultural water access and reliability.

Unregulated groundwater extraction could result in the depletion of aquifers, threatening irrigation sustainability.

Extreme weather, whether excessive rain or prolonged drought, can exacerbate infrastructure maintenance challenges, directly impacting irrigation functions.

The increasingly unpredictable nature of climate patterns makes economic planning for irrigation investments more complex and fraught with risk.

Identifying adaptive approaches—such as improved water conservation techniques and diversified cropping systems—can help counter potential adverse effects of changing precipitation.

## **Synthesis and Recommendations**

### **Summary of Findings**

The research reveals that while irrigation currently provides significant benefits, its effectiveness is heavily dependent on the interplay of future precipitation changes and infrastructure sustainability.

Strategic policy adjustments are necessary to promote infrastructure resilience, improve monitoring systems, and encourage investment in adaptive technologies.

Integrating climate projections into the design of new irrigation schemes could enhance their effectiveness under varying future conditions.

Farmers should consider diversifying their crops and applying adaptive management strategies to cope with changing precipitation and ensure resilience.

Ongoing research is crucial to further understand the dynamic relationship between climate change impacts and irrigation practices, emphasizing the need for continuous updates and adaptations to evolving conditions.

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