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Nationwide optimization of Agro-meteorological weather stations placement using spatial multi-criteria evaluation



MSc Dissertation submitted in partial fulfilment of the requirements for the award of the Master of Science in Geo-Information for Environment Sustainable and Development

Submitted by

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DECLARATION

I declare that this MSc dissertation entitled “**Nationwide Optimization of Agro-Meteorological Weather Station Placement Using Spatial Multi-Criteria Evaluation**” submitted for an award of Master’s degree in Geo-Information for Environment and Sustainable Development at the University of Rwanda, College of Science and Technology, School of Architecture and the Built Environment. It is my own original work and has never been submitted in any higher learning institution.

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APPROVAL

This is to certify that the study entitled “**Nationwide Optimization of Agro-Meteorological Weather Station Placement Using Spatial Multi-Criteria Evaluation**” was conducted by Leonard MUNYESHYAKA in partial fulfilment of the requirements for the award of the Degree of Master of Science in Geo-Information for Environment and Sustainable Development, in the School of Architecture and Built Environment.

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DEDICATION

This dissertation is dedicated to my beloved parents

My beloved blood brother CPA Gabriel NTAKIYIMANA

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ACRONYMS AND ABBREVIATIONS

AHP	: Analytic Hierarchy Process
EWS	: Early Warning System
GIS	: Geographic information System
GPS	: Global positioning system
GR	: Government of Rwanda
ICPAC	: IGAD Climate Prediction and Applications Centre
IGAD	: Intergovernmental Authority on Development
LULC	: land use and land cover
NAP	: National Adaptation Plan
RM	: Rwanda Meteorological Service
SMCE	: Spatial Multi-Criteria Evaluation
SEWAA	: Strengthening Early Warning Systems for Anticipatory Action
SOFF	: Systematic Observations Financing Facility
USA	: United State of America
WMO	: World Meteorological Organization
AHP	: Analytic Hierarchy Process
GIS-MCA	: GIS-based multi-criteria analysis
KML	: Keyhole markup language

ABSTRACT

Accurate weather and climate data play an important role in enhancing agricultural productivity and resilience. However, the reliability of agrometeorological data in Rwanda is undermined by complex terrain, microclimatic variability, and a poorly distributed network of stations, many of which are suboptimal located in environmental unsuitable areas. Despite the importance of accurate data for agricultural planning and disaster management, no prior study has addressed the spatial optimization of agrometeorological weather station placement, revealing a critical gap in both research and infrastructure planning.

This study aimed to optimize the spatial distribution of agrometeorological weather stations in Rwanda using a Spatial Multi-Criteria Evaluation (SMCE) approach. Nine suitability criteria were defined based on World Meteorological Organization (WMO) standards and expert consultation, including slope, elevation, hillshade, proximity to water bodies and infrastructure, land use/land cover, and existing station distribution. The Analytic Hierarchy Process (AHP) was employed to assign weights to these criteria, which were integrated through a weighted overlay to produce a national suitability map for guiding the relocation and installation of weather stations.

Results indicated that 17.8% of Rwanda's land area (4,487.08 km²) is highly suitable for agrometeorological station placement, represented by 13,146 polygons. Slope and proximity to water bodies were identified as the most influential factors affecting suitability. The analysis further revealed that several existing stations are suboptimally located due to steep terrain, closeness to roads or rivers, and nearby obstructions that may compromise data accuracy. The generated suitability map facilitated a spatial gap analysis, identifying underserved area and supporting recommendations for the relocation of four existing stations and the establishment of three new stations. These interventions are expected to enhance network coverage, data representativeness, and the overall reliability of Rwanda's agrometeorological monitoring system.

This study provides a replicable methodology for optimizing station placement and offers a strategic framework to guide future investments in meteorological infrastructure, thereby supporting climate-smart agriculture and national food security initiatives.

Key words: Analytic Hierarchy Process, Geographic Information System, Spatial Multi-Criteria Evaluation, Agro-meteorological station.

1. INTRODUCTION

1.1. Background

Agrometeorological weather stations play important role in providing high-quality weather and climate data tailored to the needs of the agricultural sector. These data form the foundation for accurate crop forecasting, irrigation planning, pest and disease management, and early warning systems for extreme weather events such as droughts, floods, and storms (Agbehadji et al., 2023; Rivera et al., 2023). Reliable agrometeorological information supports climate-resilient farming practices, enhances food security, and contributes to sustainable rural development. Moreover, such data inform disaster risk reduction strategies and support national efforts to adapt to climate change impacts (World Meteorological Organization, 2017).

To ensure the reliability and representativeness of agrometeorological data, optimal placement of observation stations is essential. The world meteorological organization (WMO) provides siting guidelines recommending installation on flat terrain with minimal environmental interference. Based on these guidelines, stations should be located away from steep slopes, artificial surfaces, and obstructions such as trees, shrubs, and buildings. Additionally, areas characterized by frequent flooding, irrigation (sprinkling), wetlands, and proximity to water bodies such as lakes and rivers should be avoided, as these factors distort microclimatic readings (World Meteorological Organization, 2012). Furthermore, considerations such as land use, land cover, and long-term site stability are greatly important to ensuring the consistency and comparability of agrometeorological data over time.

Stations must also be easily reachable for maintenance, yet protected from disturbances related to human activity and land-use changes. Avoiding areas with rapidly growing vegetation or ongoing infrastructure development helps preserve uninterrupted data collection (World Meteorological Organization, 2014). In practice, siting has evolved over time. Early networks prioritized accessibility and placed stations in urban centres and easily accessible locations (Zhang et al., 2021). Over time, the need for spatial representative data prompted the expansion of networks into various environments such as rural, mountainous, and remote areas supported by improved siting methodologies (Neves et al., 2017; Pokhrel et al., 2024).

Despite global advancements, the distribution of weather stations remains highly uneven. For instance, The United States of America and European Union, operate 636 radar weather stations, while Africa, has only 37, resulting in major gaps across rural agricultural regions (Otto, 2023). This shortage of weather stations has resulted in limited access to localized meteorological data, undermining agricultural planning and climate resilience across the continent (Baqi Ahady et al., 2023; Dinku, 2019). The implications are particularly severe in areas dependent on rain-fed agriculture, where localized forecasts and timely weather warnings are highly important for productivity and risk reduction.

In Rwanda, agrometeorological data collection began in the early 20th century, with the first weather station established at Save, Gisagara District in 1906. The network grew after the creation of the Rwanda Meteorological Service (RMS) in 1963, but the 1994 Genocide against the Tutsi severely disrupted infrastructure, with over 80% of meteorological stations destroyed between 1990 and 1994 (Kigali, 2011). In the post-genocide period, the Rwanda Meteorological Agency (METEO Rwanda) prioritized rebuilding its network, by making spatial distribution based on administrative and service infrastructure nodes for ease of access and security. As of 2024, Rwanda operates 9 agrometeorological stations alongside other station types, including synoptic, climatological, and rainfall stations (Rwanda Meteorology Agency, 2024).

Despite this progress, Rwanda's agrometeorological station network remains uneven spatial distribution. Many agricultural zones, especially in highland and remote areas, lack adequate ground-based observation coverage. This limits the accuracy of localized forecasts and weakens early warning systems useful for farming activities. For example, two closest areas may experience contrasting weather conditions, such as rainfall in one area and dryness in another, which cannot be detected without a dense station network (Alahacoon et al., 2022). Addressing this spatial gap is necessary to improve agricultural decision-making and building climate resilience.

Spatial multi-criteria evaluation (SMCE) offers a scientific robust approach to optimizing agrometeorological station placement. As a GIS-based decision-support method, SMCE integrates multiple criteria to identify optimal locations for observation stations (Malczewski & Jankowski, 2020). Countries such as the United States of America, China, Germany, and Australia have applied SMCE to enhance the spatial coverage and representativeness of meteorological network,

especially in support of agriculture, disaster management, and environmental monitoring (NiuBoL, 2023).

In Rwanda, SMCE has been applied to environmental risk mapping and agricultural planning, including flood and landslide susceptibility, and land suitability assessments (Hirwa et al., 2023; Nahayo et al., 2019; Nzeyimana, 2018). However, no study has applied SMCE specific to optimize the placement of agrometeorological stations. Given the importance of agriculture to Rwanda's economy and the country's high vulnerability to climate variability, addressing this research gap is crucial. Systematic and spatial balanced agrometeorological station network will strengthen weather based decision-making, increase agricultural resilience, and support national strategies for food security and climate adaptation (Rojas Briceño et al., 2021).

1.2. Problem statement

Rwanda's complex terrain, microclimatic variability and anthropogenic heat emission pressing the challenges to the collection of reliable agrometeorological data, which are essential for agricultural planning, and climate resilient farming system (Dinku, 2019). These challenges are exacerbated by an inadequate network of agrometeorological weather stations, characterized by uneven spatial distribution, and suboptimal placement (Kigali, 2011). Limited weather station coverage, particularly in remote, topographic diverse and agriculturally sensitive areas, creates substantial data gaps that hinder effective monitoring of crops relevant weather variable such as rainfall, temperature, humidity, and solar radiation.

Rwanda's diverse topography results in localized climatic conditions that are not full captured by the existing agrometeorological network. As result, forecasts and data driven advisories often fail to reflect microclimatic realities, undermining decision making in key function areas such as crops selection, planting schedules, irrigation management and pest and disease control (Ministry of Environment Rwanda, 2019). This inadequacy contributes to reduced agriculture productivity, increased vulnerability to extreme weather events, and weakened resilience among smallholder farmers.

The increasing frequency and intensity of extreme weather events such as prolonged droughts and intense rainfall, pose a challenge to the commitment of Rwanda in promoting sustainable agriculture and food security (Sustainability et al., 2022). In response, the government of Rwanda

has prioritized the improvement of agrometeorological services, including accurate weather forecasting, early warning systems, and climate informed agricultural planning (Ministry of Environment Rwanda, 2019). These goals are closely linked to the availability of high quality location specific to agrometeorological stations.

Despite these strategic efforts, gaps persist in the spatial and temporal resolution of agrometeorological observation. These limitations are largely attributable to the sparse and poorly optimized placement of agrometeorological stations. Many existing stations are located in areas that are environmental or artificial unsuitable. Such as river, tall vegetation, swamps, heat sources like paved roads and buildings. All of those compromising data accuracy due to micro-environmental distortions (World Meteorological Organization, 2014). This underscores the need for the strategic and scientific guided placement of agrometeorological stations to improve data quality and support evidence- based decision making in the agriculture sector (MINEMA, 2023).

Although several studies in Rwanda have used weather stations data. For instance to examine climate trends and variability, such as rainfall and temperature changes (Twahirwa et al., 2023), precipitation distribution and its impacts on vegetation (Shema & Lanhai, 2024), and the analysis of extreme temperature indices (Sebaziga & Safari, 2023). None has specifically focused on optimizing the spatial placement of agrometeorological stations. For instance, (Kazora et al., 2021), examined spatiotemporal rainfall variability and its influencing factors but did not address the strategic placement of station generating such data.

To date, no study has assessed the optimal placement Rwanda's agrometeorological weather stations, despite its importance for enhancing agricultural resilience, improving early warning system, and support climate smart farming practices. Therefore, this research seeks to fill that gap by assessing the optimization of METEO Rwanda's agrometeorological weather station placement using a spatial multi-criteria evaluation approach, with Rwanda as the case study.

1.3. Research objectives and questions

This study aims to achieve one general objective, which is supported by three specific objectives. Each specific objective addresses a corresponding research question that has been formulated in alignment with these objectives.

1.3.1. General Objective

To evaluate and propose an optimized placement for agro-meteorological weather stations, using the case study of Rwanda.

1.3.2. Specific Objectives

1. To identify the established criteria in evaluating the suitability of agro-meteorological weather station locations in Rwanda.
2. To assess the alignment of existing agro-meteorological weather stations with optimum placement criteria.
3. To identify suitable location for new agro-meteorological weather stations and recommend relocations where necessary.

1.3.3. Research questions

How can established criteria be applied to evaluate the suitability of agro-meteorological weather station locations in Rwanda?

To what extent do the existing agro-meteorological weather stations comply with established optimal placement criteria?

Where are the most suitable locations for new agro-meteorological weather stations and which existing stations require relocation?

1.4. Motivation and significance of the study

The significance of this research lies in its potential to strengthen Rwanda's agricultural resilience and food security. Improved agrometeorological data availability will enable farmers to make better decisions regarding planting, irrigation, pest management, and harvesting. Additionally, accurate localized weather information supports early warning systems for droughts, floods, and other extreme events, contributing to disaster preparedness and risk reduction.

The findings will also inform policy development and investment in agricultural infrastructure, benefiting sectors such as agribusiness, environmental conservation, and rural development. Ultimately, this study contributes to building a robust agrometeorological network that underpins

evidence-based planning and enhances Rwanda’s capacity to adapt to climate change, ensure food security, and promote sustainable development.

1.5. Research design

The diagram below present the research design that was followed to complete the study on the optimization of METEO Rwanda weather station locations. This design illustrate all the chapters and their respective sub-sections that were covered in the study.

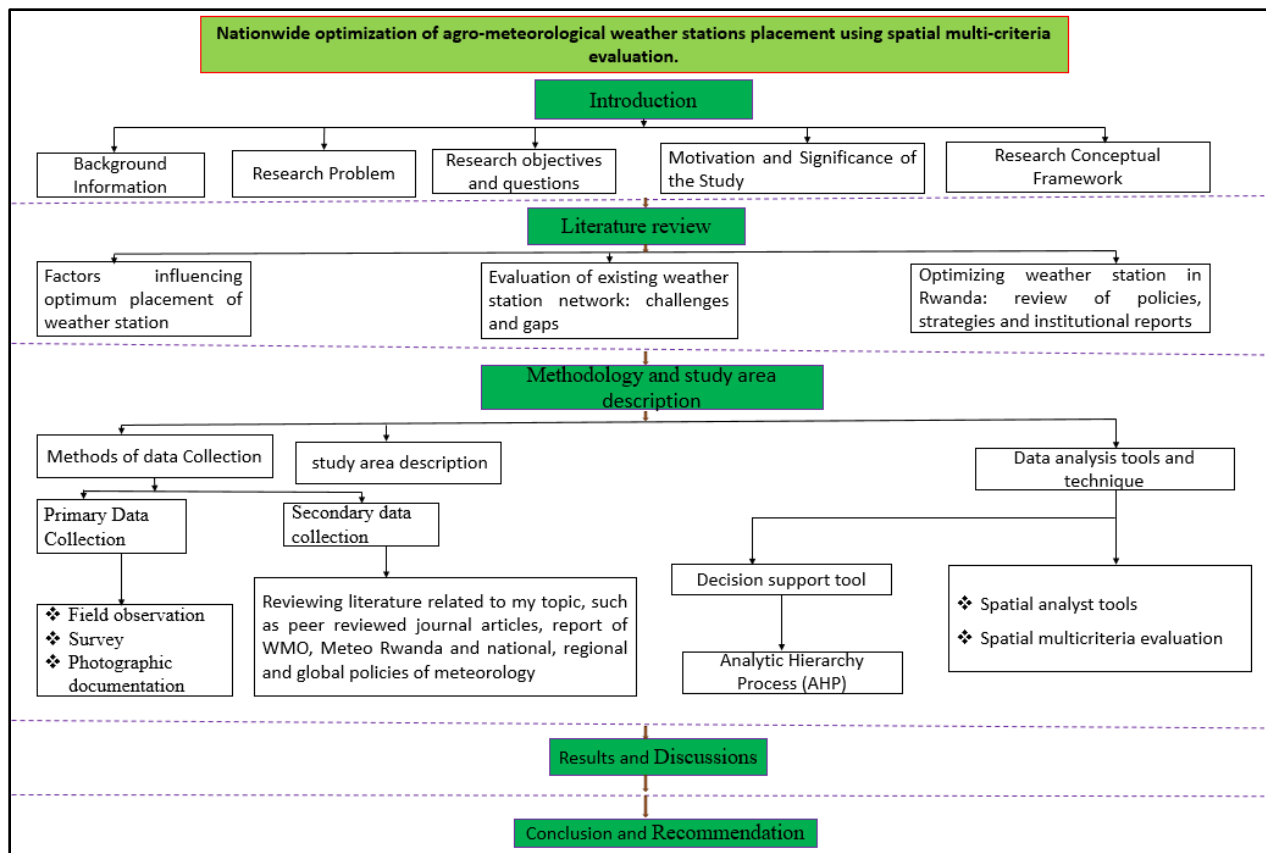


Figure 1: Research design

1.6. Theoretical/conceptual/analytical frameworks

1.6.1. Theoretical Framework

The theoretical framework for optimizing weather station placement using Spatial Multi-Criteria Evaluation (SMCE) is grounded in several interrelated theories that support spatial decision-making, environmental monitoring, and meteorological network optimization.

1.6.2. Multi-Criteria Decision Analysis (MCDA) within Decision Theory

Multi-Criteria Decision Analysis (MCDA), a subset of decision theory, is a robust methodology for structuring complex decision-making processes by evaluating multiple conflicting factors (Montello, 2018). It facilitates the comparison of alternatives based on defined criteria, ensuring that the most relevant environmental, operational, and spatial aspects are considered (Adem Esmail & Geneletti, 2018). In the optimization of weather station placement, MCDA plays important role by integrating various factors of weather station optimization such as Slopes, hillshade, waterbodies, roads, heat sources, obstructions such as tall vegetation and buildings and land use and land cover to enhance site selection. By assessing these criteria, MCDA improves the effectiveness of decision-making process, ultimately contributing to a more reliable and efficient meteorological monitoring network.

1.6.3. Conceptual and Analytical Framework

The conceptual framework illustrates the relationships between key variables influencing weather station placement and identifies how various criteria interact in the decision-making process while analytical framework outlines the methodological approach used to apply Spatial Multi-Criteria Evaluation (SMCE) for optimizing weather station placement. This framework integrates spatial data acquisition, processing, criteria selection, suitability modelling, and validation.

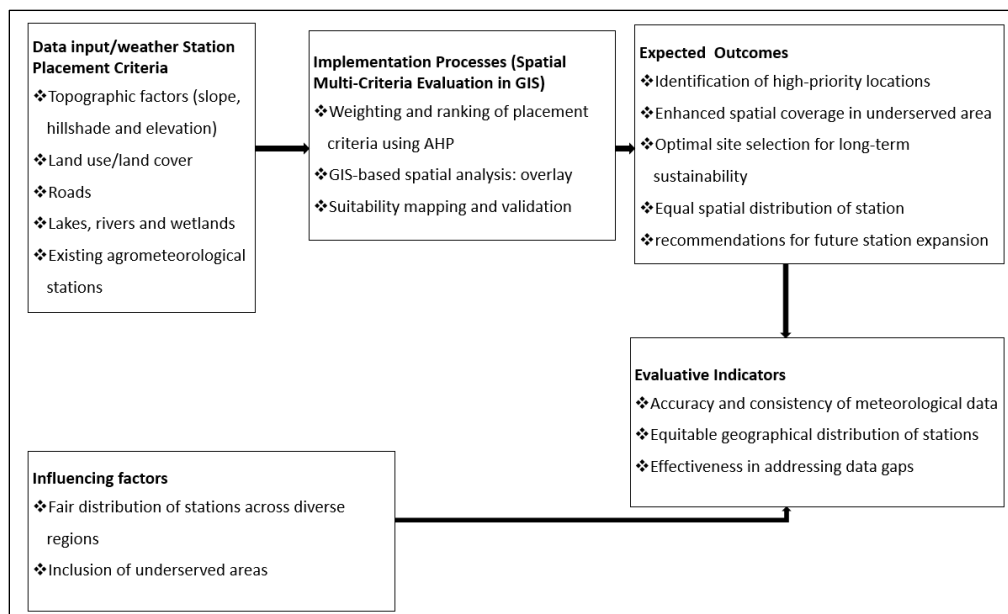


Figure 2: Conceptual and analytical framework

2. LITERATURE REVIEW

This chapter discusses the key factors influencing the optimum placement of agrometeorological weather stations, examines the challenges associated with these stations distribution and its functionality, and reviews Rwandan policies, strategies, and institutional measures undertaken to address these issues.

2.1. Factors for optimum placement of agrometeorological weather station

2.1.1. Topographic conditions

Terrain slope

Steep slopes alter wind patterns, solar radiation, and water runoff, leading to localized climate variations that do not represent broader regional conditions (Barry & Blanks, 2016). For instance, south-facing slopes receive more solar radiation, resulting in higher soil temperatures and lower moisture levels compared to north-facing slopes (Burnett et al., 2008). These variations lead to biases in measurements of temperature, precipitation, and evapotranspiration. Uneven terrain also generates air turbulence, affecting wind speed and temperature readings.

Studies indicate that topographic shading causes variations in meteorological fields within valleys, affecting temperature inversion and local wind patterns (Katurji et al., 2013; Song & Shao, 2023). In contrast, flat or gently sloping areas minimize these localized effects, promoting consistency in data collection across broader spatial scales. Therefore, it is essential to analyze the most suitable slope for weather station placement, one that minimizes the risk of erosion, flooding, and other environmental hazards that may damage weather instruments. In addition, the selected slope should be representative of the surrounding area to ensure the collection of accurate and reliable meteorological data.

Terrain hillshade

Terrain hillshade is a key factor in optimizing the placement of agrometeorological weather stations, as it influences microclimatic conditions that affect the accuracy and spatial representativeness of recorded meteorological data (Elnaker & Zaleski, 2022). It models the variation in solar illumination across the landscape by incorporating terrain characteristics such as slope and aspect (Bennie et al., 2008). These topographic elements regulate localized temperature

and solar radiation patterns, which are important in understanding surface energy balance (Elnaker & Zaleski, 2022).

Hillshade brightness varies between 0 and 255, with 0 fully shaded and 255 fully exposed to sunlight. Therefore, areas with different brightness values experience varying levels of surface temperature and evapotranspiration due to differential solar exposure (Olson & Rupper, 2019). As a result, weather stations located in areas of persistent shading record skewed data that fails to represent the general climatic conditions of the surrounding region. Therefore, it is important to notify these issues while optimizing agrometeorological weather station placement in order to record accurate data.

Terrain elevation

Elevation is an important factor in optimizing agrometeorological weather station placement due to its influence on temperature, precipitation, and wind patterns (M, 2024). The lapse rate principle dictates that temperature decreases with altitude, necessitating the strategic positioning of agrometeorological weather stations at different elevation to capture climate variability. In addition, orographic effects influence precipitation distribution, as higher elevations often experience increased rainfall due to moisture-laden air ascending and cooling (Ntwali et al., 2016). Moreover, elevation influences wind speed and direction by shaping airflow patterns.

2.1.2. Physical accessibility (Distance to the roads)

Accessibility plays an important role in optimizing the placement of weather stations. It facilitates routine maintenance activities such as timely calibration, sensor inspection, and reliable data retrieval, all of which are useful for ensuring accurate meteorological observations (Oke, 2018). Moreover, easily reachable sites promote collaboration with academic and governmental institutions, supporting research and training (Assessment, 2016). However, while optimizing for accessibility, it is important to adhere to the World Meteorological Organization siting guidelines and standards. These standards emphasize the avoidance of environmental obstructions and artificial influences that can compromise data quality (World Meteorological Organization, 2014).

2.1.3. Land use and land cover

Land use and land cover (LULC) are important factors in assessing and identifying optimum locations for agrometeorological weather stations because they influence the accuracy and reliability of collected meteorological data. Different LULC types such as forests, urban areas, agricultural lands, and wetlands affect local climate conditions due to their surface properties like albedo, evapotranspiration, heat storage, and surface roughness (Vargo et al., 2013). Therefore, it is essential to place agrometeorological weather stations in areas that best represent the dominant LULC of the region to obtain accurate and representative data (López-Espinoza et al., 2020).

Placing stations in areas with diverse or rapidly changing land cover, like cities, reduce data quality. For example, urban stations record higher temperatures due to the urban heat island effect, which do not reflect nearby rural conditions (Kabisch et al., 2023). Therefore, WMO advises placing stations in stable natural or rural environments to avoid disturbances in long-term records (*Guide to Meteorological Instruments and Methods of Observation.*, 1983). Change in land use and land cover such as urbanization or deforestation alter weather patterns near stations (Mahmood et al., 2010).

2.1.4. Distance to obstructions

The proximity of agrometeorological weather stations to obstructions such as buildings, trees, and other artificial structures compromises the accuracy of meteorological observations and alters local wind patterns, creating turbulence and wind shadows that distort wind speed and direction measurements (Deshmukh et al., 2022). Furthermore, the shading effect from nearby vegetation or buildings influences solar radiation and air temperature recordings, leading to biased and non-representative data (Shi et al., 2022).

Thermometers placed too close to heat-retaining surfaces such as walls, buildings, or pavements record biased temperatures (Ghenai et al., 2023). The World Meteorological Organization (WMO) recommends that weather stations must be sited in open areas, 100m away from heat sources and water bodies and at a distance away from the nearest obstruction, to minimize interferences (World Meteorological Organization, 2014).

2.1.5. Proximities to waterbodies

Water bodies are one of the factor for optimizing agrometeorological weather station placement due to their influence on local and regional climate conditions, an expanses of water such as lakes, rivers, and wetlands modify microclimates through their thermal inertia, resulting in moderated temperature fluctuations and increased humidity levels in surrounding areas (Jandaghian & Colombo, 2024). This microclimatic effect meteorological monitoring, as stations located near water bodies capture unique atmospheric conditions that do not likely appear in inland areas.

These weather conditions include high humidity levels, increased fog formation, localized convection, enhanced precipitation patterns due to higher evaporation rates, which are important parameters in hydro meteorological modelling, high cloud formation, higher temperatures during the night, and cooler temperatures during the day due to the influence of land and sea breezes (Gross, 2017; Xu et al., 2022). Therefore, consideration of water bodies in agrometeorological weather station placement ensures greater spatial representativeness of climatic data, especially in regions with complex hydro-climatic interactions.

2.1.6. Proximities to existing weather station

Proximity to existing agrometeorological weather stations is an important factor in the optimum placement of new stations due to it reduction in redundancy and ensures efficient spatial coverage of meteorological data (Campbell, 2025). Placing new stations too close to existing ones result in overlapping data, which limits the expansion of the observation network and wastes resources (*Guide to Meteorological Instruments and Methods of Observation.*, 1983).

In contrast, identifying areas that are distance from current stations help to address the issues of data gaps, particularly in regions with complex topography and diverse climates where localized weather patterns are not well captured (Kong, 2022). Optimum placement of agrometeorological stations improves data representativeness, supports accurate weather forecasting and climate modelling (NiuBoL, 2023). Therefore, considering the proximity to existing stations supports a balanced and cost-effective weather observation system.

2.1.7. Flood zone

Agrometeorological station should not be located within or nearby a flood-prone zone due to the risk of data loss, equipment damage, and compromised measurement accuracy (World Meteorological Organization, 2012). Floodwaters can submerge sensitive instruments such as, soil temperature sensors, grass minimum temperature and bac evaporation, leading to malfunction or complete failure of data collection systems. Moreover, flooded areas do not accurately represent the agro-climatic conditions of surrounding farmland, leading to biased or unrepresentative data that can misinform decision-making processes (World Meteorological Organization, 2012). Therefore, to ensure the long-term reliability, accessibility, and scientific integrity of agrometeorological observations, weather station must be placed in suitable area, which is not vulnerable to flooding.

2.2. Weather stations placement challenges

Despite efforts to expand meteorological monitoring networks, the strategic placement of weather stations remain challenged by uneven spatial distribution, limited number of stations, outdated and lack of maintenance of weather instruments and suboptimum placement across varied region.

2.2.1. Uneven spatial distribution

Uneven spatial distribution of weather station creates spatial data gaps that undermine localized weather prediction, climate modelling, and disaster preparedness (Dinku, 2019). For instance, the World Meteorological Organization (WMO) has identified that many developing regions, particularly in Africa and South America, suffer from sparse weather station networks. These gaps lead to challenges in monitoring extreme weather events, such as droughts, storms, and floods, which disproportionately affect rural communities (World Meteorological Organization, 2021).

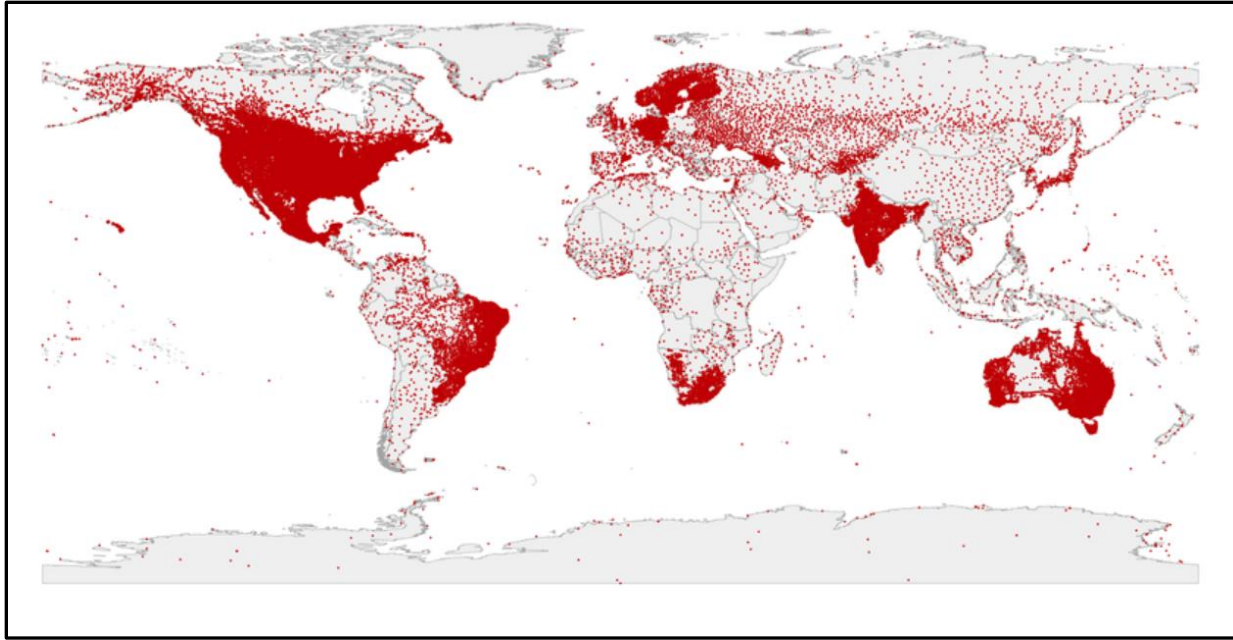


Figure 3: Uneven global distribution of Historical Climatology weather stations in 2020

Source: Ortiz-Bobea (2021)

The figure 3 illustrates the global spatial distribution of weather stations within the Historical Climatology Network (HCN) as of 2020, revealing a pronounced imbalance in coverage across different regions. Densely clustered stations are evident in North America, Europe, Australia, parts of South America, and India, reflecting longstanding investments in climatological monitoring infrastructure. In contrast, vast areas particularly in Africa, as well as portions of Asia and South America remain underrepresented. This uneven distribution presents considerable challenges for accurate climate monitoring, weather forecasting, and data-driven decision-making, especially in developing regions. Addressing these spatial data gaps by expanding observation networks in underserved areas is essential for improving global climate models and promoting more equitable access to meteorological and climate-related services.

A striking example of this issue occurred in May 2023 when severe flooding around Lake Kivu, which borders Rwanda and the Democratic Republic of the Congo (DRC) led to significant casualties and displacement. The lack of weather stations in the DRC hindered the accurate assessment of rainfall patterns, complicating timely disaster response and mitigation efforts (Otto, 2023).

2.2.2. Limited number of weather station

Africa's weather monitoring infrastructure is inadequate compared to other regions; this inadequacy affects its capacity to effectively monitor and respond to extreme weather events. The continent, home to approximately 1.2 billion people, operates only 37 weather radar stations, while the United States and the European Union, with a combined population of 1.1 billion, and operate 636 such stations. This disparity highlights a shortfall in Africa's meteorological capabilities (Otto, 2023). The World Meteorological Organization (WMO) recommends a minimum density of weather stations to ensure adequate data collection for accurate forecasting and early warning systems. However, Africa averages just one weather station per 26,000 square kilometres, which is eight times lower than the WMO's advised level. This sparse distribution is caused by a low number of stations and leaves vast areas unmonitored, particularly in a region of Central Africa, exacerbating the continent's vulnerability to extreme weather events (Kingdom et al., 2006).

2.2.3. Outdated and lack of maintenance of weather instrument

Outdated and lack of maintenance of weather instruments compounding the issue of a limited number of weather stations, the majority of existing weather stations are non-functional or fail to meet international standards. As of 2018, approximately 54% of Africa's surface weather stations and 71% of its upper-air weather stations were unable to capture accurate data (Ahmed, 2024). This issue is often due to inadequate maintenance and funding, leading to a decline in the number of operational stations over recent decades.

Therefore, the lack of reliable weather monitoring infrastructure has negative consequences. Without accurate data, the effectiveness of early warning systems declines, leaving populations unprepared for natural disasters. For instance, in south-eastern Africa during Cyclone Idai in 2019, the absence of timely warnings contributed to over 1,000 fatalities (Mozambique, 2019). In contrast, regions with enhanced weather monitoring and early warning systems, such as the United States during Hurricane Ida in 2021, experienced fewer casualties (Beven et al., 2021).

2.2.4. Suboptimal placement

The accuracy and reliability of meteorological data depends on the placement of weather stations. Suboptimal siting results in inaccurate readings, which impacts climate modelling, agricultural planning, and disaster preparedness (NiuBoL, 2023). Several factors contribute to suboptimal

station placement, including inadequate spatial coverage, interference from urban structures, and the failure to account for the diversity of local microclimates (Weatherhead et al., 2017). Improper station siting, such as positioning near artificial heat sources or obstructions, distort temperature and precipitation measurements (Fiebrich et al., 2010).

For instance, urban heat island effects, which are caused by the concentration of human activities, lead to elevated temperatures in weather stations located near urban centres (Ghenai et al., 2023). Furthermore, stations situated in low-lying areas may overestimate rainfall due to the localized pooling of water, which is not representative of the surrounding region (Suri & Azad, 2024). Therefore, to mitigate these issues it is necessary to place weather stations in open area and free from obstruction.

2.3. Optimizing Weather Station Placement in Rwanda: A Review of Policies, Strategies, and Institutional Reports

Accurate meteorological data is important for Rwanda's socio-economic development, particularly in agriculture, disaster management, and climate resilience. The strategic placement of weather stations ensures reliable and timely data collection, which supports decision-making across various sectors. This literature review examines Rwanda's policies, strategies, and institutional initiatives aimed at optimizing weather station placement to enhance meteorological data accuracy and reliability.

2.3.1. Policy Framework for Meteorological Services in Rwanda

The Government of Rwanda (GR) has developed policies that emphasize the enhancement of meteorological services to support climate monitoring and early warning systems. Rwanda National Meteorological Policy highlighted the need for a well-distributed and adequately equipped network of weather stations to improve climate resilience and sustainable development (Kigali, 2011). This policy align with international standards established by the World Meteorological Organization (WMO), ensuring that Rwanda's meteorological network is well integrated into the global observation system.

Furthermore, the National Adaptation Plan (NAP) highlights the role of accurate meteorological data in supporting climate adaptation strategies and reducing the risks associated with extreme weather events. This objective is also reflected in the National Environment and Climate Change

Policy, which emphasizes the need to promote the generation and accessibility of accurate weather and climate information for better planning (Ministry of Environment Rwanda, 2019).

2.3.2. Strategic Initiatives and Investments in Meteorological Infrastructure

To address the gaps in weather stations placement, Rwanda has undertaken significant investments aimed at strengthening its meteorological observation capacity. The country recently secured a \$3.5 million grant from the Systematic Observations Financing Facility (SOFF) to rehabilitate three surface weather stations and establish its first upper-air (radiosonde) station (SOFF, 2024). This initiative aims to enhance data collection, improve numerical weather prediction, and ensure better integration with regional and global meteorological networks. Such developments contribute to more precise climate modelling, which is essential for sectors such as agriculture, water resource management, and disaster risk reduction.

In addition to financial investments, Rwanda has focused on developing human capacity and technological advancements in meteorology. The implementation of the Early Warning System (EWS) by the Rwanda Meteorology Agency (Meteo Rwanda) provides real-time weather updates, and improving preparedness for extreme weather (Symonds, 2022). The EWS has been particularly beneficial for farmers and communities vulnerable to climate-induced disasters. Furthermore, satellite-based remote sensing technologies have been integrated with ground-based observations to enhance spatial coverage and data accuracy.

2.3.3. Institutional Roles and Development

Meteo Rwanda plays a central role in ensuring the strategic placement and maintenance of weather stations. Its mandate includes establishing a national meteorological data centre, improving telecommunication networks for data exchange, and ensuring compliance with WMO guidelines (Kigali, 2011). One of the most advancements in Rwanda's meteorological sector has been the establishment of a state-of-the-art calibration laboratory for meteorology, hydrology, and air quality monitoring. This facility enhances the precision of meteorological instruments and ensuring high-quality data collection (Christian et al., 2023). Previously, sensor calibration had to be conducted outside the country, causing delays and potential damage during transport. The new laboratory addresses these challenges and strengthens Rwanda's capacity for accurate climate monitoring.

In addition, Rwanda has actively engaged in regional collaborations aimed at optimizing weather stations placement and enhancing climate resilience through improved weather and climate monitoring systems. A notable example is the expansion of the Strengthening Early Warning Systems for Anticipatory Action (SEWAA) project to Uganda and Rwanda. Launched by the IGAD Climate Prediction and Applications Centre (ICPAC) in partnership with other organizations, this initiative represents a significant step toward strengthening early warning systems and disaster preparedness in Eastern Africa (ICPAC, 2025). As a member of the Intergovernmental Authority on Development (IGAD), Rwanda benefits from ICPAC's technical support, particularly in climate data sharing and forecasting. This partnerships contributing to improved climate modelling and enhancing meteorological services within the Country.

3. METHODOLOGY

3.1. Study area description

Rwanda, situated in East-Central Africa, covers a total area of 26,338 km². Geographically, it lies between latitudes 1°04'S and 2°51'S, south of the equator, and longitudes 28°53'E and 30°53'E, east of the Greenwich Meridian. The country shares its borders with Uganda to the north, Tanzania to the east, Burundi to the south, and the Democratic Republic of the Congo to the west (DHS, 2018).

Rwanda's topography is characterized by diverse terrain, including numerous hills, valleys, and mountains. The country's elevation ranges from 950 meters in the Bugarama low-lying plain to 4,507 meters at Mount Karisimbi, the highest peak in Rwanda. Due to its extensive mountainous landscape, Rwanda is often referred to as the Land of a Thousand Hills (Black, 2019).

Rwanda experiences a tropical temperate climate due to its geographical location between the tropics and its high elevation. Rainfall and temperature patterns vary across the country, influenced by topography and environmental factors such as water bodies, forests, steep slopes, and lowlands. Based on these variations, Rwanda is divided into four main climatic regions: the eastern plains, the central plateau, the highlands, and the areas surrounding Lake Kivu (*SURF Strategic Plan*, 2024).

The eastern plains receive annual rainfall ranging from 700 mm to 1,100 mm, with average temperatures between 20°C and 22°C. In the central plateau, annual rainfall varies from 1,100 mm to 1,300 mm, and mean temperatures range between 18°C and 20°C. The highlands, which include the Congo-Nile Ridge and the Birunga volcanic chain, experience higher rainfall levels of 1,300 mm to 1,600 mm, with temperatures ranging from 10°C to 18°C. The regions around Lake Kivu and the Bugarama plains receive between 1,200 mm and 1,500 mm of rainfall per year, with average temperatures ranging from 18°C to 22°C (MOE, 2023).

buildings, forests, and other factors that compromise data accuracy, including heat sources, concrete surfaces, and water bodies. Surveys complemented field observations by utilizing Global positioning system (GPS) tools to record and update station coordinates. Additionally, photographs were taken to capture key environmental conditions such as land cover and obstructions.

Field observation

Field observations were conducted to assess the environmental characteristics of existing sites for agro-meteorological weather stations across the country. These assessments included evaluating land use patterns, topography, vegetation cover, water bodies and any human-made structures that could interfere with data collection. The observations also served to verify GIS-based spatial analyses with real ground conditions. During the site visits, I identified stations that needed to be relocated due to unavoidable constraints.

Surveys

Surveying in this study focused on the accurate collection of spatial coordinates (latitude, longitude, and elevation) of all existing agro-meteorological weather stations across the country. This data was essential for mapping the current distribution of stations and for identifying spatial gaps in coverage. Using GPS devices, the exact locations of stations were recorded to ensure precision in the spatial analysis phase. The collected coordinates were integrated into the GIS-based multi-criteria evaluation to assess the effectiveness of the current network and to support the optimization of new station placements.

Photographic documentation

Photographic documentation was used to visually capture the environmental characteristics of each surveyed site, including land cover, surrounding infrastructure, and environmental conditions. These images served as visual evidence to complement field notes and GIS analyses. They also helped in validating the suitability of existing sites by providing a clear picture of the site's context and any potential obstacles. Photographs were archived and referenced during data analysis and reporting to strengthen the credibility and transparency of the site optimization process.

3.2.2. Secondary Data Collection

Secondary data was used extensively in this study through a comprehensive review of literature relevant to the research topic. This included scholarly sources such as peer-reviewed journal articles, conference proceedings, and academic books that provided theoretical frameworks and methodological insights. In addition, national and institutional documents were examined, including reports from Rwanda Meteorological Agencies, which offered context-specific information on the country's climate monitoring and forecasting systems.

Policy documents at national, regional, and global levels related to meteorology and climate services were also reviewed to understand the broader governance and institutional frameworks that guide meteorological practices. Furthermore, reports and technical publications from the World Meteorological Organization (WMO) were analysed, as they present international recognized standards, best practices, and global perspectives on meteorological data management and station placement. Collectively, these sources supplied critical background knowledge that shaped the conceptual foundation of the study, informed the identification of research gaps, and supported the development of the literature review chapter.

3.3. Spatial multi-criteria evaluation framework and implementation

This study adopted a Geographic Information System (GIS)-based Spatial Multi-Criteria Evaluation (SMCE) framework to determine the optimal locations for agrometeorological weather stations across Rwanda. The SMCE technique enabled the integration and analysis of various spatial datasets to support systematic and data-driven decision-making. The methodological framework combined theoretical principles from Multi-Criteria Decision Analysis (MCDA), Analytic Hierarchy Process (AHP), and spatial modelling to generate suitability maps, assess the performance of existing stations, and propose new optimal sites.

3.3.1. Factor Maps Generation

The first step involved identifying and generating factor maps from spatial datasets deemed influential in agrometeorological weather station siting. Based on World Meteorological Organization (WMO) siting guidelines and referring to other publication worldwide relevant to this study, nine key criteria were selected:

Topographic and surface factors: Slope, elevation, terrain hillshade

Land cover and use: Land use/land cover (LULC)

Accessibility factors: distance to roads

Proximity-based factors: Distance to rivers, lakes, wetlands, and existing stations

Each of these criteria was processed using GIS tools to derive standardized raster layers representing spatial influence across the country. These factor maps were then normalized to a common scale, forming the basis for subsequent evaluation.

Table 1: Data for optimum placement of agrometeorological weather stations in Rwanda

Criteria	Data required	source
Slope, hillshade and elevation	DEM	https://geohub.data.undp.org
Rivers and lakes	Waterbodies	https://waterportal.rwb.rw
Roads	Roads	https://www.rtda.gov.rw
Land use/ land cover	LULC raster	https://rcmrd.africageoportal.com
Existing agrometeorological stations	Existing station	https://www.meteorwanda.gov.rw
Wetlands	Wetlands	https://rwanda.africageoportal.com

3.3.2. Criteria Weighting Using Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was employed to assign relative importance (weights) to each of the selected criteria. A panel of experts with meteorological and spatial planning expertise conducted pairwise comparisons of the criteria using Saaty's fundamental 9-point scale, evaluating how each factor contributes to optimal station placement.

The first steps is the primary aim of this study as to evaluate and propose an optimized placement for agro-meteorological weather stations in Rwanda by evaluating the suitability of different locations, ranging from not suitable to high suitable. To achieve this objective, the analytic hierarchy process (AHP) was employed as a multi-criteria decision-making tool.

The second steps began with the identification and selection of nine relevant criteria that influence the suitability of weather station placement. These criteria were chosen based on their significance in meteorological applications and spatial planning, informed by both literature review and WMO siting guideline and standards.

Each of the nine selected criteria was then compared pairwise against the others to quantify their relative importance using the AHP scale. This step was conducted by a panel of experts with specialized training in meteorology and site selection for weather stations. Their expertise ensured that the judgment used in the comparisons was appropriate and scientific valid.

The derived weights from the pairwise comparisons were subsequently integrated into a spatial multi-criteria evaluation framework. A weighted overlay analysis was performed in a geographic information system environment to generate a suitability map for optimum agrometeorological weather station placement. This approach allowed for the spatial representation of site suitability across the study area.

The use of AHP in this study was particularly valuable as it provided a transparent, systematic, and rational method for prioritizing various criteria. This enhanced the objectivity and scientific rigor of the site selection process, ensuring that decisions were based on a well-founded analytical framework rather than subjective judgment alone.

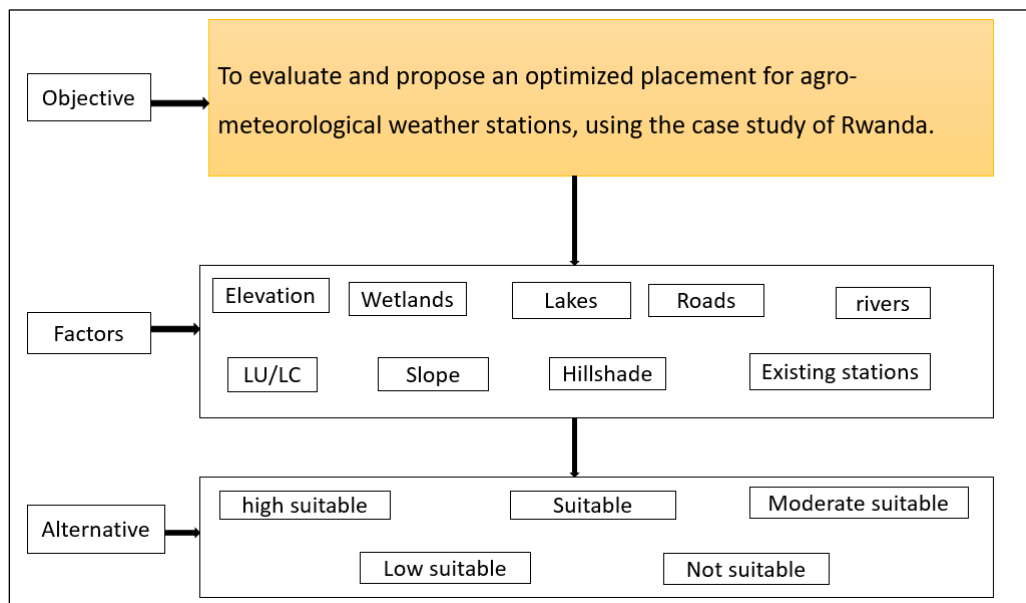


Figure 5: Analytic Hierarchy process (AHP) Steps

The figure 5 illustrates the Analytic Hierarchy Process (AHP) used to optimize the placement of agro-meteorological weather stations in Rwanda. The process is structured into three levels: the objective, which is to propose optimal station locations; the factors, including elevation, slope, LU/LC, wetlands, hillshade, lakes, rivers, roads, and existing stations; and the alternatives, categorized by suitability levels ranging from "high suitable" to "not suitable." This hierarchical model enables systematic evaluation of multiple spatial criteria, supporting data-driven decision-making for effective environmental infrastructure planning.

Table 2: Saaty scale of relative importance used for comparison of two criteria to construct a Pairwise comparison matrix

Importance	Definition	Explanation
1	Equal Importance	Both elements have equal contribution in the objective
3	Moderate Importance	Moderate advantage of one element compared to the other
5	Strong Importance	Strong favouring of one element compared to the other
7	Very Strong Importance	One element is strongly favoured and has domination in practice, compared to the other element
9	Extreme Importance	One element is favoured in comparison with the other, based on strongly proved evidence and facts
2, 4, 6, and 8	Intermediate Values	
1/2, 1/3, 1/4, 1/5, 1/7, 1/9	Values for Inverse Comparison	

Source: Felipe (2024)

Expert-Based Pairwise comparison matrix for agrometeorological weather station placement

To optimize the placement of agrometeorological weather stations in Rwanda, a pairwise comparison matrix was developed using the analytic hierarchy process (AHP). This matrix was constructed based on the judgments of experts, who evaluated the relative importance of 9 selected criteria. These experts assigned scores using Saaty's 9 point fundamental scale, which ranges from 1 (equal importance) to 9 (extreme importance), to indicate the influence of each criteria in relation to the others.

The matrix is square it mean: it has the same number of rows and columns, with each cell representing a comparison between two criteria. The diagonal of the matrix contains the value 1 for all entries, because any criteria compared with itself is of equal importance.

The upper triangular part of the matrix (above the diagonal) was filled based on expert judgments. Each value in this section represents how much more important one criteria is over another with respect to optimum station placement. Once this part was completed, the lower triangular part (below the diagonal) was derived by taking the reciprocal of the corresponding upper-triangular values. This reciprocal relationship is a fundamental feature of AHP, ensuring the matrix maintains consistency.

For example, if an expert judges that Criterion A is 3 times more important than Criterion B, then the matrix cell corresponding to (A, B) is 3, while the reciprocal cell (B, A) is 1/3.

Example of Pairwise Comparison

Consider the comparison between two criteria: slope and lakes. The question posed to the experts were: How important is slope with respect to lakes in determining suitable locations for agrometeorological weather stations?

In the pairwise comparison process, slope was judged to be equal to moderate more important than lakes, corresponding to a value of 2 on Saaty's scale. This is represented numerical with a value of 2 in the comparison matrix when slope is evaluated relative to lakes. By applying the principle of reciprocity, the reverse comparison is automatical defined: lakes are considered half as important

as slope, which is expressed as 1/2 in the corresponding position of the matrix. This reciprocal relationship guarantees the mathematical consistency of the pairwise comparison matrix.

Table 3: Pairwise comparison matrix

Criteria	Slope	lakes	Wetlands	rivers	elevation	roads	LU/LC	hillshade	Existing stations
Slope	1	2	2	3	4	3	4	3	4
lakes	0.5	1	2	3	3	4	3	4	4
Wetlands	0.5	0.5	1	2	3	4	3	4	4
rivers	0.3333	0.3333	0.5	1	2	3	2	2	3
elevation	0.25	0.3333	0.3333	0.5	1	3	2	2	4
roads	0.3333	0.25	0.25	0.3333	0.3333	1	2	2	3
LU/LC	0.25	0.3333	0.3333	0.5	0.5	0.5	1	2	3
hillshade	0.3333	0.25	0.25	0.5	0.5	0.5	0.5	1	2
Existing stations	0.25	0.25	0.25	0.25	0.3333	0.3333	0.3333	0.5	1

Normalized pair-wise comparison matrix

Normalised pairwise comparison is obtained by taking the value of relative importance of each cell in column of pair-wise comparison matrix divide by the sum of the column corresponding to the cells; here is the sum of the column in the pair-wise comparison.

SUM	3.7499	5.2499	6.9166	11.0833	14.6666	19.3333	17.8333	20.5	28
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Table 4: Normalized pair wise comparison matrix

Criteria	Slope	lakes	Wetlands	rivers	elevation	roads	LU/LC	hillshade	Existing stations	Sum	CW= S/No of criteria	%Weight
Slope	0.266674	0.38096	0.289159	0.270678	0.272729	0.155173	0.224299	0.146341	0.142857143	2.14887	0.238763291	23.8763291
lakes	0.133337	0.19048	0.289159	0.270678	0.204546	0.206897	0.168225	0.195122	0.142857143	1.801301	0.200144514	20.01445142
Wetlands	0.133337	0.09524	0.14458	0.180452	0.204546	0.206897	0.168225	0.195122	0.142857143	1.471255	0.163472797	16.34727973
rivers	0.088882	0.063487	0.07229	0.090226	0.136364	0.155173	0.11215	0.097561	0.107142857	0.923275	0.102586166	10.25861661
elevation	0.066668	0.063487	0.048188	0.045113	0.068182	0.155173	0.11215	0.097561	0.142857143	0.799379	0.08881993	8.881993024
roads	0.088882	0.04762	0.036145	0.030072	0.022725	0.051724	0.11215	0.097561	0.107142857	0.594022	0.066002492	6.600249199
LU/LC	0.066668	0.063487	0.048188	0.045113	0.034091	0.025862	0.056075	0.097561	0.107142857	0.544189	0.060465398	6.046539817
hillshade	0.088882	0.04762	0.036145	0.045113	0.034091	0.025862	0.028037	0.04878	0.071428571	0.42596	0.047328871	4.732887129
Existing stations	0.066668	0.04762	0.036145	0.022556	0.022725	0.01724	0.01869	0.02439	0.035714286	0.291749	0.03241654	3.241653967

Criteria weight

Criteria weight was calculated by averaging all element in the row of normalised pair-wise comparison matrix.

Table 5: Criteria weight based on AHP

Criteria	Weight	Weight %	Integer value
Slope	0.238763291	23.8763291	24
Lakes	0.200144514	20.01445142	20
Wetlands	0.163472797	16.34727973	16
Rivers	0.102586166	10.25861661	10
Elevation	0.08881993	8.881993024	9
Roads	0.066002492	6.600249199	7
LU/LC	0.060465398	6.046539817	6
Hillshade	0.047328871	4.732887129	5
Existing stations	0.03241654	3.241653967	3

As shown in the table 6, the weighted criteria generated using the Analytic Hierarchy Process (AHP). Among the factors, slope and water expenses hold the highest weights due to their significant influence on the placement of agrometeorological weather stations.

Consistency

To ensure the reliability and logical coherence of the pairwise comparisons used in the Analytic Hierarchy Process (AHP), a consistency check was conducted. This involved evaluating the extent to which the judgments made in the comparison matrix were logical consistent. The consistency analysis was performed by multiplying the unnormalized pairwise comparison matrix by the derived criteria weight, followed by the calculation of the Consistency Index (CI) and Consistency Ratio (CR). A CR value below the threshold of 0.1 indicates an acceptable level of consistency, thereby validating the reliability of the expert judgments employed in the weighting process of this study.

Table 6: Consistency matrix

Criteria	Slope	lakes	Wetlands	rivers	elevation	roads	LU/LC	hillshade	Existing stations	WSV	WC	Ratio of WSV & WC	
Slope	0.238763	0.400289	0.326946	0.307758	0.35528	0.198007	0.241862	0.141987	0.12966616	2.340558	0.238763291	9.802838459	
lakes	0.119382	0.200145	0.326946	0.307758	0.26646	0.26401	0.181396	0.189315	0.12966616	1.985078	0.200144514	9.91822262	
Wetlands	0.119382	0.100072	0.163473	0.205172	0.26646	0.26401	0.181396	0.189315	0.12966616	1.618947	0.163472797	9.903461946	
rivers	0.07958	0.066708	0.081736	0.102586	0.17764	0.198007	0.120931	0.094658	0.09724962	1.019096	0.102586166	9.934049283	
elevation	0.059691	0.066708	0.054485	0.051293	0.08882	0.198007	0.120931	0.094658	0.12966616	0.86426	0.08881993	9.73046992	
roads	0.07958	0.050036	0.040868	0.034192	0.029604	0.066002	0.120931	0.094658	0.09724962	0.61312	0.066002492	9.289352809	
LU/LC	0.059691	0.066708	0.054485	0.051293	0.04441	0.033001	0.060465	0.094658	0.09724962	0.561962	0.060465398	9.293935764	
hillshade	0.07958	0.050036	0.040868	0.051293	0.04441	0.033001	0.030233	0.047329	0.06483308	0.441583	0.047328871	9.330099464	
Existing stations	0.059691	0.050036	0.040868	0.025647	0.029604	0.021999	0.020153	0.023664	0.03241654	0.304078	0.03241654	9.380337969	

The weighted sum value is obtained by summing the elements of each row in the consistency table. The ratio of the weighted sum value to the criteria weight is calculated by dividing criteria weight to the corresponding the weighted sum value

Random access calculation (λ_{max})= The average ratio of weighted sum value and criteria weight.

$$\lambda_{max} = 86.58276823 / 9 = 9.620307581$$

$$CI = \lambda_{max} - n / n - 1$$

Where: λ_{max} is the maximum eigenvalue of the pairwise comparison matrix (Random access).

n is the number of criteria.

$$Consistency\ index\ (CI) = (9.620307581 - 9) / (9 - 1)$$

$$CI = 0.077538448$$

Consistency check was performed by calculating the Consistency Ratio (CR). The result yielded a CR less than 0.10, which is within the acceptable threshold established by AHP methodology. This indicates that the judgments made by the experts are consistent enough to proceed with the next steps in AHP.

$$Consistency\ ratio\ (CR) = Consistency\ index\ (CI) / Random\ index\ (RI)$$

The value of Random index depends on the number of criteria. Below is the table that show random index from $n= 1$ up to $n=10$ where n is the number of criteria.

Table 7: Random index value

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Srisawat & Payakpate (2014)

CR = 0.077538448 / 1.45 which is equal to 0.053474792 less than to <0.10 standard.

This result (CR = 0.0535) is less than the commonly accepted threshold of 0.10, indicating an acceptable level of consistency in the pairwise comparisons. Therefore, the judgments used in the decision matrix are considered reliable and consistent for further analysis.

3.3.3. SMCE implementation and suitability mapping

With the weighted criteria ready, a Weighted Overlay Analysis was conducted in GIS to produce a Suitability Map for optimal weather station placement. Each pixel in the map represents a combined suitability score derived from the weighted sum of all criteria layers. The final map was classified into five categories: High suitable, suitable, moderately suitable, low suitable and not suitable

This suitability map serves as a decision-support tool for identifying where new agrometeorological stations should be installed.

3.3.4. Evaluation of existing stations' placement

To evaluate the suitability of existing agrometeorological weather stations, their current locations were overlaid on the final suitability map. This analysis revealed whether the current stations were situated in high suitable zones or in less optimal areas (e.g., low or not suitable). Stations falling outside the top suitability classes (high suitable and suitable class) can be considered for relocation to improve monitoring quality and spatial coverage. This evaluation ensures that METEO Rwanda agrometeorological weather station network maintains operational efficiency and spatial equity, particularly in supporting agriculture, climate services, and disaster preparedness.

3.3.5. Identification of suitable locations for new stations

The final stage of the SMCE process involved identifying new optimal sites for weather station expansion. These areas, categorized as high suitable or suitable were cross-referenced with regions lacking coverage to maximize spatial distribution and coverage gaps. Priority was given to underserved areas, agricultural zones, and regions prone to climate extremes.

The flowchart below illustrates the methodological framework used for this study; steps include criteria selection, data acquisition and pre-processing, data standardization, and assigning weight through the Analytic Hierarchy Process (AHP). In addition, weighted overlay analysis was conducted to generate a suitability map, followed by validation against existing station distributions to look for stations that can be advised to be relocated for optimizing its placement that resulted on recording accurate meteorological data.

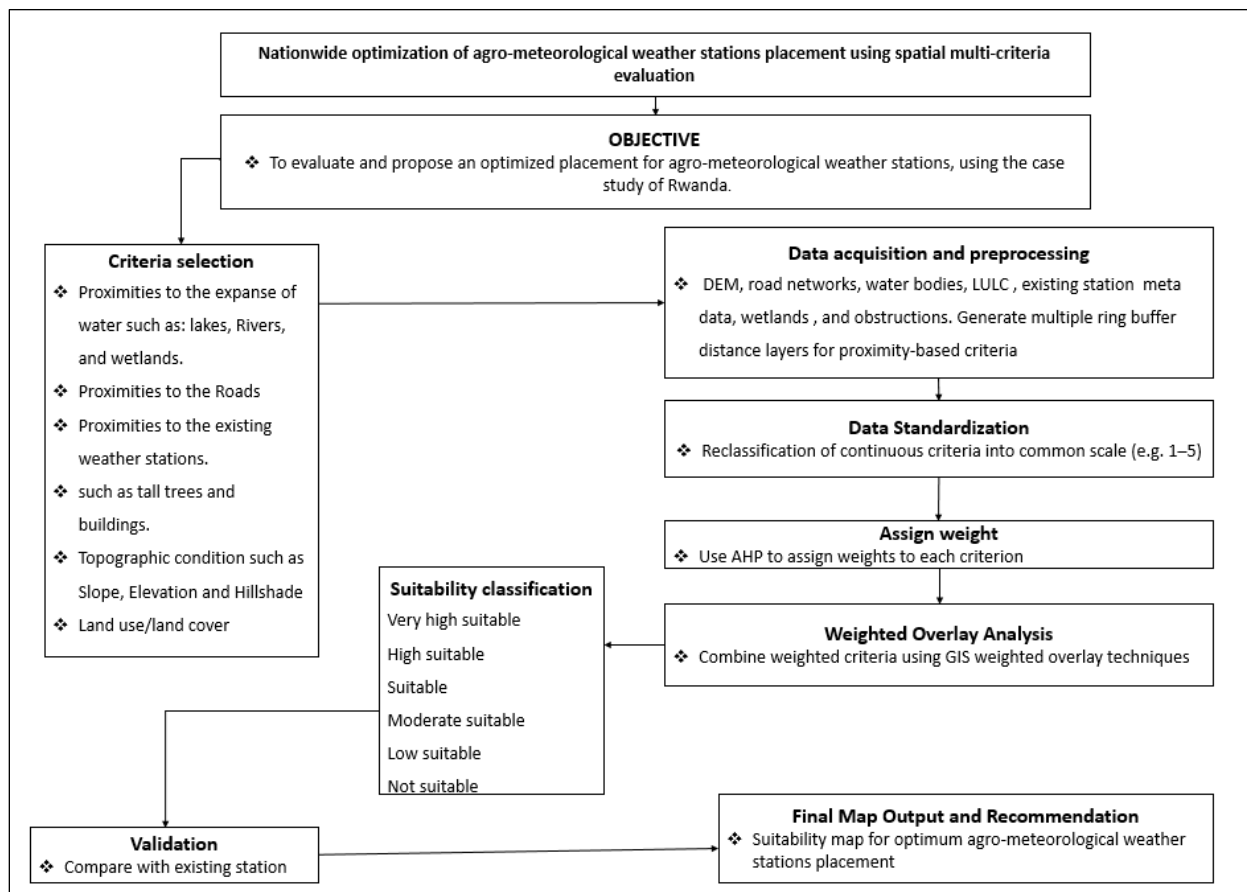


Figure 6: Flowchart for optimizing the placement of weather stations

CHAPTER 4. RESULTS

4.1. Identification of established criteria for evaluating suitability of agrometeorological station locations

To identify the optimum placement for agrometeorological weather stations in Rwanda, nine important criteria were selected and analysed using a spatial multi-criteria evaluation approach. These criteria were chosen based on their influence on weather parameters as well as in accordance with the world meteorological organization recommendations and guidelines for siting agrometeorological stations.

In addition, relevant scientific publications on the suitability assessment of agricultural meteorological station locations informed the selection process. This integrative approach ensures that the selected criteria not only reflect international best practices but also respond to the specific Agro-climatic and geographic conditions of Rwanda.

The identified criteria are detailed in the table below. Those factors provide a comprehensive framework for guiding the spatial optimization of agrometeorological station placement to improve the accuracy, reliability, and representativeness of Agro-climatic data across Rwanda.

Table 8: Criteria used in the study, their description and source for reference

No	Criteria	Description	Reference source
1	Slope	Weather stations should be placed in stable, gently sloping areas to minimize soil erosion and topographic interference, which helps improve data accuracy and representativeness	(World Meteorological Organization, 2012)
2	Hillshade	persistency shaded areas result in recording lower temperatures, higher relative humidity, and lead to biased evaporation measurement which is not representative for Agro-ecological zone	(Rojas Briceño et al., 2021)

3	Elevation	Elevation affects temperature, pressure, and precipitation patterns. Ensuring a representative of varied elevation improves spatial accuracy and reflects to different Agro-ecological zones.	(Rojas Briceño et al., 2021)
4	Wetlands	Wetlands modify local humidity, temperature, and evapotranspiration. Stations placed too close to wetlands may record microclimatic anomalies of the site itself and compromising data representativeness for surrounding agricultural areas.	(Alejo, 2018)
5	Roads	Accessibility for station maintenance and data collection is essential. However, to avoid heat-induced temperature bias from black concrete roads which absorb heat. Stations should be located at 100 m away from roads.	(Felipe et al., 2024)
6	Rivers	Rivers influence local humidity, fog formation, and temperature moderation. Stations should be sited at 100m away the rivers to avoid localized anomalies and flooding risks.	(World Meteorological Organization, 2014)
7	Lakes	Lakes affect microclimates through heat storage and moisture regulation; it is important to place weather station away from the lakes in order to be the representative of an area	(Czaczyk, 2012)
8	LU/LC	Some LU/LC types like urban areas, forests and water bodies, affect temperature, humidity, and wind patterns. For instance, urban areas often experience the urban heat island effect, which distort temperature readings. Therefore, it is important to choose an area with stable and representative land cover of an area.	(Alejo, 2018)

9	Existing stations	Existing station is essential because it ensures that new or relocated stations fill data gaps, meet standards, and support long-term data integrity	(Alejo, 2018)
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4.1.1. Criteria weight using Analytic Hierarchy Process (AHP)

The analytic hierarchy process (AHP) results presented in the diagram below show the criteria weight based on their relative importance in determining optimum locations for agrometeorological station placement. Among the nine evaluated factors, slope weight the highest, followed by lakes, wetlands, rivers, elevation, roads, land use and land cover (LULC), hillshade, and existing stations.

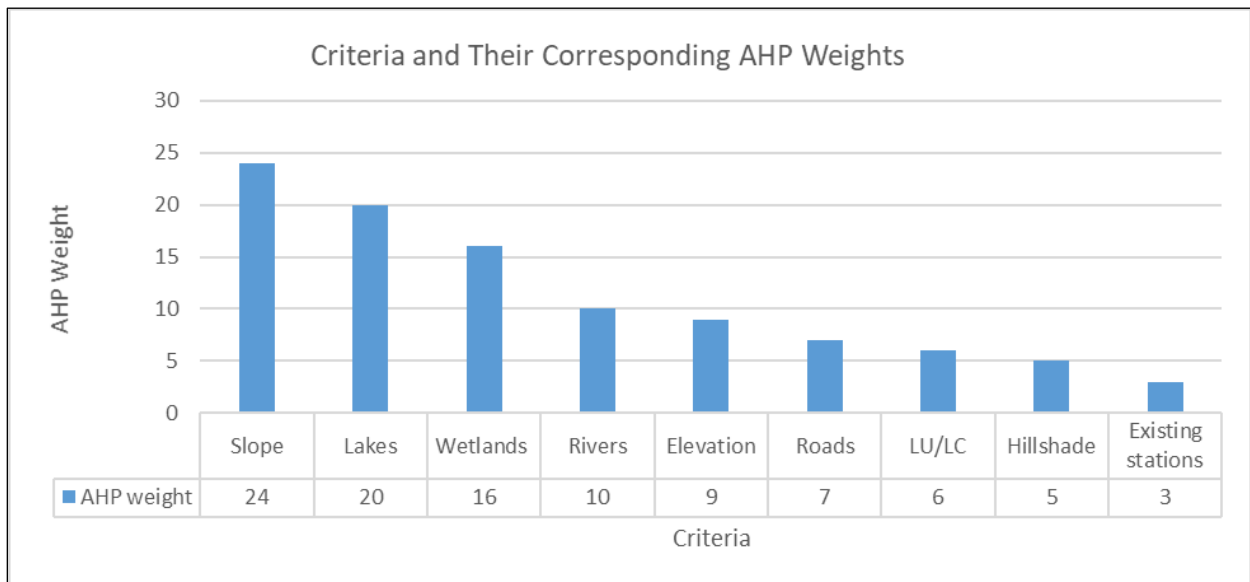


Figure 7: Criteria weight using the Analytic Hierarchy Process (AHP)

The weight of AHP shows that slope and proximity to waterbodies were assigned the highest weights among the considered criteria. This indicates that these two factors play an important role in determining optimum locations for the placement of weather stations. A high slope value suggests that steep terrain poses challenges in terms of station installation, stability, accessibility, and the potential distortion of meteorological readings. Likewise, areas in close proximity to waterbodies, such as lakes, rivers, or wetlands, may influence localized microclimatic conditions, resulting in unrepresentative data, especially for agricultural or upland regions.

Additionally, these locations may be at greater risk of flooding or corrosion, affecting the long-term sustainability of the equipment. Therefore, during the planning and decision-making process, particular attention must be paid to avoiding sites with steep slopes and those near waterbodies to ensure the accuracy, reliability, and durability of the weather-monitoring network.

Figures 8 present the resulting maps for each criteria considered in this study. Each map illustrates the spatial suitability for agrometeorological weather station placement based on the respective criteria. The analysis was guided by the world meteorological organization (WMO) spatial siting standards, ensuring that the proposed locations maximize data quality, accuracy, and representativeness. These individual suitability layers form the foundation for spatial multi-criteria evaluation. See the figure below

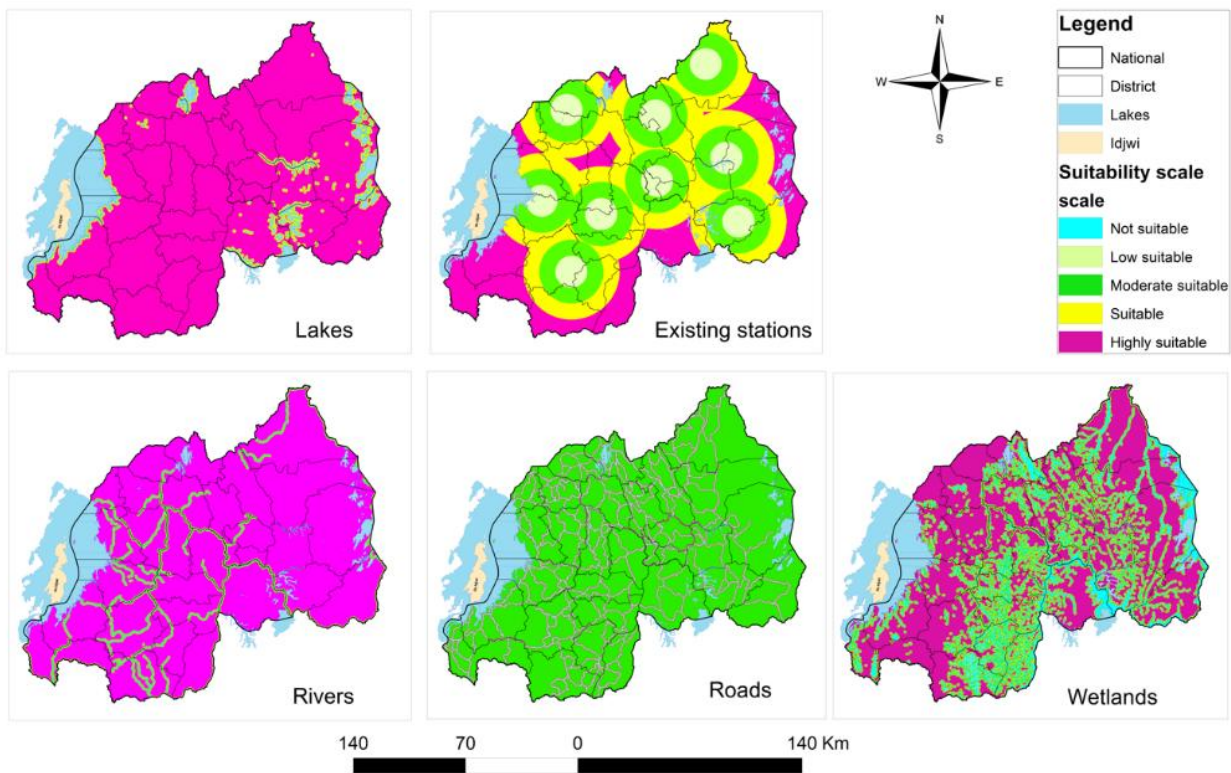


Figure 8 (a): Suitability maps for individual criteria in weather station placement

Source: www.geoportal.rwb.rw

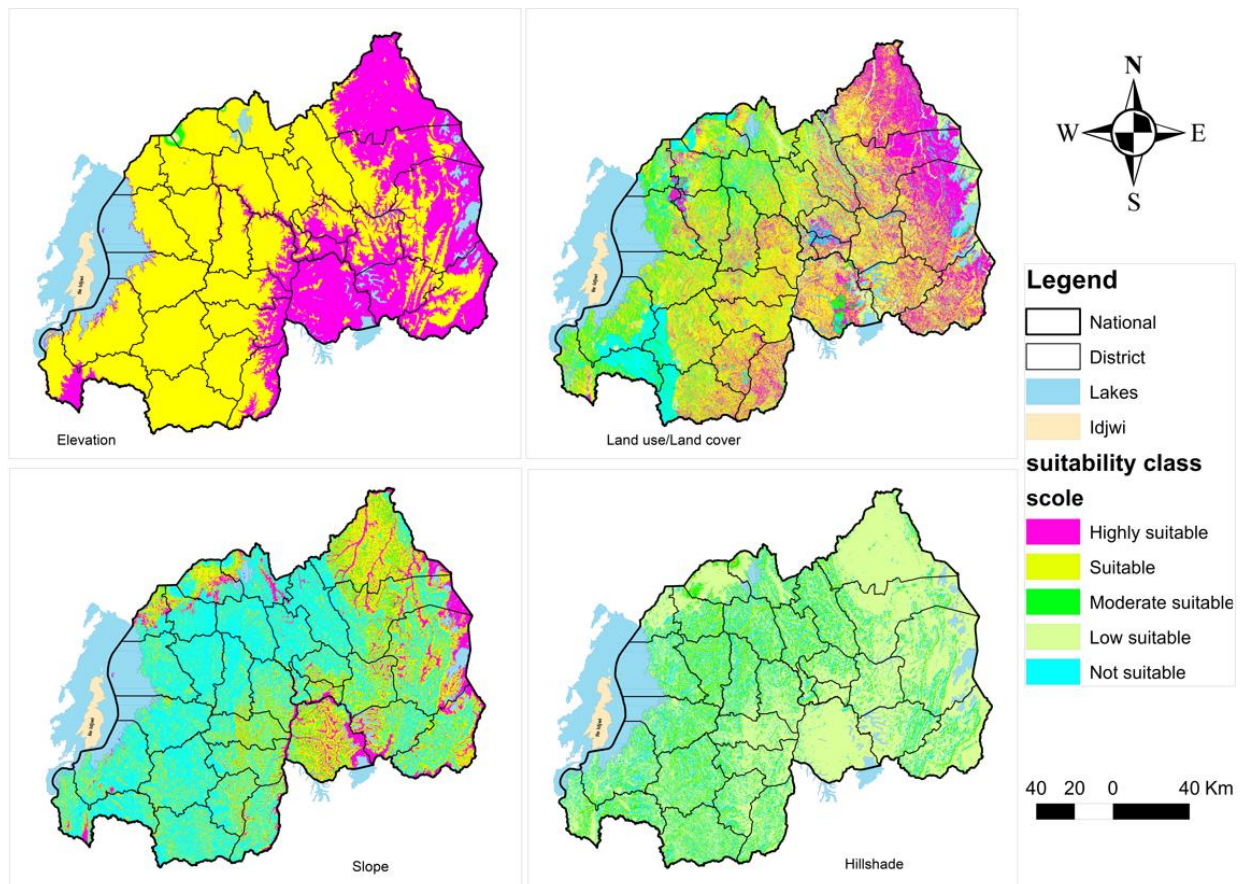


Figure 9 (b): Suitability maps for individual criteria in weather station placement

Source: www.geoportal.rwb.rw

4.1.2. Criterion-based assessment of optimization: A discussion of analytical and ground truth data

Rivers

Rivers influence microclimates through evapotranspiration and humidity, which are an important for monitoring Agro-hydrological conditions. However, siting stations too close to rivers may lead to overestimation of moisture or risk of flooding during high rainfall events. The analyses reveal that 1 out of 9 assessed existing agrometeorological stations in Rwanda is located within a 100m buffer zone from a river.

Rubengera agrometeorological weather station located in Karongi district, western province, is approximately sited in 15m from Musogoro River, according to field observation. This close proximity presents evidenced risk of flooding to the meteorological instruments and suggests

potential microclimatic bias, as the data collected may reflect the riverine environment rather than the broader regional conditions. Such a placement is therefore considered suboptimal for generating representative Agro-meteorological data. See the figure below



Figure 10: Rubengera agrometeorological weather station located in Karongi district

Source: Field survey, May 2025

Roads

A spatial analysis using both national and district road data, the result revealed that Gitega, Kazo, and Nyamagabe agrometeorological weather stations are positioned within 100m buffer of adjacent roads. This spatial proximity contravenes the World Meteorological Organization standards, which recommend that weather stations must be sited at least 100 meters away from artificial heat sources such as roads, buildings, and paved surfaces.

The rationale behind this guideline is to minimize the influence of localized anthropogenic heat emissions, which can bias temperature and humidity measurements. Proximity to roads, which absorb and re-emit heat, particularly during dry and sunny conditions, can result in elevated temperature recordings that do not reflect natural environmental conditions.

Although Gicumbi agrometeorological station were not identified in the analyses due absence of roads data that cover up the station location, field observations further confirm these concerns at this stations located in Gicumbi district, northern province of Rwanda, where nearby paved roads surfaces are in 8m from the stations, this contribute to localized warming. These artificial surfaces create microclimatic effects, common referred to as the urban heat island (UHI) phenomenon.

As a result, temperature and humidity readings from this station are like to be artificial elevated, leading to data distortions. Such inaccuracies undermine the integrity of long-term climate monitoring efforts and compromise the reliability of agrometeorological data used to inform agricultural planning, early warning systems, and climate-smart decision-making at both local and national levels.

Ensuring adherence to WMO siting standards is therefore essential for maintaining the quality, comparability, and scientific validity of climate datasets used in sectors such as agriculture and disaster risk reduction. This can be achieved through optimizing weather station placements. Below is the figure that illustrate Byumba agrometeorological weather station and their closest paved roads.



Figure 11: Location of Byumba agrometeorological weather station

Source: Field survey, May 2025

Elevation

This study, was considered an elevation as a key factor in optimizing the placement of agrometeorological weather stations. The elevation data were classified into four categories: Class 1 (804–1500 meters), Class 2 (1500–3000 meters), Class 3 (3000–3500 meters), and Class 4 (3500–4480 meters). After performing a spatial join and analysis to relate elevation with the distribution of existing agrometeorological stations, the results revealed spatial imbalance in distribution of agrometeorological weather station a cross Rwanda.

Class 1 contains only one weather station, class 2 contains eight stations, while classes 3 and 4 have no stations at all. This uneven distribution highlights significant spatial inequalities in the current weather station network across different elevation zones in the country. Such disparities may limit the accuracy and representativeness of agrometeorological data in higher altitude areas, which could hinder effective climate monitoring and agricultural decision-making.

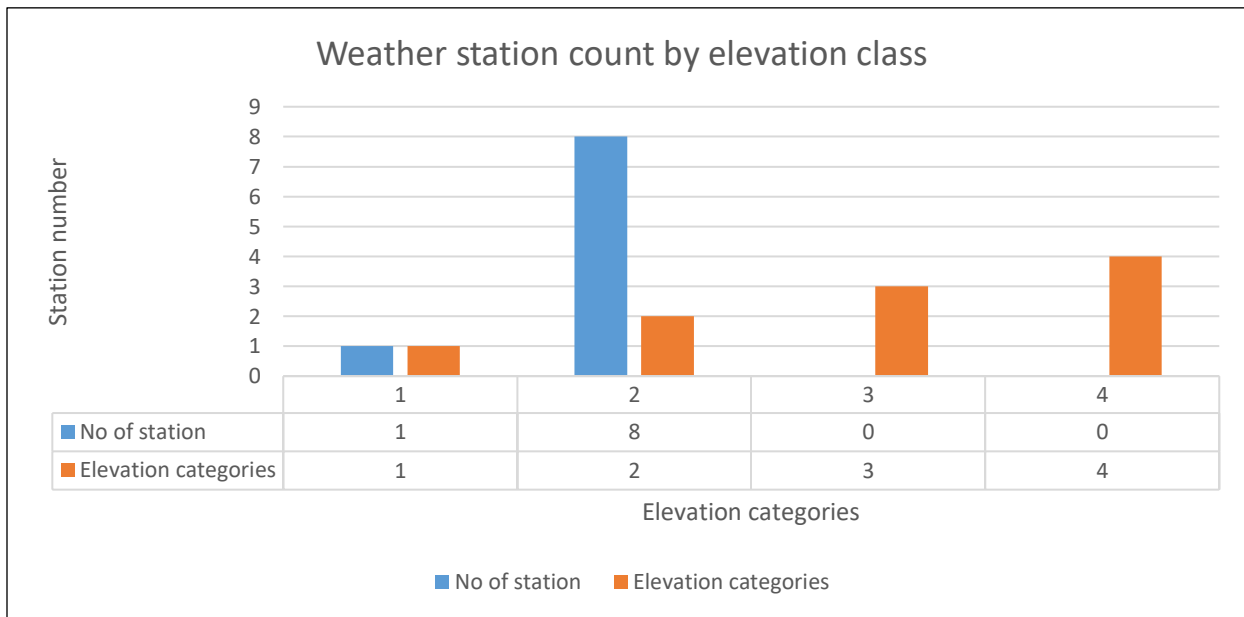


Figure 12: Distribution of existing agrometeorological weather stations by elevation in Rwanda

Slopes

According to the World Meteorological Organization (WMO) guidelines, weather stations should be installed on slopes of less than 19 degrees to ensure the collection of accurate and representative data. Specific to weather parameter like temperature, wind speed, and precipitation. Steep slopes can distort local wind patterns, influence surface runoff, and create microclimatic variability, all

of which may introduce biases into agrometeorological measurements. This study reveals that 5 out of the 9 evaluated stations comply with the WMO’s recommended siting standards for surface observations. However, the remaining 4 stations which are Gitega, Byumba, Nyamagabe and Kazo agrometeorological weather stations are located on slope exceeding 19 degrees, thereby violating the established standards. Such deviations from recommended siting conditions can compromise the reliability of the data collected. The graph below illustrates the slope characteristics of each stations in relation to the WMO standards.

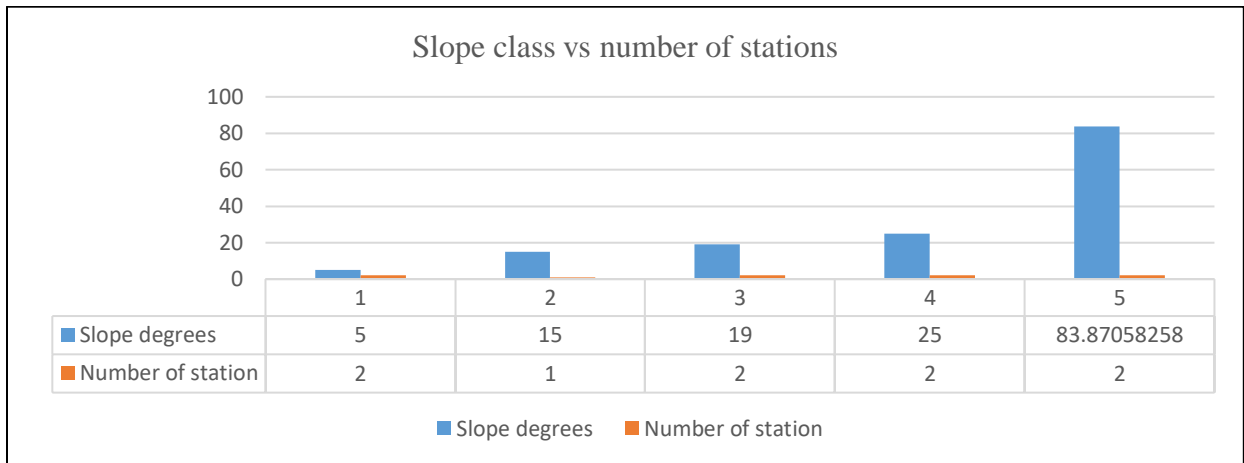


Figure 13: Distribution of existing agrometeorological weather stations by slope in Rwanda

Obstructions

In addition to the analytical findings, field observations indicate that Gitega, Byumba, and Kawangire, agrometeorological weather stations are affected by nearby obstructions (tall trees). These physical barriers, situated in close proximity to the stations, interfere with the accurate measurement of wind parameters and cast shadows over certain meteorological instruments. Such conditions compromise the reliability of data collected from these stations, particularly for variables that are sensitive to surrounding environmental features.



Figure 14: Location of Kawangire Agrometeorological Station, Kayonza District

Source: Field survey, May 2025

Unnatural artificial surface

Byumba, Gitega, and Nyagatare agrometeorological weather stations are located in areas that are in close proximity to artificial surfaces, such as paved roads and concrete playgrounds surfaces. These unnatural features influence the accuracy and reliability of meteorological observations. Artificial surfaces absorb and retain more heat than natural ones, leading to localized warming effects that can result in biased temperature readings. This is particular observed during daytime and dry seasons, where stations surrounded by such surfaces may overestimate air temperature. In addition, nearby paved areas can disturb the local radiation balance and create microclimates that alter humidity levels, thereby compromising the accuracy of environmental data. As a result, the meteorological data collected from these stations do not accurate represent the broader regional conditions, which is important for agrometeorological applications. These findings underscore the

importance of relocating weather stations to more natural and representative sites to minimize anthropogenic interference and enhance the quality of collected data.



Figure 15: concrete playgrounds closer to the station site

Source: satellite image, May 2025

4.2. Assessment of existing stations against the optimum placement criteria

The effectiveness of a weather station network depends on the strategic placement of each station. Proper placement ensures maximum coverage, operational efficiency, and accessibility. This assessment aims to evaluate the current locations of existing agrometeorological stations against established optimum placement criteria. By analysing spatial distribution, service area reach, demand alignment, and accessibility factors, the assessment seeks to identify any gaps, and inefficiencies in the current setup.

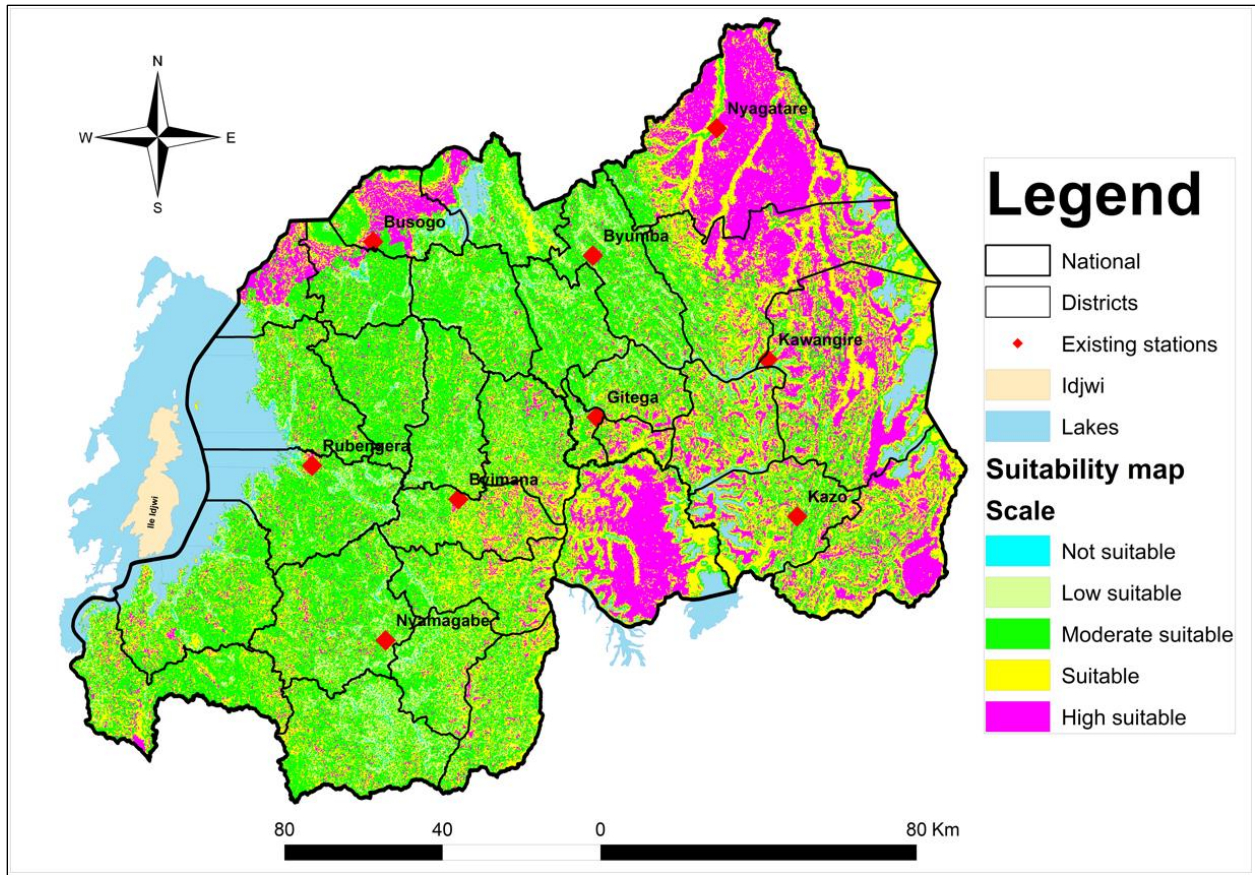


Figure 16: Alignment of existing stations with site suitability

Source: Rwanda Meteorology Agency (2024)

The figure 15 illustrate the spatial distribution of existing agrometeorological weather stations across the country. These stations have been overlaid onto a suitability map in order to evaluate the alignment between current station locations and areas identified as suitable for agrometeorological monitoring. This spatial analysis serves to assess the effectiveness of the current network in recording representative climatic data relevant for agricultural decision-making.

The overlay reveals the extent to which existing stations are located among the suitability classes. Stations situated in high suitable areas indicate good spatial alignment and support efficient data collection. Conversely, the presence of suitable zones without nearby stations suggests potential coverage gaps. Identifying such gaps is essential for optimizing the placement of future stations to ensure comprehensive monitoring and support for agricultural planning and risk management. The

statistical diagram below present the count of existing agrometeorological weather stations and their corresponding suitability classes.

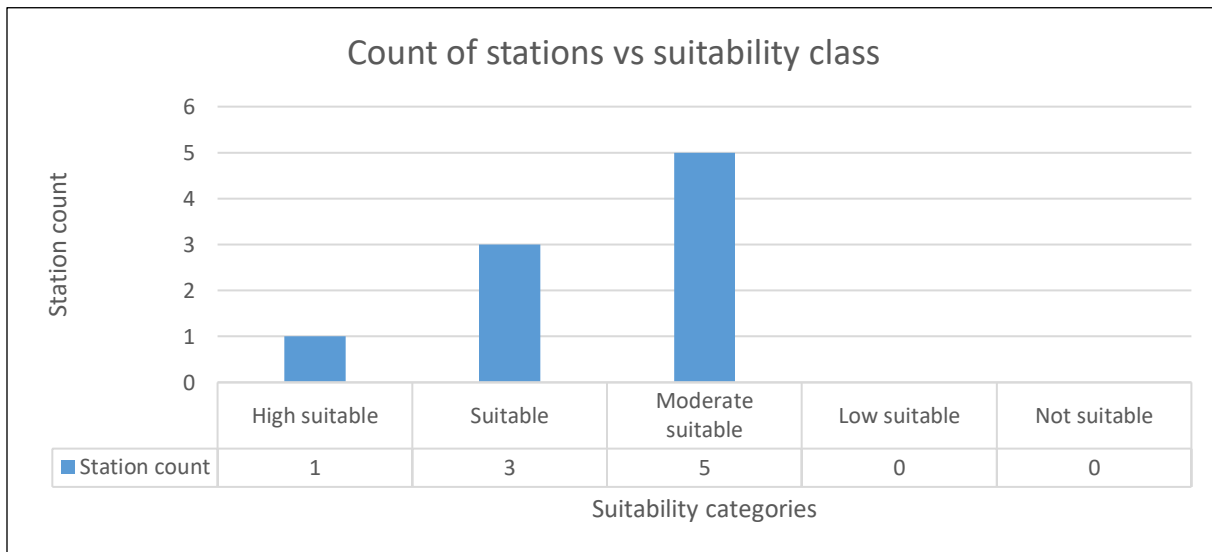


Figure 17: Distribution of weather stations across suitability classes

The suitability analysis reveals that the majority of agrometeorological stations fall within the moderate to suitable categories. Five stations such as Byumba, Rubengera, Nyamagabe, Gitega and Kazo are located in moderately suitable areas, indicating some alignment with the optimum placement criteria but with room for improvement. Three stations such as Kawangire, Byimana, and Busogo are located in suitable zones, suggesting they are well placed to meet agrometeorological-monitoring needs. Notably, only one station, Nyagatare, falls in the high suitable zone, implying optimal alignment with the identified suitability factors.

As seen, there are no stations found in low or not suitable areas, which reflects a generally sound placement strategy. However, the limited number of stations in the high suitable category suggests a potential to optimize the network further by relocating or adding stations in those high suitable zones to enhance data quality and spatial coverage.

4.3. Identification of suitable new locations and recommendations for relocation

4.3.1. Suitability model

The suitability map was generated using a GIS-based Spatial Multi-Criteria Evaluation (SMCE) approach, integrating diverse geospatial factors to guide agrometeorological station site selection.

Key criteria included slope, hillshade, elevation, land use/land cover, and proximity to features such as wetlands, lakes, rivers, roads, and existing stations. These were weighted using the Analytic Hierarchy Process (AHP), a structured method for evaluating complex decisions.

A weighted overlay analysis was then applied to classify the study area into five suitability categories: not suitable, low suitable, moderate suitable, suitable, and high suitable. The model aligns with World Meteorological Organization (WMO) standards and international best practices, offering a robust decision-making tool for policymakers to optimize station placement and improve the quality of meteorological data for agriculture, disaster risk reduction, and climate research. Below is the figure 15 that illustrate suitability model

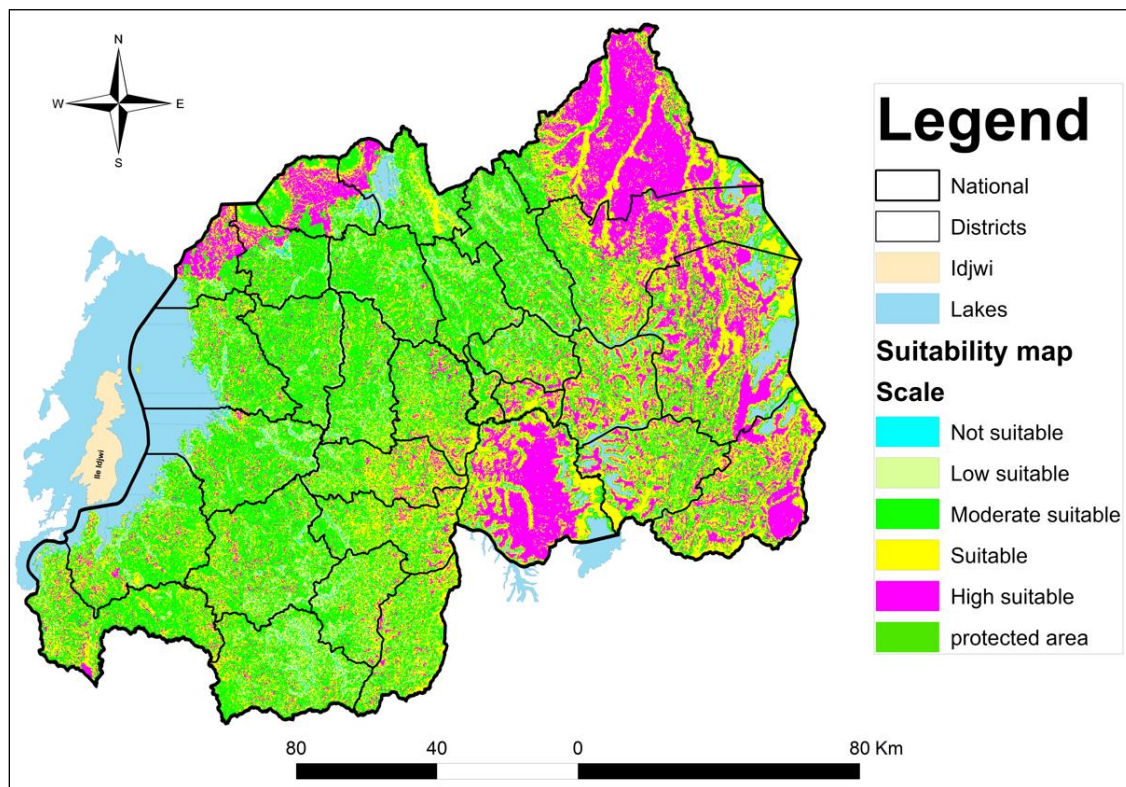


Figure 18: Suitability map

Source: www.geoportal.rwb.rw

The figure 17 presents the suitability analysis for agro-meteorological weather stations in Rwanda, classified into five categories: high suitable, suitable, moderate suitable, low suitable, and not

suitable. High suitability areas are mainly found in eastern, reflecting favorable environmental and infrastructural conditions.

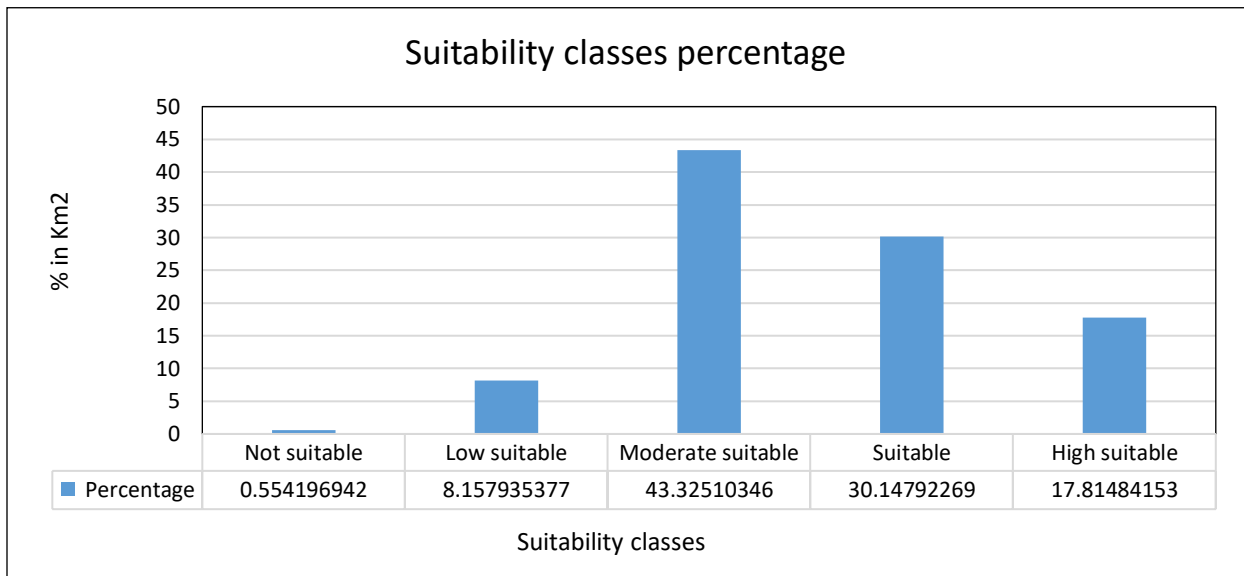


Figure 19: Percentage coverage of suitability classes.

Figure 18. Distribution of land suitability classes for agrometeorological weather station placement in Rwanda. The classification indicates that 0.55% of the land is not suitable, 8.16% is low suitable, 43.33% is moderately suitable, 30.15% is suitable, and 17.81% is highly suitable.4.3.2. Underserved area.

After generating the suitability map, a spatial gap analysis was conducted by overlaying the locations of existing agrometeorological stations, each with a 30 km buffer, onto the map. This analysis helped identify highly suitable areas for station placement that are outside the coverage range of current stations. These highly suitable yet uncovered areas are considered underserved due to the insufficient number of agrometeorological stations in the network. The presence of these gaps clearly shows that the current distribution of stations does not fully meet the coverage needs, and therefore, additional stations are required in these areas to improve spatial coverage, data accuracy, and decision-making in agriculture and climate monitoring. The figure 19, illustrate the served area and underserved suitability classes

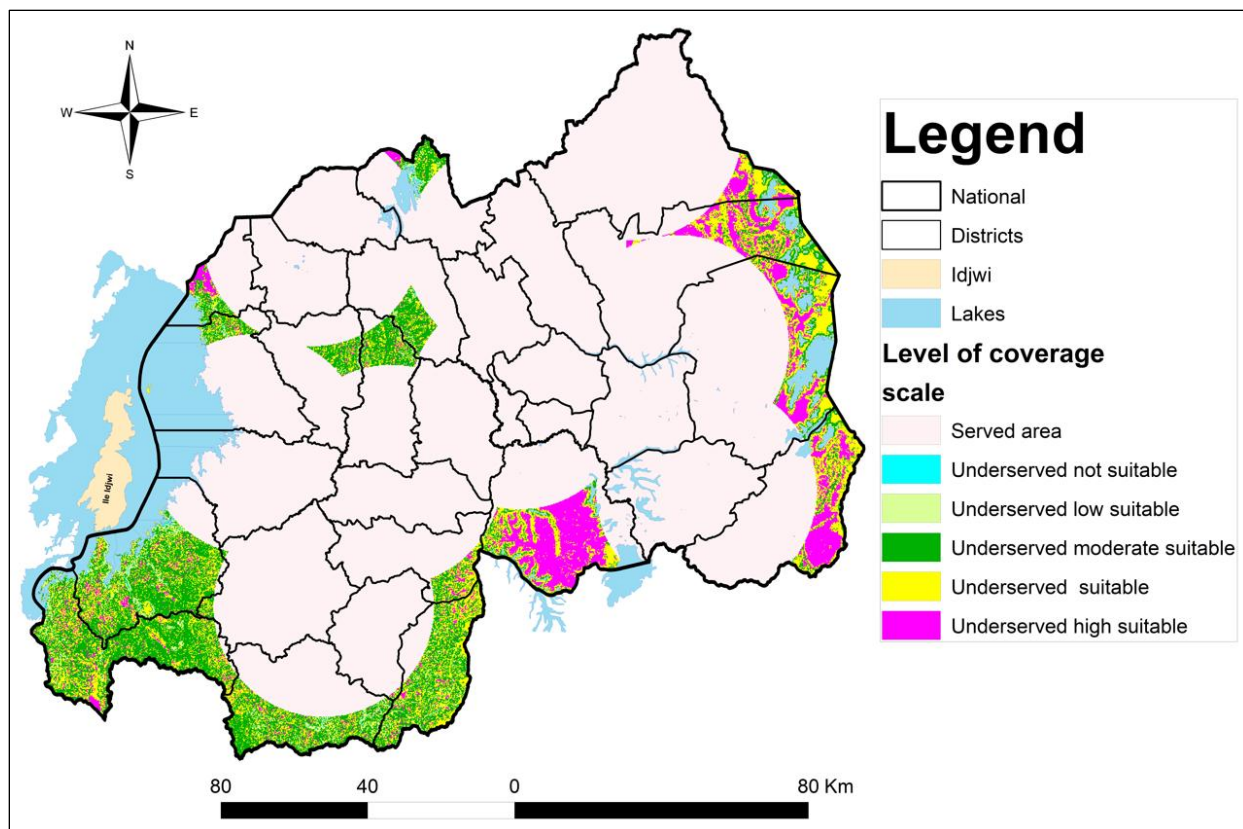


Figure 20: Levels of coverage in underserved area

Source: Rwanda Meteorology Agency (2024)

4.3.3 Site identification

To identify high suitable point site for optimizing the placement of agrometeorological stations, the analysis utilized the highly suitable suitability class across both currently served and underserved areas. Using Feature to Point tool in ArcGIS with the Inside Polygon option enabled, a single representative point was generated for each polygon classified as high suitable. These points indicate the most favourable locations for agrometeorological station installation or relocation.

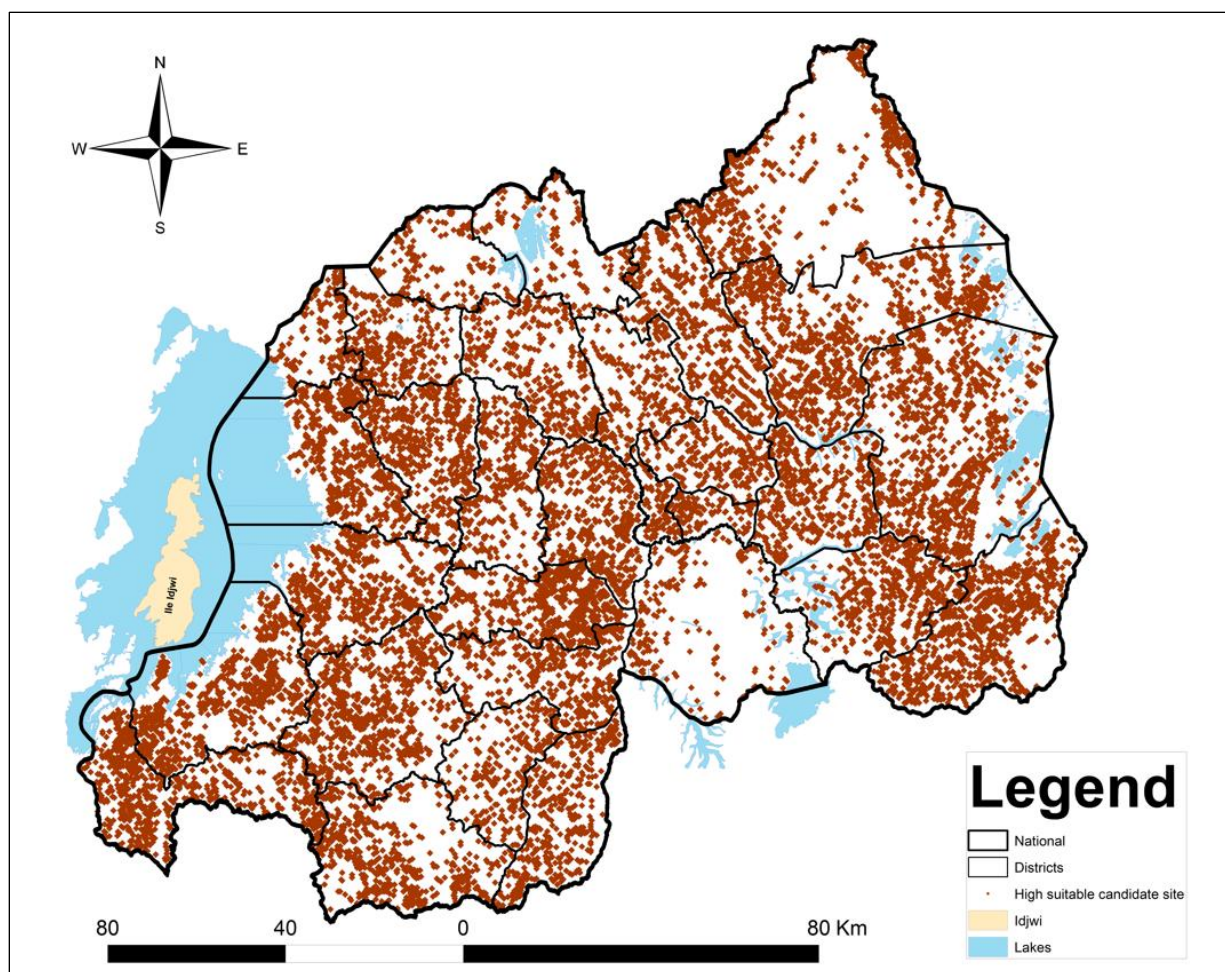


Figure 21: Spatial distribution of high suitable site for agrometeorological stations

Source: www.geoportal.rwb.rw

This approach facilitates the precise identification of optimal sites within each highly suitable area. In particular, it allows for the consideration of relocating existing stations currently situated in moderately suitable zones to these newly identified high-suitability areas. Such relocation is essential to align station placement with Agro-ecological requirements and to improve the spatial accuracy and representativeness of collected meteorological data.

In total, 13,146 points representing highly suitable locations were identified, These points serve as priority candidates for both the relocation of existing stations and the installation of new ones to enhance the overall performance of the agrometeorological network.

4.3.4. Proposed new site

Using conversion tool, layer to KML have applied to served and underserved suitability map. A total of 13,146 highly suitable points were analysed for potential agrometeorological station placement. Although all identified points exhibit a high level of suitability, three specific locations have been prioritized for new station installations in order to minimize data gaps across the country. See the map and table below.

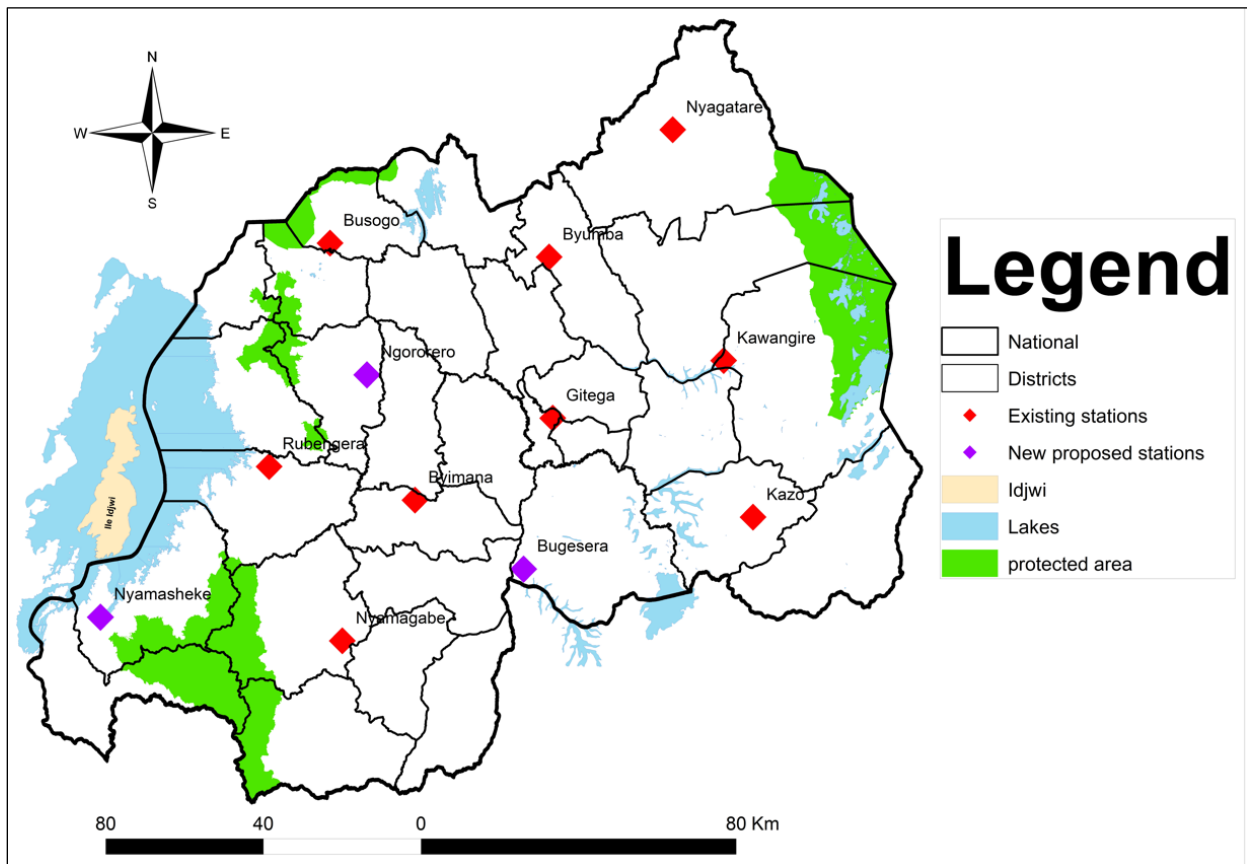


Figure 22: Spatial distribution of existing agrometeorological stations and proposed sites in underserved areas

Source: Rwanda Meteorology Agency (2024) & Field survey, May 2025

Figure 21 illustrates spatial distribution of existing and proposed agro-meteorology stations across Rwanda. The current existing stations are relatively well distributed but exhibit notable gaps, particularly in Nyamasheke, Ngororero, and Bugesera districts. To address these underserved

areas, new stations are proposed, the selection of these sites considers both geographic coverage and the need for climate data in agriculturally important but under-monitored regions. This strategic placement supports enhanced agro-meteorological services, particularly in regions facing climatic variability and lacking observational infrastructure.

Table 9: The spatial location (coordinates) of the new proposed site and their district of destination.

New proposed station site	longitude	latitude
Bugesera	29.991364	-2.302402
Nyamasheke	29.025716	-2.412122
Ngororero	29.634954	-1.835200

Source: Field survey, May 2025

The three proposed agrometeorological station sites in Bugesera, Nyamasheke, and Ngororero Districts were selected based on spatial multi-criteria suitability analysis and their potential to enhance geographic coverage in current underserved areas. Their establishment is expected to enhance the quality and applicability of agrometeorological data in Rwanda, thereby supporting evidence-based decision-making in agriculture and contributing to educational initiatives by providing accurate, local relevant data for training, research, and curriculum development in meteorology and related fields.

The first proposed site, located in Bugesera District, occupies a highly suitable zone identified through spatial analysis. Its strategic position enables it to not only improve coverage within Bugesera but also extend its observation to reach an adjacent regions, including parts of Nyanza and other part of Gisagara Districts. This site is valuable due to Bugesera’s vulnerability to climatic extremes such as droughts. Enhanced agrometeorological data from this site will support more precise monitoring of rainfall, temperature, evapotranspiration, and soil moisture, all of which are essential for managing crop production, irrigation scheduling, and drought preparedness in the region. Moreover, it will provide key inputs to agricultural extension services, early warning systems, and water resource planning.

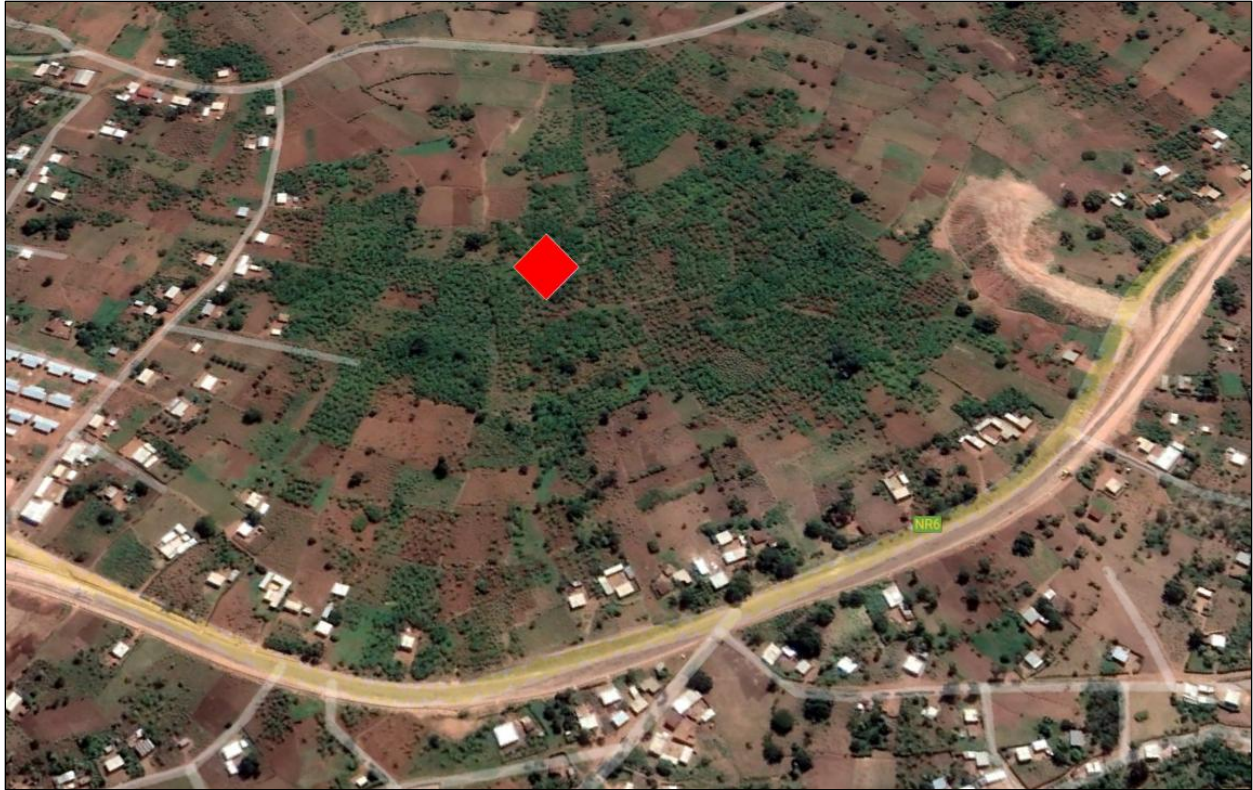


Figure 23: Location of highly suitable proposed site in Bugesera District

Source: Field survey, May 2025 & <https://earth.google.com/>

The second site in Nyamasheke District is surrounded by highly suitable areas for agrometeorological monitoring based on the research. Its proposed position allows it to serve both Nyamasheke and Rusizi Districts. Regions characterized by diverse topography and microclimates. The station will minimize the issues of data gaps in in this region, and improving the spatial density of weather observations. This will facilitate better calibration of Agro-climatic models, enabling accurate weather forecasts and seasonal climate outlooks that are essential for agricultural planning and pest and disease control. The data will also support tea and coffee farming sectors that dominate the region's economy and are highly sensitive to climate variability.



Figure 24: Location of highly suitable proposed site in Nyamasheke District

Source: Field survey, May 2025 & <https://earth.google.com/>

The third proposed station in Ngororero District is located within a cluster of highly suitable zones. It has the potential to address agrometeorological data deficiencies in Ngororero itself as well as in neighbouring Muhanga and Gakenke Districts. These areas are typified by hilly terrain and variable rainfall patterns, necessitating localized weather data to support precision agriculture. The station will enhance monitoring of Agro-climatic parameters, thus supporting sustainable land management, soil conservation initiatives, and agricultural research. In addition, the availability of localized weather data will benefit rural development programs and infrastructure planning.

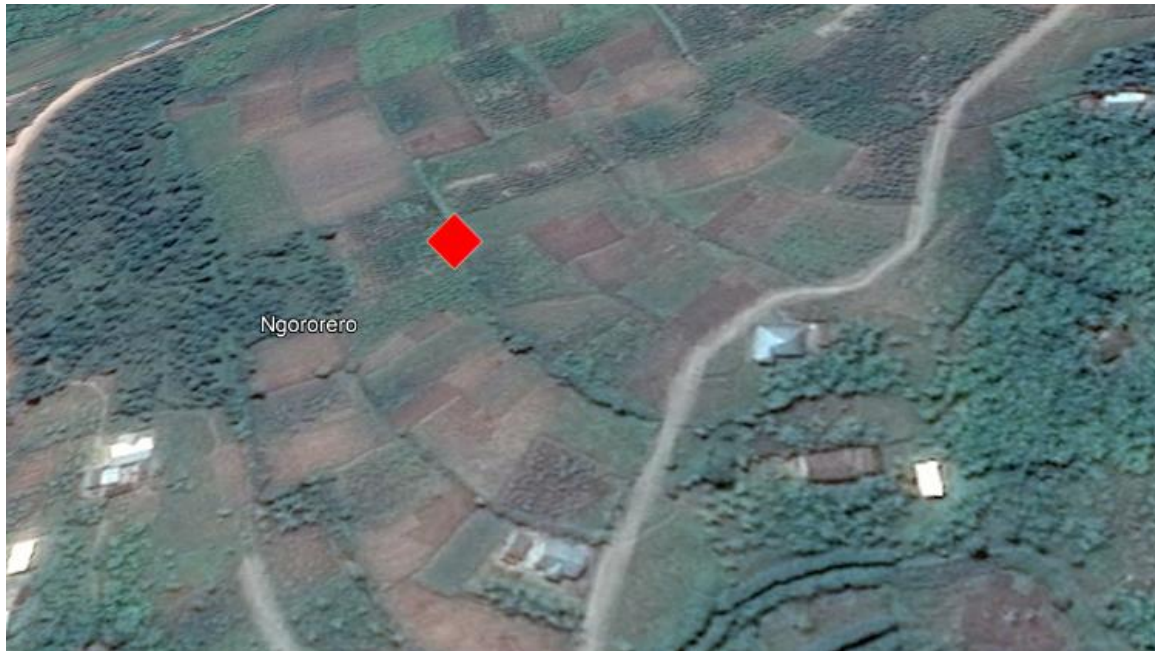


Figure 25: Location of highly suitable proposed site in Ngororero District

Source: Field survey, May 2025 & <https://earth.google.com/>

4.3.5 Proposed relocation site

Suitability analysis indicates that Rubengera, Gitega, Byumba, Gikongoro (Nyamagabe), and Kazo agrometeorological stations fall within the moderately suitable category based on analysed criteria. This classification suggests partial misalignment with the standards recommended by the World Meteorological Organization (WMO). Particularly, Rubengera station is situated within a 100-meter buffer zone from a river, which raises concerns due to the potential influence of nearby water bodies on temperature and humidity readings.

Gitega, Byumba, Gikongoro, and Kazo are positioned within 100 meters of artificial surfaces particular paved roads. Such proximity to non-natural structures is discouraged by the WMO, as it may lead to biased or inaccurate meteorological measurements due to heat retention and radiation reflection. The combined results of the GIS-based suitability analysis and field observations highlight the environmental burdens affecting these stations and suggest the relocation of at least four of them. This recommendation aims to ensure that the stations capture representative regional climatic data rather than localized microclimatic conditions, thereby improving the overall

reliability and usefulness of the agrometeorological data for climate monitoring and agricultural decision-making.

Table 10: High suitable proposed relocation site in four existing agrometeorological weather station

Proposed relocation station site	longitude	latitude	Suitability scale
Rubengera	29.408788	-2.054293	High suitable
Gitega	30.033247	-1.949226	High suitable
Byumba	30.055177	-1.557875	High suitable
Gikongoro (Nyamagabe)	29.530429	-2.486996	High suitable

Source: Field survey, May 2025

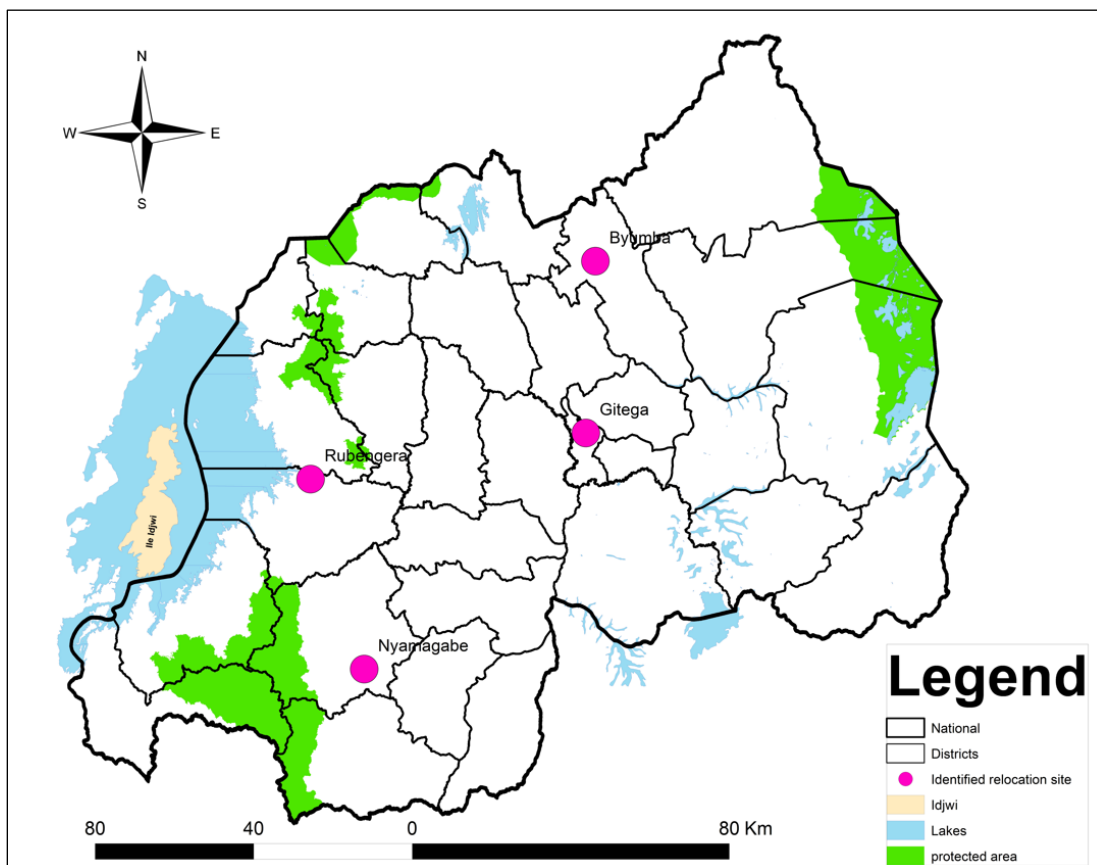


Figure 26: High suitable proposed relocation site for weather stations

Source: Field survey, May 2025 & <https://rwanda.africageoportal.com/>

The proposed relocation points for the agrometeorological weather stations is expected to enhance the accuracy and representativeness of the collected data. By placing the station in a location that is free from artificial surfaces and anthropogenic disturbances such as buildings, paved roads, and concrete structures. The measurements will more accurately reflect the natural climatic conditions of the surrounding agricultural environment. This improved placement ensures that measurements parameters, including temperature, humidity, wind speed, and rainfall, are not influenced by localized heat sources or altered airflow, thereby supporting more reliable and scientific valid data for agricultural planning and research.

High suitable proposed relocation site of Rubengera agrometeorological station

The current location of the Rubengera agrometeorological station is situated in a flood-prone area that experiences seasonal wetness. This is largely due to its proximity to the Musogoro River and its terrain, which displays characteristics typical of wetlands. Based on these hydrological and topographical conditions, the site has been assessed as moderately suitable for agrometeorological monitoring. Such conditions can compromise the accuracy and representativeness of the data collected at this station.

To address this concern, particular attention was given to identifying a suitable site for relocation. Through a comprehensive evaluation using nine suitability criteria, the sites were identified. The proposed locations meet all the evaluated factors, making them high suitable for the relocation of the agrometeorological station.

It is therefore recommended that Meteo Rwanda proceed with relocating Rubengera agrometeorological station to identified sites. Doing that will enhance compliance with WMO standards and guideline, improve the reliability and credibility of the generated data, and ultimately contribute to informed decision-making in agriculture and climate resilience planning. Furthermore, relocation the station will supports national efforts toward sustainable development and resilience-building in the face of climate variability.

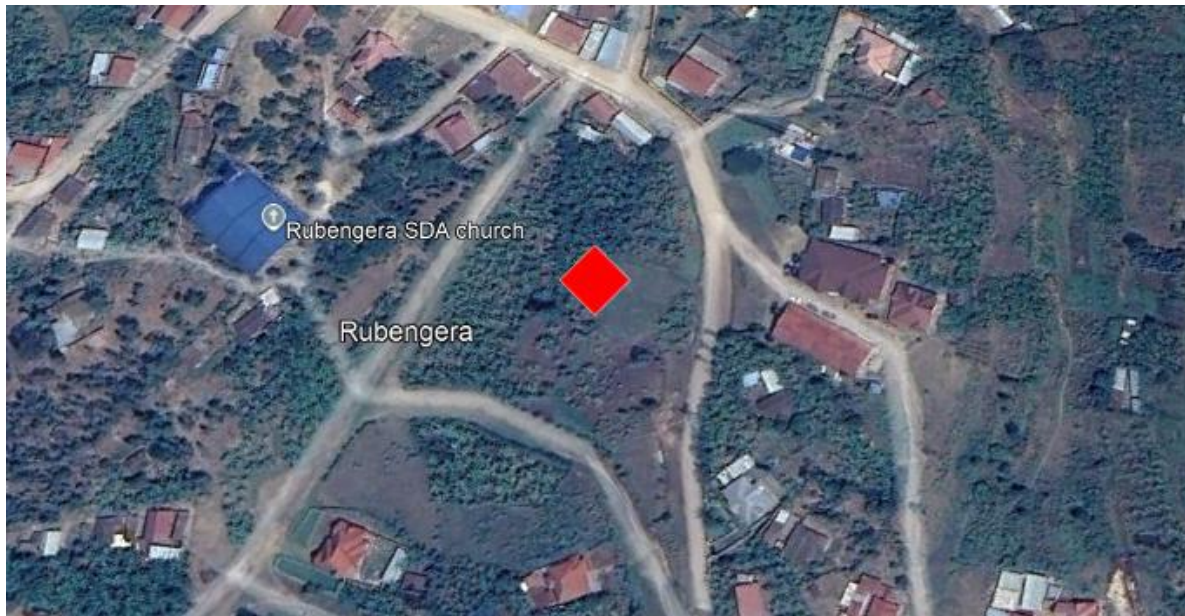


Figure 26: Location of high suitable relocation site for Rubengera agrometeorological station

Source: Field survey, May 2025 & <https://earth.google.com/>

High suitable proposed relocation site of Gitega agrometeorological station

Gitega agrometeorological station is current located within an urbanized area that is undergoing rapid infrastructural development. The surrounding environment is characterized by new constructed paved roads and an increasing volume of vehicular traffic. These urban features contribute to the generation of excess heat, commonly known as urban heat island, which cause a biases in temperature and other meteorological measurements. As a result, the data collected from this station is not accurate represent the climatic conditions of surrounding agricultural zones.

In addition to urban heat effects, the station is affected by the presence of tall trees in close proximity. These trees cast shadows on the Stevenson screen, particularly during critical times of the day, thereby interfering with the accurate recording of temperature. Furthermore, the current position of the station is situated in area, which restricts the observer's ability to view the sky in different directions. This limitation hinder sky condition observations that are important for certain meteorological assessments. Such disturbances reduce the reliability of the station's data, undermining its usefulness for agrometeorological analysis and agricultural planning.

Given these challenges, it is recommended that the Gitega station be relocated to a more stable and agricultural representative area. The new site should be free from urban infrastructure, vehicular emissions, and dense vegetation that could alter or obstruct measurements. Furthermore, a clearly defined buffer zone should be established around the station to protect it from future encroachments or developments that could distort climatic observations. This buffer zone would serve as a safeguard, ensuring long-term data integrity and accuracy.



Figure 27: Location of high suitable relocation site for Gitega agrometeorological station

Source: Field survey, May 2025 & <https://earth.google.com/>

High suitable proposed relocation site of Byumba agrometeorological stations

The current location of the Byumba Agrometeorological Weather Station presents several limitations that compromise the quality and reliability of its recorded observations. The station is positioned in close proximity to paved roads and regular vehicular movement. This setting exposes the instruments to artificial influences such as increased surface temperatures and dust, which affect the accuracy of temperature, and other weather parameter measured at this station.

In addition, the station is surrounded by abstraction (trees) in close proximity. These obstructions not only interfere with the airflow and solar radiation measurements but also restrict visibility of the sky from the station. As a result, the observer stationed there is unable to make reliable visual observations of the sky, such as cloud type, cloud cover, or atmospheric phenomena which is an essential part of manual meteorological reporting. Based on this challenges I suggest resolving measures to this issues by proposing a high suitable relocation site which will limit all the challenges observed on the current site. The new identified site is extracted from 13146 points of high suitable based on the analyses at it is chosen based on its strategic position to comply with WMO standards.



Figure 28: Location of high suitable relocation site for Byumba agrometeorological station

Source: Field survey, May 2025 & <https://earth.google.com/>

High suitable proposed relocation site of Gikongoro agrometeorological stations

Gikongoro weather station is classified as moderately suitable due to its failure to meet essential siting standards. particular, the station is located within 100 meters of a paved road and situated on a slope exceeding 19 degrees. These two conditions violate standard for weather station placement.

Proximity to artificial surface (paved roads) influences heat, dust, and pollution, which distort temperature and other weather measurement. Similar to a steep slopes affect the accuracy of meteorological data by altering wind patterns, radiation exposure, and runoff behaviour. These environmental interferences reduce the representativeness and reliability of the recorded data.

As a result, the station's current location compromises the quality and precision of agrometeorological information, affecting agricultural planning and climate analysis. To enhance data accuracy and ensure compliance with international standards, the station should be relocated to a more appropriate site.



Figure 29: Location of high suitable relocation site for Gikongoro agrometeorological station

Source: Field survey, May 2025 & <https://earth.google.com/>

Comparison of existing, new proposed, and relocation sites based on suitability criteria

The map below integrates the spatial assessment of existing and potential locations for agrometeorological weather stations, highlighting zones classified as high suitable. It distinguishes between current preferred existing stations, proposed new installation points, and suggested relocation areas, based on compliance with siting criteria such as slope, elevation, hillshade, land use/land cover, wetlands, roads, lakes, rivers, and existing agrometeorological stations.

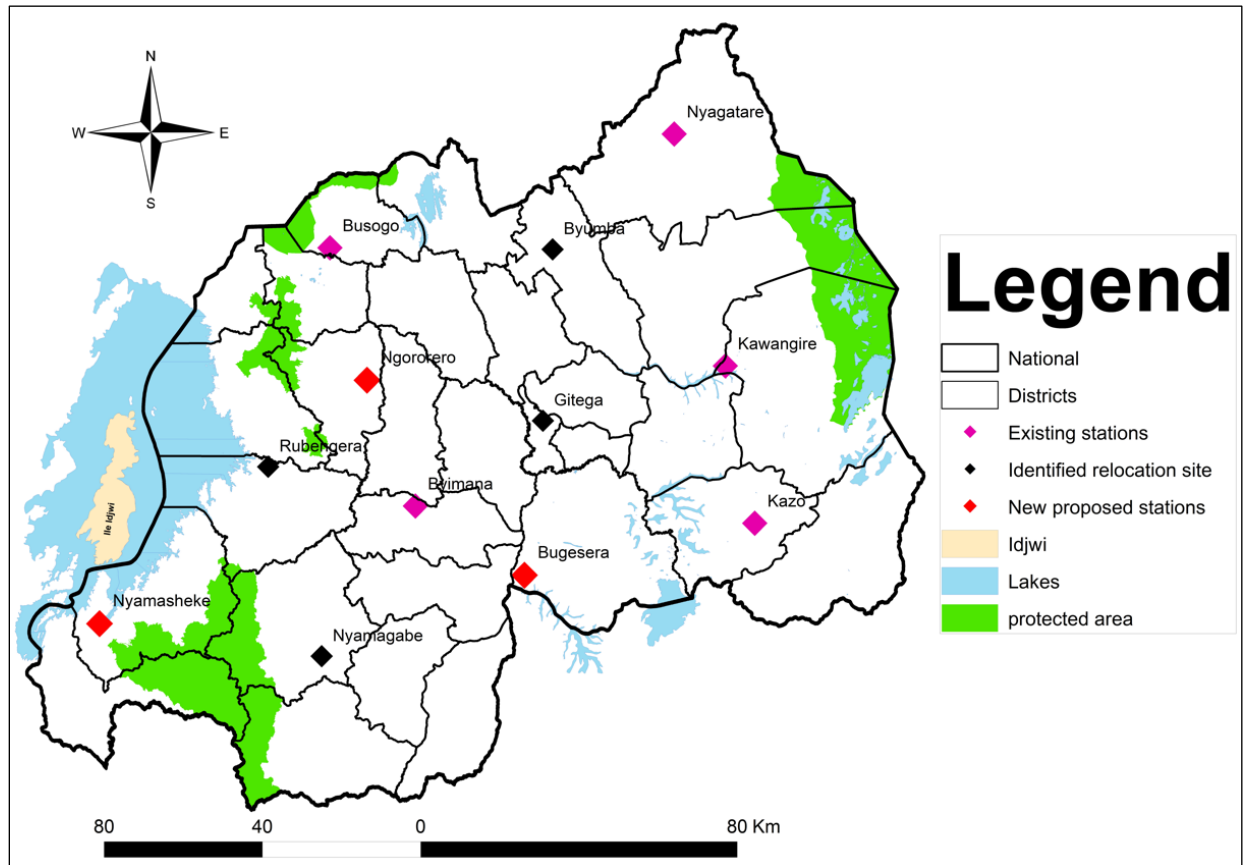


Figure 30: Distribution of preferred existing weather stations, new proposed stations, and stations proposed for relocation

Source: Rwanda Meteorology Agency (2024)

Spatial suitability analysis for agrometeorological weather station siting, an enhancement the distribution of weather stations across the country. Involves the strategic relocation of certain existing stations, the installation of new stations in underrepresented areas, and the maintenance of current optimal stations. In particular, the establishment of protective measures to minimize the

influence of anthropogenic activities, thereby ensuring data integrity, should support the preservation of preferred existing stations. Such a reconfiguration will enable the generation of reliable and timely weather and climate information, which is important for socio-economic development of Rwanda. Well-distributed and scientific sited weather stations will not only support agricultural planning by providing site-specific climate data but will also improve disaster preparedness and risk management.

5. DISCUSSION

5.1 Integration of Suitability Criteria with International Best Practices

This study applied GIS based spatial multi-criteria evaluation approach, guided by Analytical Hierarchy Process (AHP) weights, to assess the optimum placement of agrometeorological stations in Rwanda. The selected criteria including slope, elevation, hillshade, land use/land cover (LULC), proximity to roads, wetlands, existing agrometeorological weather stations and waterbodies such as lakes and rivers. These factors are strong align with international siting standards, particularly those outlined by the World Meteorological Organization (World Meteorological Organization, 2014, 2012).

Slope was given the highest weight in the AHP analysis. This is consistent with the work done by (Rojas Briceño et al., 2021), who demonstrated that steep terrain alters wind speed, increases runoff, and generates localized temperature variability, thereby compromising the quality of meteorological observations. Likewise, proximity to water bodies was shown to be problems. Studies have established that areas near rivers or wetlands often exhibit atypical humidity and temperature profiles that are not representative of broader agro-ecological zones (Alejo, 2018; Iakunin, 2022). These microclimatic effects distort data when stations are placed too close to such features.

The influence of anthropogenic infrastructures such as roads was also an important consideration. Weather stations located near heat-absorbing surfaces like asphalt experience elevated temperature readings due to thermal radiation (Jabbar et al., 2023), a concern echoed in WMO guidelines, which recommend a minimum 100 meter buffer from such surfaces (World Meteorological Organization, 2014).

5.2 Limitations of Existing Station Locations

Spatial analysis revealed that several existing stations in Rwanda violate international siting standards. Notably, Rubengera station is situated within 15 metres of a river, exposing it to flood risks and microclimatic anomalies that can skew humidity and temperature readings (Felipe et al., 2024; NiuBoL, 2024). Likewise, Gitega, Byumba, and Nyagatare station are located adjacent to paved surfaces, contradicting WMO and Environmental Protection Agency (EPA)

recommendations, which emphasise the need for a 100-metre buffer from artificial heat-emitting surfaces (Scientific, 2015).

These misplacements mirror findings in other developing contexts, such as Ethiopia and Kenya, where stations near wetlands or urban centres exhibited inconsistent data due to thermal or moisture bias (Felipe et al., 2024; Gebreegziabher et al., 2023). Such similarities highlight a broader global issue and reinforce the urgency of reviewing Rwanda's current station network

5.3 Spatial and elevation gaps in network coverage

The study also identified a notable spatial imbalance in the distribution of stations across elevation zones. Most stations are concentrated in mid-altitude zones (1,500–3,000 m), with no representation above 3,000 metres. This imbalance undermines climate monitoring in Rwanda's highland areas, where weather variability and lapse rates are more pronounced (Minder, 2010). Ensuring coverage across different elevation bands is essential, particularly for crops sensitive to climatic variations, such as potatoes, wheat, and pyrethrum (World Meteorological Organization, 2012)

Similar challenges have been noted in Central America, where station clustering around urban centres failed to reflect the full spectrum of agro-ecological variability (Fonseca et al., 2019). Without correction, this uneven distribution may compromise forecasting accuracy and limit adaptive responses to climate risks.

5.4 Validity of Suitability Model and Strategic Site Recommendations

The suitability model developed using a GIS-based Spatial Multi-Criteria Evaluation (SMCE) approach, guided by AHP weighting, and has demonstrated strong alignment with international methodologies. Similar approaches have been successfully applied in Peru (Rojas Briceño et al., 2021), highlighting the transferability and scientific validity of this model.

The identification of over 13,000 high-suitability points across the country suggests significant potential for network expansion and optimization. These findings are highly important in the context of underserved areas such as Bugesera, Nyamasheke, and Ngororero district, where climate vulnerabilities are high due to erratic rainfall, drought, and topographical constraints.

Expanding the agrometeorological network into these regions aligns with Rwanda's National Strategy for Transformation (NST1) and the National Climate Change Policy, which emphasize strengthening climate information services for improved agricultural productivity and resilience (GoR, 2017; Ministry of Environment Rwanda, 2019). Enhanced station coverage will not only improve spatial data resolution and reduce forecasting uncertainties but also support District Development Strategies (DDSs) by enabling localized climate-smart agricultural planning and early warning systems. This is essential for achieving the goals outlined in Rwanda's National Adaptation Plan (NAP) and the Green Growth and Climate Resilience Strategy (GGCRS), which underscore the need for robust, decentralized climate data to inform evidence-based decision-making at both local and national levels (Government of Rwanda, 2006; Republic of Rwanda, 2022).

5.5 Implications of Proposed Relocation and Expansion

Relocation of stations currently situated in moderately suitable areas such as Rubengera, Gitega, and Byumba to new identified high suitable zones is justified not only by WMO standards but also by empirical evidence from similar relocation studies. For instance, the study done in Visayas Region, Philippines found that relocating stations from urban or river adjacent locations to rural, unobstructed zones improved data consistency and forecast reliability (Alejo, 2018).

The proposed installation of agrometeorological stations in Bugesera, Nyamasheke, and Ngororero is critical due to the districts' climatic diversity and agricultural importance. These regions frequently experience droughts, erratic rainfall, and topography-induced microclimates, which limit the effectiveness of national-scale forecasts. Localized weather stations will enhance early warning systems, irrigation planning, and precision agriculture by providing high-resolution data tailored to local conditions (Gather & Wollni, 2024; Nkurunziza et al., 2023).

6. CONCLUSION AND RECOMMENDATION

This study aimed to optimize the placement of agrometeorological weather stations in Rwanda using a spatial multi-criteria evaluation (SMCE) approach. The methodology was guided by WMO guidelines and standards. Particularly, the Guide to Agricultural Meteorological Practices (WMO-No. 134), as well as other relevant scientific publications.

Nine important criteria were identified as essential for determining suitable locations for agrometeorological stations such as slope, hillshade, elevation, proximity to lakes, proximity to rivers, wetlands, land use and land cover, accessibility (proximity to roads), and existing station distribution. Each criteria was assigned a weight using the Analytic Hierarchy Process (AHP), based on its relative importance to the performance and accuracy of agrometeorological measurements. The weights assigned were as follows: slope (24%), lakes (20%), wetlands (16%), elevation (9%), rivers (10%), accessibility (7%), land use and land cover (6%), hillshade (5%), and existing station distribution (3%).

An individual assessment of each criteria was carried out to evaluate the extent to which existing stations comply with optimal placement conditions. The analysis, supported by field observations, revealed that several current stations do not meet the recommended criteria and are therefore sub-optimally located.

All criteria were then integrated using a weighted overlay analysis. The results highlighted spatial gaps in the current network, especially in important agriculture areas. The study identified optimal locations for new station installations and found that approximately 17.8% of Rwanda's territory (4,487 km² out of 25,187 km²) is highly suitable for agrometeorological weather stations.

These findings offer valuable insights for enhancing Rwanda's agrometeorological network. A well-optimized network is crucial for accurate climate monitoring, effective early warning systems and the contribution to sustainable agricultural practices. Despite some limitations related to data availability, the approach presented in this study provides a robust and replicable framework that can be adapted for other regions.

This study recommends that future agrometeorological weather stations in Rwanda will be better when located in areas identified as high suitable through spatial multi-criteria evaluation using analytical hierarchy process (AHP) approach. These areas were determined based on a

combination of topographic factors, land use and land cover, accessibility, proximity to waterbodies, wetlands, and existing stations. To improve the accuracy and spatial representativeness of meteorological data, it is also recommended that stations currently situated in moderately suitable zones be relocated to nearby highly suitable areas.

Further refinement of the placement strategy can be achieved by incorporating additional factors such as obstructions (e.g., trees and buildings) and detailed agricultural zoning in future research. Notably, this study represents the first application of such a comprehensive and spatial grounded methodology for weather station optimization, thereby establishing a valuable foundation for evidence-based decision-making, policy development, and future scholar inquiry. Moreover, the proposed framework offers a practical and adaptable tool that can be extended to other regions facing similar agrometeorological planning challenges.

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Annexes

Annex 1. Research matrix

The research matrix outlined below provides a systematic framework that aligns the research objectives with their corresponding research questions, anticipated data requirements, and appropriate methods and data sources.

Research objective	Research question	Methods and data source	Expected data
1. To identify the established criteria in evaluating the suitability of agro-meteorological weather station locations in Rwanda.	1. How can established criteria be applied to evaluate the suitability of agro-meteorological weather station locations in Rwanda?	<p>Review of the literature about WMO guidelines on agro- meteorological station placement.</p> <p>Review of the literature on criteria that are used in the existing publication for optimum placement of agro-meteorological stations on various countries.</p> <p>Proximity analyses, weighted overlay analyses, AHP and SMCE</p>	<p>Description of WMO standard/ Guideline for agro-meteorological weather station placement.</p> <p>A summarized table showing others criteria applied for suitability analyses on different regions</p> <p>Factor influencing the suitability of weather station placement</p>

<p>2. To assess the alignment of existing agro-meteorological weather stations with optimum placement criteria.</p>	<p>2. To what extent do the existing agro-meteorological weather stations comply with established optimal placement criteria?</p>	<p>Review of documented Metadata of existing agro-meteorological weather stations.</p> <p>Field observation on all agro- meteorological weather stations to observe their compliance with guideline and standards</p>	<p>A comprehensive summary of current agrometeorological weather station locations (coordinates and status)</p> <p>An overview of the existing network's spatial distribution and coverage.</p> <p>-A mapping analysis showing the alignment between existing station locations and the optimal criteria.</p>
<p>3. To identify suitable location for new agro-meteorological weather stations and recommend relocations where necessary.</p>	<p>3. Where are the most suitable locations for new agro-meteorological weather stations and which existing stations require relocation?</p>	<p>Carry out site inspections and field surveys to validate suitability.</p> <p>Analyze literatures on best practices in weather station siting and relocation strategies.</p>	<p>Spatial analysis to pinpoint undeserved area for station</p> <p>A GIS-based assessment of new sites that meet the standards.</p> <p>Detailed justification for recommended relocations, outlining expected benefits in terms of data quality.</p>

Annex 2: work plan

NO	Legend	color	Year										
	Activities in progress		2024	2025									
	Activities completion		Month										
	Activity	N	D	J	F	M	A	M	J	J	A		
1	Topic formulation												
2	Proposal writing												
3	Proposal defense												
4	Literature review												
5	Data collection and analyses												
6	Result interpretation and discussion												
7	First draft submission												
8	Final thesis submission												
9	Thesis defense												

Annex 2 provides a structured timeline outlining the progression of the research from topic formulation to thesis defense. The phased approach ensures that each stage including proposal development, data collection, analysis, and report writing are completed within the given timeframe

Annex 3. Factors and possible criteria setting

Land use/ land cover	Suitability scale	Scale value	The corresponding evaluation scale in the weighted overlay set from 1 to 9, with an interval of 1
Open Areas or Grass, Bare Soil	Highly Suitable	1	9. Most suitable
Agriculture (Seasonal)	Suitable	2	7. Very suitable
Sparse forest,	Moderately Suitable	3	5. Moderate suitable

Agriculture (Perennial), Wetlands,	Low suitable	4	3. Less suitable
Forest, Water, Mines, Settlements and Building	Not Suitable	5	1. Least suitable
Slope(degrees)	Suitability scale	Scale value	
0 - 5	Highly Suitable	1	9. Most suitable
5 - 15	Suitable	2	7. Very suitable
15 - 19	Moderately Suitable	3	5. Moderate suitable
19 - 25	Low suitable	4	3. Less suitable
>25	Not Suitable	5	1. Least suitable
Hillshade	Suitability scale	Scale value	
200 - 254	Highly Suitable	5	9. Most suitable
150 - 200	Suitable	4	7. Very suitable
100 - 150	Moderately Suitable	3	5. Moderate suitable
50 - 100	Low suitable	2	3. Less suitable
0 - 50	Not Suitable	1	1. Least suitable
Proximity to the lakes (m)	Suitability scale	Scale value	
>1000	Highly Suitable	5	9. Most suitable
500 - 1000	Suitable	4	7. Very suitable
300 - 500	Moderately Suitable	3	5. Moderate suitable
100 - 300	Low suitable	2	3. Less suitable
0 - 100	Not Suitable	1	1. Least suitable
Proximity to the rivers (m)	Suitability scale	Scale value	
>800	Highly Suitable	5	9. Most suitable
500 - 800	Suitable	4	7. Very suitable
200 - 500	Moderately Suitable	3	5. Moderate suitable
100 - 200	Low suitable	2	3. Less suitable
0 - 100	Not Suitable	1	1. Least suitable
Proximity to the roads (m)	Suitability scale	Scale value	
>500	Moderately Suitable	5	5. Moderate suitable

300 - 500	Highly Suitable	4	9. Most suitable
200 - 300	Suitable	3	7. Very suitable
100 -200	Low suitable	2	3. Less suitable
0 - 100	Not Suitable	1	1.Least suitable
Proximity to the existing Stations (km)	Suitability scale	Scale value	
>30	Highly Suitable	4	9. Most suitable
20 - 30	Suitable	3	7. Very suitable
10 - 20	Moderately Suitable	2	5. Moderate suitable
0 - 10	Low suitable	1	3. Less suitable
Wetlands	Suitability scale	Scale value	
>800	Highly Suitable	5	9. Most suitable
500 - 800	Suitable	4	7. Very suitable
200 - 500	Moderately Suitable	3	5. Moderate suitable
100 - 200	Low suitable	2	3. Less suitable
0 - 100	Not suitable	1	1.Least suitable
Elevation	Suitability scale	Scale value	
804 - 1500	Highly Suitable	1	9. Most suitable
1500 - 3000	Suitable	2	7. Very suitable
3000 - 3500	Moderate Suitable	3	5. Moderate suitable
3500 - 4480	Low suitable	4	3. Less suitable

Annex 3 presents the factors considered in determining suitable sites for agro-meteorological stations. Criteria such as land use, slope, hillshade, elevation, and proximity to water bodies, roads, and existing stations are systematic categorized using suitability scales. It also show the scale value used in reclassifying the criteria and **The corresponding evaluation scale in the weighted overlay set from 1 to 9, with an interval of 1 that have applied.**

Annex 4. Questionnaire survey

AHP Pairwise Comparison Questionnaire

Study Title: Nationwide Optimization of Agro-Meteorological Weather Stations Placement Using Spatial Multi-Criteria Evaluation.

Purpose: This questionnaire is designed to collect expert judgments for the pairwise comparison of criteria influencing the optimal placement of agro-meteorological weather stations in Rwanda. The Analytic Hierarchy Process (AHP) method will be used to derive weights for each criterion.

Instructions: For each pair of criteria, please indicate which one is more important with respect to optimizing agro-meteorological station placement, and how much more important it is on a scale of 1 to 9 based on Saaty's scale:

Pairwise Comparison Questions

No.	Criteria A	Criteria B	Which criterion is more important (A or B)?	Importance (1–9)
1	Slope	Lakes	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
2	Slope	Wetlands	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
3	Slope	Rivers	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
4	Slope	Elevation	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
5	Slope	Roads	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9

6	Slope	Land Use/Land Cover	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
7	Slope	Hillshade	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
8	Slope	Existing Stations	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
9	Lakes	Wetlands	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
10	Lakes	Rivers	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
11	Lakes	Elevation	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
12	Lakes	Roads	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
13	Lakes	Land Use/Land Cover	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
14	Lakes	Hillshade	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
15	Lakes	Existing Stations	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
16	Wetlands	Rivers	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9

17	Wetlands	Elevation	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
18	Wetlands	Roads	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
19	Wetlands	Land Use/Land Cover	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
20	Wetlands	Hillshade	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
21	Wetlands	Existing Stations	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
22	Rivers	Elevation	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
23	Rivers	Roads	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
24	Rivers	Land Use/Land Cover	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
25	Rivers	Hillshade	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
26	Rivers	Existing Stations	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
27	Elevation	Roads	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9

28	Elevation	Land Use/Land Cover	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
29	Elevation	Hillshade	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
30	Elevation	Existing Stations	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
31	Roads	Land Use/Land Cover	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
32	Roads	Hillshade	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
33	Roads	Existing Stations	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
34	Land Use/Land Cover	Hillshade	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
35	Land Use/Land Cover	Existing Stations	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9
36	Hillshade	Existing Stations	<input type="checkbox"/> A <input type="checkbox"/> B	<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6 <input type="checkbox"/> 7 <input type="checkbox"/> 8 <input type="checkbox"/> 9

Thank you for your participation. Your expert input is vital for improving the spatial planning and efficiency of agro-meteorological stations in Rwanda.