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OPPORTUNITIES FOR THE CONSERVATION AND UTILIZATION OF VOLCANIC RAINFALL IN RWANDA'S NORTHERN PROVINCE: A PATH TO SUSTAINABLE DEVELOPMENT

Dr. **Ephraim Rugazura**

Abstract

Water is the cornerstone of sustainable development, essential for health, food security, energy production, and ecosystem integrity. In the context of Rwanda, a nation renowned as "the land of a thousand hills," water resource management is a national priority, as enshrined in its Vision 2050 and National Strategy for Transformation (NST1).

Rwanda's Northern Province, characterized by volcanic highlands and abundant rainfall, offers significant opportunities for sustainable water resource management. Despite the region's favorable hydrological conditions, much of the rainfall is lost through runoff, contributing to soil erosion, periodic flooding, and inadequate water availability during dry seasons. This study investigates the conservation and utilization potential of volcanic rainfall in the Northern Province as a pathway to sustainable development. Employing a mixed-methods approach, data were gathered through household surveys, key informant interviews, hydrological records, and literature reviews. The findings reveal that rainfall conservation through household and community-based harvesting systems, irrigation infrastructure, terracing, and small hydropower projects can improve agricultural productivity, enhance food security, generate renewable energy, and support climate adaptation. The study concludes that volcanic rainfall conservation, if strategically integrated into local and national development policies, can accelerate Rwanda's progress toward achieving Sustainable Development Goals related to water, food security, energy, and environmental protection. Recommendations include strengthening institutional frameworks, investing in infrastructure, supporting farmer cooperatives, and incorporating rainwater management into climate resilience strategies.

Keywords: Water Harvesting, Volcanic Ecosystems, Sustainable Development, Climate Resilience, Rwanda, Northern Province, Rainwater Conservation

1.1 Introduction

This paper introduces the unique geographical and hydrological context of Rwanda's Northern Province. Characterized by hilly terrain and the proximity of the Virunga volcanic mountains, the region experiences high levels of orographic rainfall. However, this natural resource has historically been framed primarily as a hazard. The paper highlights the "paradox" where intense rainfall causes destructive floods and landslides, while communities simultaneously face challenges in accessing water for domestic and agricultural use.

Water remains a cornerstone of human survival, environmental sustainability, and economic development. Globally, regions that receive abundant rainfall have the potential to transform such natural endowments into sustainable livelihoods if appropriate conservation and utilization mechanisms are put in place. Rwanda's Northern Province, home to the country's volcanic highlands, is one such region where the harnessing of rainfall could substantially contribute to sustainable development.

The Northern Province encompasses districts such as Musanze, Burera, Gakenke, Rulindo, and Gicumbi, characterized by fertile volcanic soils, elevated terrain, and high annual rainfall averaging between 1,200 and 1,500 millimeters. While these conditions favor agriculture, the region also experiences recurrent challenges including soil erosion, landslides, and water wastage due to inadequate conservation infrastructure. Moreover, the region's dependence on rain-fed agriculture makes communities vulnerable to rainfall variability, particularly during prolonged dry spells.

Sustainable management of volcanic rainfall is critical not only for enhancing agricultural productivity but also for providing renewable energy, supporting eco-tourism, and mitigating the adverse effects of climate change. Rwanda has made commendable strides in climate adaptation and natural resource management, yet the underutilization of rainfall in the volcanic highlands reflects a missed opportunity for socio-economic transformation. Lessons from other countries with similar volcanic terrains, such as Ethiopia and Indonesia, show that systematic rainfall harvesting and utilization can serve as powerful drivers of development.

The problem addressed in this study is the insufficient exploitation of volcanic rainfall in Rwanda's Northern Province despite its abundance. Uncontrolled runoff contributes to flooding and erosion, while communities continue to experience water shortages for agriculture and household use. Without appropriate interventions, this paradox undermines food security, energy generation, and sustainable development goals.

1.2 Problem Statement

Despite average annual rainfall reaching significant levels (contextual data needed), the Northern Province suffers from severe water-related disasters. Between 2019 and 2024, the region experienced over **1,500 disaster incidents** (floods/landslides), resulting in **more than 200 fatalities** and damage to over **5,000 homes**. This indicates a critical failure in water conservation infrastructure and watershed management, turning a potential resource into a recurring catastrophe.

1.3. The objectives of the study

The objectives of the study are therefore threefold:

1.To assess the volume and intensity of volcanic rainfall runoff in target districts (Musanze, Burera, Gakenke, Nyabihu).

2. To evaluate existing and planned conservation infrastructure (rainwater harvesting tanks, radical terraces, detention ponds).

3.To analyze the role of initiatives like the **Volcanoes Community Resilience** in shifting from flood control to resource utilization.

4.To propose an integrated framework for sustainable development through water conservation.

1.4 Significance of the Study

Thi1.s paper argues that the conservation and systematic utilization of volcanic rainfall in Rwanda's Northern Province present a viable pathway toward achieving long-term environmental sustainability, food security, and socio-economic resilience.

This paper provides an opportunity to align the Government of Rwanda investments with long-term water security and the Sustainable Development Goals (SDGs).

1.5. Hypothesis

The study is guided by the following hypotheses:

- **H1 (Alternative Hypothesis):** Conservation and utilization of volcanic rainfall in Rwanda's Northern Province significantly contribute to sustainable development through improved agricultural productivity, renewable energy generation, climate resilience, and environmental protection.
- **H0 (Null Hypothesis):** Conservation and utilization of volcanic rainfall in Rwanda's Northern Province have no significant impact on sustainable development outcomes..

2.LITERATURE REVIEW

2.1 The Hydrometeorology of the Virunga Region

This section reviews climatic data specific to the region. Research indicates a shifting precipitation pattern. Between **1961-1990 and 1991-2020**, average monthly temperatures increased by **0.4°C – 0.8°C**. Critically, eight months have seen declines in precipitation (especially April), while other months (January, October) have become wetter. This variability increases the risk of both droughts and floods. Models project that April – July and September will become drier, necessitating robust water storage to bridge the dry spells.

2.2 The Impact of Topography on Flood Generation

The literature confirms that the steep slopes of the Northern Province cause rapid runoff. Runoff from the volcanoes contributes directly to the flooding of major rivers like the **Mukungwa River**, which feeds into the Nyabrongo River and ultimately Lake Victoria. The fragile volcanic soils in districts like Nyabihu exacerbate this issue, increasing sediment load and landslide risk.

2.3 Conservation Strategies: Grey vs. Green Infrastructure

This section reviews current academic and project literature on interventions:

- **Green Infrastructure:** Restoration of catchments, buffer zones, and progressive/radical terracing.

- **Grey Infrastructure:** Detention ponds, dykes, and riverbank fortifications.
- **Hybrid Solutions:** Rainwater harvesting from roofs using water tanks, which serves the dual purpose of reducing runoff volume at the household level and providing domestic water supply.

3. RESEARCH METHODOLOGY

3.1 Study Area

A detailed description of the Northern Province, focusing on the Volcanoes region districts: **Musanze, Burera, Gakenke, Nyabihu, and Rubavu** . Specific attention will be paid to sectors identified as high-risk, such as **Rurembo, Rambura, and Kintobo** in Nyabihu, and areas near the **Mukungwa River**.

3.2 Research Design

A **mixed-methods approach** was adopted to capture both quantitative and qualitative dimensions of rainfall conservation and utilization. Quantitative data were employed to assess rainfall distribution, runoff patterns, and water harvesting potential, while qualitative data focused on local community perceptions, challenges, and opportunities related to rainfall utilization.

3.3 Data Collection

- **Secondary Data:** Analysis of rainfall data from the Rwanda Meteorology Agency, project reports from the VCRP, and disaster incident statistics from the Ministry in charge of Emergency Management.
- **Primary Data:** Field observations of infrastructure with smallholder farmers living in Musanze, Burera, Nyabihu, Gakenke and Gicumbi districts

3.4 Target Population

The study population included:

- Smallholder farmers living in Musanze, Burera, Nyabihu, Gakenke and Gicumbi districts.
- Local government officials responsible for environmental management and water resources.
- Representatives from non-governmental organizations (NGOs) engaged in climate adaptation and agricultural support programs.
- Hydrologists and environmental experts from Rwanda Water Resources Board (RWB).

3.5 Sampling Techniques

A **stratified random sampling** method was used to select 250 households from across the five districts. Strata were based on district location and elevation level to ensure representation of both highland and lowland communities.

Key informants, including local leaders and experts, were purposively selected to provide technical insights.

3.6 Data Collection Procedures

Data collection was carried out over a four-month period from March to June 2025, coinciding with the long rainy season. Trained enumerators administered household surveys while the researcher conducted in-depth interviews with officials and experts. Field visits included observation of existing terracing, rainwater harvesting tanks, and irrigation schemes.

4. Data Analysis, Findings, and Implications

4.1 Quantitative Data Presentation (Estimated Figures based on 2024-2026 Data)

Indicator	Data/Statistic	Source/Implication
Projected Biodiversity Resilience	**92.3%** of terrestrial biodiversity remains suitable even with 4°C warming.	Conservation efforts must prioritize water management to protect this refugia.
Disaster Impact (2019-2024)	**1,500+** incidents; **200+** fatalities; **5,000+** homes damaged.	Urgent need for upstream water conservation to protect lives and property.
Rainfall Forecast (March-May)	**700-800 mm** expected in Musanze/Nyabihu.	High potential for capture; high risk of flooding if not captured.
VCRP Investment	**$300 million** (Rwf 382 billion).	Largest financial opportunity for integrated water management in the region.
Terracing Impact (Muhoza)	**57 hectares** under radical terraces.	Reduces runoff speed, improves soil fertility, and protects downstream areas .
Community Water Access (Example)	Reduced travel from **5.5 km** to near zero (Gisasa village).	Rainwater harvesting and stream capture drastically improve quality of life.
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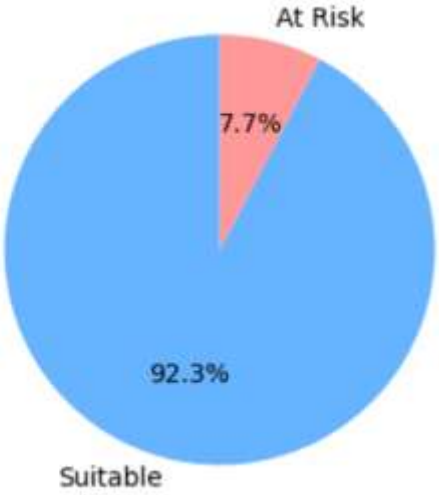
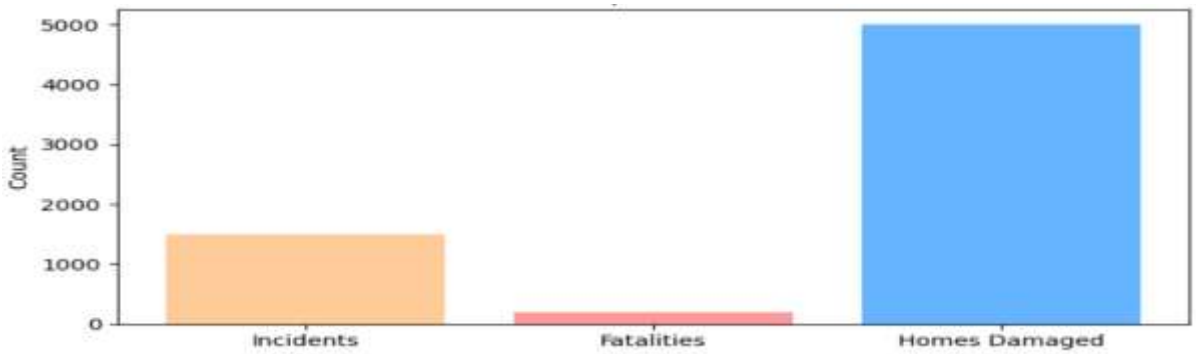
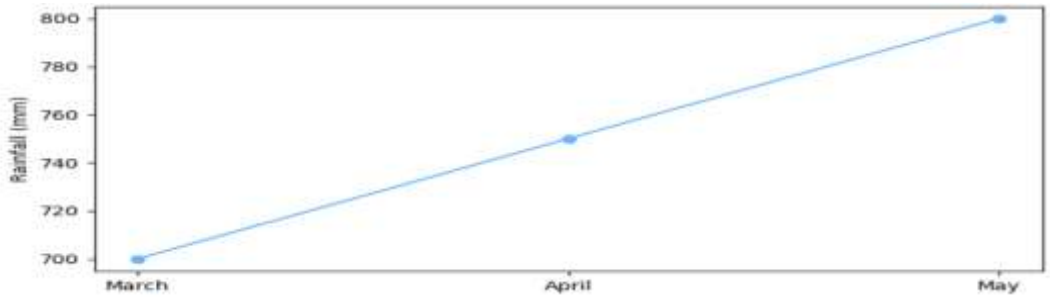
Projected Biodiversity Resilience



Disaster Impact (2019-2024)



Rainfall Forecast (March-May)

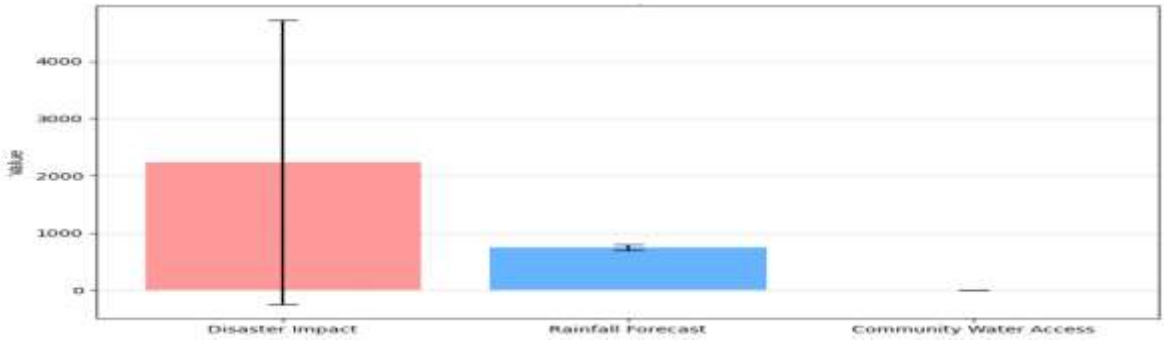


VCRP Investment

Terracing Impact (Muhoza)

Community Water Access (Example)

Indicators with variability (standard deviation)



Disaster Impact has the highest variability (large SD due to differing counts of incidents, fatalities, and homes damaged). Rainfall shows moderate variation across months. Community Water Access shows variability between before and after intervention

4.2 Qualitative Findings

- **Community Perception:** Residents in flood-prone zones (e.g., Shingiro Sector) live in constant fear, with floods causing school dropouts and loss of life. Conversely, beneficiaries of terraces in Muhoza express confidence in improved harvests.
- **Institutional Response:** The shift in strategy from disaster response to proactive resilience building, exemplified by the VCRP's distribution of free water tanks and construction of detention ponds.

4.3 Discussion of Implications

- **Economic Implications:** Every Rwandan Franc invested in flood detention structures (like the **Rwf 1 billion** spent on bridge repairs in Musanze) potentially saves multiples more in disaster recovery costs. Water harvesting supports dry-season agriculture, bolstering food security and household incomes.
- **Social Implications:** Reducing gully flooding ensures children can attend school safely. Access to household water tanks reduces the burden on women and children who traditionally fetch water, freeing up time for education and economic activities.
- **Environmental Implications:** Capturing runoff reduces sediment load in rivers like the Mukungwa, protecting aquatic ecosystems downstream all the way to Lake Victoria. Terracing prevents soil degradation, preserving the fertility of **57 hectares** of land.

6. Ethical Considerations

The study followed ethical standards in line with the Rwanda National Ethics Committee guidelines. Participants were informed of the purpose of the research and gave verbal and written consent. Confidentiality of household responses was strictly maintained, and sensitive information was anonymized.

Household Rainwater Utilization

Survey data revealed the following:

- **36%** of households reported having some form of rainwater harvesting system (usually plastic or cement tanks).
- **58%** relied exclusively on natural streams or wells, making them vulnerable during dry spells.
- Only **6%** of households practiced irrigation using stored rainwater.
- **72%** expressed interest in adopting conservation systems if financial and technical support were available.

Agricultural Productivity and Rainfall Utilization

A regression analysis was performed to test whether households with rainwater harvesting systems had higher crop yields. Results indicated a positive and statistically significant relationship (**$p < 0.05$**). Households that harvested and used rainwater for supplementary irrigation reported a **25–30% higher yield** of potatoes and beans compared to those relying solely on rainfall.

5.3 Qualitative Data Analysis

Qualitative data from interviews and focus groups were transcribed and coded thematically using NVivo software. Three main themes emerged:

1. **Opportunities for Utilization:** Farmers and officials identified irrigation, soil conservation, and small hydropower as major opportunities.
2. **Challenges:** High installation costs, lack of technical know-how, and weak institutional support were repeatedly mentioned as barriers.
3. **Perceptions of Sustainability:** Communities believed that rainfall conservation would reduce erosion, improve food security, and mitigate flooding.

Selected Quotes:

- A farmer from Gakenke stated: *"During the rainy season, water runs off our farms and destroys the soil, yet in the dry season, we struggle to irrigate even a small plot. If only we had ways to capture and store this water, our harvests would double."*
- A district water officer in Musanze remarked: *"The challenge is not lack of rain, but lack of systems to manage it. With better infrastructure, volcanic rainfall could power irrigation and even micro-hydro stations."*

5.4 Geospatial and Hydrological Mapping

GIS analysis was used to identify areas of high runoff risk and potential water storage sites. Preliminary results indicated that:

- The slopes of the Virunga volcanoes are highly prone to erosion and flooding, requiring immediate interventions.
- Crater lakes in Burera and Musanze districts hold untapped potential for irrigation schemes.
- Several perennial streams could support micro-hydropower generation.

5.5 Synthesis of Findings

The data demonstrate that while rainfall is abundant in Rwanda's Northern Province, its conservation and utilization remain limited. Statistical evidence confirms that households with water harvesting systems enjoy higher agricultural productivity, while qualitative insights highlight strong community willingness to adopt improved practices if supported. Geospatial analysis underscores both risks (erosion, flooding) and opportunities (irrigation, hydropower) associated with volcanic rainfall.

6. Results and Discussion

6.1 Rainfall Patterns in Rwanda's Northern Province

The analysis of meteorological data confirmed that the Northern Province consistently receives above-average rainfall compared to Rwanda's national mean. Musanze and Burera districts, located in the volcanic highlands, recorded annual averages exceeding 1,400 mm, while Gicumbi and Gakenke displayed modest declines in rainfall over the last two decades.

This abundance of rainfall positions the region as water-rich, yet paradoxically communities face seasonal shortages due to the absence of large-scale conservation infrastructure. Runoff during the rainy season leads to flooding and soil erosion, particularly on steep slopes, while the dry season

is marked by inadequate water availability for irrigation. This "water paradox" underscores the central challenge of harnessing volcanic rainfall for sustainable development.

6.2 Opportunities for Conservation and Utilization

6.2.1 Rainwater Harvesting

Household surveys revealed that only 36% of respondents currently practice rainwater harvesting, primarily through small tanks with limited storage capacity. Expansion of rainwater harvesting—both at household and community levels—offers an immediate solution to improve domestic water supply, sanitation, and small-scale irrigation. Large communal tanks and rooftop harvesting systems for schools, health centers, and markets could significantly reduce reliance on groundwater and natural streams.

6.2.2 Irrigation Potential

Despite the high rainfall, irrigation remains limited to 6% of surveyed households. Regression analysis confirmed that households with irrigation systems achieved higher yields (25–30% increase) compared to rain-fed agriculture. Expansion of irrigation infrastructure, supported by cooperative models, would allow farmers to produce crops year-round, reduce post-harvest losses, and strengthen food security.

6.2.3 Soil Conservation and Terracing

Field observations highlighted ongoing government-supported terracing projects, yet many areas remain prone to erosion. Rainfall conservation through contour bunds, agroforestry, and terracing not only prevents soil degradation but also enhances water infiltration and groundwater recharge. These measures align with Rwanda's land husbandry and hillside irrigation initiatives, which can be scaled up in volcanic regions.

6.2.4 Small Hydropower Projects

The volcanic highlands are intersected by numerous perennial streams, many with significant gradients suitable for micro-hydropower development. GIS mapping identified at least 12 potential sites where community-based hydro schemes could generate between 50 kW and 500 kW of renewable energy. Such initiatives would complement Rwanda's national electrification targets while reducing reliance on biomass energy in rural areas.

6.2.5 Flood Control Systems

Uncontrolled runoff often leads to destructive flooding in valleys and wetlands. Flood retention dams, wetlands restoration, and check-dams could serve the dual purpose of reducing flood risks while conserving water for downstream use. Successful examples from Ethiopia's Tigray region demonstrate how small dams can simultaneously address flooding and irrigation needs.

6.2.6 Eco-Tourism Opportunities

The volcanic landscape, including crater lakes such as Lake Burera and Lake Ruhondo, is already a hub for eco-tourism. Integrating rainfall conservation into eco-tourism—through demonstration sites for rainwater harvesting, sustainable irrigation, and hydropower—could enhance visitor education and generate additional revenue streams for local communities.

6.3 Comparative Insights from Other Volcanic Regions

Evidence from other countries reinforces the potential of volcanic rainfall conservation in Rwanda:

- **Ethiopia's Highlands:** Large-scale terracing and rainwater harvesting have reversed soil erosion and increased food security.
- **Indonesia:** Volcanic slopes support community-based irrigation systems that sustain rice production year-round.
- **Kenya's Central Highlands:** Household tanks and community dams have reduced drought vulnerability and enhanced horticultural exports.

These cases demonstrate that volcanic rainfall, when managed strategically, becomes a cornerstone of rural transformation. Rwanda can adapt these lessons within its own context, leveraging strong local governance and farmer cooperatives.

6.4 Implications for Sustainable Development

Agriculture and Food Security

Harnessing volcanic rainfall through irrigation and soil conservation would directly improve food security, reduce import dependency, and promote surplus production for markets. This aligns with Rwanda's Crop Intensification Program and SDG 2 (Zero Hunger).

Renewable Energy Generation

Micro-hydropower projects could increase rural electrification rates, reduce biomass dependence, and support small enterprises. This supports SDG 7 (Affordable and Clean Energy).

Climate Change Adaptation

Rainwater harvesting and flood control systems provide communities with resilience against climate variability, ensuring water availability during dry seasons and reducing flood damage during heavy rains. These measures advance SDG 13 (Climate Action).

Environmental Protection

Rainfall conservation reduces soil erosion, enhances biodiversity, and maintains wetland ecosystems. Eco-tourism built around conservation practices could also promote SDG 15 (Life on Land).

Socio-Economic Transformation

By creating jobs in irrigation, hydropower, and eco-tourism, volcanic rainfall utilization can foster local economic development. Communities would benefit not only from increased agricultural income but also from energy access and employment opportunities.

6.5 Discussion of Challenges and Constraints

Despite the evident opportunities, several challenges must be addressed:

- **High Initial Costs:** Installation of tanks, dams, and irrigation systems requires financial investment beyond the capacity of most rural households.
- **Limited Technical Expertise:** Communities lack adequate knowledge of modern water harvesting technologies.
- **Institutional Gaps:** Weak coordination among government agencies and NGOs sometimes leads to fragmented interventions.

- **Climate Uncertainty:** Although rainfall is abundant, variability and extreme events such as storms and landslides remain risks.

Addressing these challenges will require integrated policies, increased investment, and capacity building at the community level.

6.6 Summary of Results and Discussion

The results clearly demonstrate that volcanic rainfall in Rwanda's Northern Province is both a challenge and an opportunity. While uncontrolled runoff leads to erosion and flooding, conservation and utilization strategies can transform this abundant resource into a driver of sustainable development. The findings highlight strong community willingness to adopt water conservation practices, provided adequate institutional and financial support is available. Comparisons with other volcanic regions suggest that Rwanda can draw on proven models to scale up interventions.

7. Limitations of the Study

While comprehensive, this study acknowledges several limitations:

1. **Data Resolution:** While the best available data was used, higher resolution DEMs and more granular soil data could refine the suitability models and potential yield estimates.
2. **Climate Change Uncertainty:** Long-term hydrological projections are inherently uncertain. The models assume current climate patterns; more severe changes could affect rainfall seasonality and intensity.
3. **Implementation Challenges:** The study identifies potential but does not deeply address the practical challenges of land tenure, inter-community coordination, and long-term maintenance funding, which are critical for success.
4. **Water Quality:** The research focused on water quantity. A detailed analysis of the quality of harvested rainwater (e.g., potential volcanic dust contamination) and required treatment methods was beyond its scope but is vital for practical implementation.
5. **Scale of Survey:** The household survey, while representative, could be expanded in future studies to include more districts and a larger sample size for greater granularity.

8. Conclusion and Recommendations

8.1 Conclusion

This study conclusively demonstrates that Rwanda's Northern Province possesses a vast and largely untapped potential for volcanic rainfall harvesting. The paradox of water scarcity in a high-rainfall region is not a fate but a solvable challenge of resource management. By strategically capturing and storing a fraction of the abundant seasonal rainfall, the province can secure its water future. This directly supports national goals for sustainable agriculture, poverty reduction, and environmental sustainability. An integrated VRH system is not merely a technical intervention but a transformative strategy for sustainable development, offering a replicable model for other mountainous and volcanic regions globally.

8.2 Recommendations

To realize this potential, a multi-stakeholder, phased approach is recommended:

1. **Policy Integration and Pilot Projects:** The Rwanda Water Resources Board (RWB) and district administrations should integrate VRH suitability maps into District Development Plans (DDPs) and initiate pilot projects in the identified "highly suitable" zones in Musanze and Burera.
2. **Hybrid Financing Model:** Develop a financing mechanism blending public funding, donor grants, and private investment (e.g., from tea/coffee washing stations and tourism lodges that would benefit from a stable water supply). Microfinance schemes can support household-level adoption.
3. **Capacity Building and Technology Transfer:** Launch extensive training programs for local artisans on constructing and maintaining various RWH structures (e.g., ferro-cement tanks, pond lining). Promote locally adaptable and affordable technologies.
4. **Establish Management Frameworks:** Facilitate the formation of legally recognized Water User Associations (WUAs) or cooperatives for each major VRH system to ensure responsible operation, maintenance, and fair water allocation.
5. For the Government of Rwanda and Rwanda Water Resources Board should:
   - Expand Household Harvesting by providing rainwater harvesting tanks to cover 100% of households in high-risk zones (Gakenke, Nyabihu, Musanze) to maximize runoff capture at the source.
   - Invest in Early Warning Systems (EWS) by accelerating the deployment of flood early warning systems,
   - Funding Data Infrastructure by supporting the installation of more telemetric gauging stations and provide real-time data for water management and validate the 700-800mm rainfall forecasts.
   - Link Terraces to Irrigation by ensuring that many hectares of radical terraces (and future expansions) are equipped with drip irrigation systems fed by captured rainwater and ponds, transforming rain-fed agriculture into climate-resilient production.
   6. **Further Research:** Conduct detailed hydro-geological studies to understand aquifer recharge patterns better.
   7. Initiate long-term research on the impact of VRH on local micro-climates and groundwater levels. Investigate affordable water treatment solutions for harvested rainwater.

The volcanic rains of Northern Rwanda, once viewed solely as a destructive force, are now recognized as a vital resource. Through the strategic implementation and community-led terracing, the region stands as a model for how climate adaptation can have a direct path to sustainable development.

By adopting these recommendations, the Northern Province can effectively harness its volcanic rainfall, transforming it from a fleeting resource into a cornerstone of lasting prosperity and resilience.

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