# Geospatial Mapping and Assessment of Weather Stations for Enhanced Weather Event Reporting in Zambia

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**ABSTRACT**
**The limited spatial distribution of weather stations in Zambia continues to hinder timely and accurate weather reporting, particularly in remote and rural regions. This inadequacy affects sectors such as agriculture, disaster risk management, and climate adaptation planning. This paper proposes a geospatial assessment framework that leverages buffer analysis to identify spatial gaps in Zambia's weather monitoring infrastructure. Each weather station was assigned a 100 km coverage radius, and a subtraction algorithm was applied against the national boundary to expose uncovered regions. These gaps were visualized in a Flutter-based mobile application that integrates real-time station metadata and interactive mapping. Results reveal significant regional disparities, particularly in North-Western and Western provinces. This system supports data-driven decisions on new station deployments and contributes to early warning systems, sustainable development, and digital meteorological services. The work builds upon previous digital spatial mapping systems such as those used for locust detection [1], integrating them with meteorological use cases to enhance Zambia's climate resilience.**
**Keywords:** ***Geospatial analysis, spatial coverage gap, weather monitoring, buffer method, mobile GIS, Zambia, climate resilience.***

## INTRODUCTION

Weather data has become increasingly critical in mitigating the impacts of climate change, ensuring food security, and supporting national planning across diverse sectors. However, in many low- and middle-income countries, weather station infrastructure remains sparse, outdated, or unevenly distributed—exacerbating vulnerability to extreme weather events and long-term climate variability [1], [2]. Sub-Saharan Africa, including Zambia, is particularly exposed due to vast unmonitored rural expanses, limited technological integration, and budgetary constraints on meteorological institutions.

In Zambia, agriculture contributes over 20% to GDP and employs nearly two-thirds of the population [3]. Yet, rainfall variability, temperature anomalies, and late warnings of drought or flooding continue to damage crop yields, displace communities, and disrupt economic activity. Accurate weather data is not just a technical requirement but a developmental necessity. Thus, enhancing meteorological reach through geospatial intelligence and digital innovation has emerged as a national priority.

Several studies have explored geospatial analytics for environmental monitoring. Halubanza et al. [4] used spatial data to track locust movements in Sikaunzwe District using IoT sensors and mobile GIS, proposing scalable models for ecological surveillance. Their work in designing low-cost monitoring frameworks with automated alerting mechanisms [5] supports the feasibility of localized, real-time decision systems. These precedents offer strong relevance to meteorological infrastructure mapping, which likewise depends on timely, spatially-grounded sensing.

Internationally, researchers have used GIS-based buffer analyses to identify optimal locations for weather stations and assess coverage gaps [6], [7]. However, many such studies are constrained to high-income nations with dense data availability and lack applicability to African terrain and connectivity limitations. Moreover, very few integrate such analyses into mobile applications or citizen-focused tools—an innovation this study seeks to introduce.

This paper presents a geospatial mapping and assessment framework for weather stations in Zambia. It uses buffer subtraction techniques to reveal underserved areas, visualizes spatial gaps on an interactive Flutter-based mobile app, and offers data to support policy makers, researchers, and national weather services in optimizing station placement. The system aims to increase climate resilience by supporting early warnings and adaptive planning at both national and community levels.

# RELATED LITERATURE AND EXISTING SYSTEMS

The deployment of weather stations and the use of Geographic Information Systems (GIS) for climate monitoring have been extensively studied across various contexts. International efforts have focused on optimizing station placement through spatial modeling and coverage analysis. Dinku et al. [1] employed Voronoi diagrams and buffer overlap techniques to assess spatial redundancy and coverage gaps in East Africa's meteorological infrastructure. Similarly, Lei et al. [2] used GIS-based optimization algorithms to determine the most efficient distribution of ground-based sensors in densely populated regions of China.

While such efforts provide useful technical baselines, they are often conducted in data-rich environments with minimal terrain or network constraints. Their models may not be directly transferable to countries like Zambia, where rugged landscapes, limited rural connectivity, and budget limitations impede uniform station deployment.

To address this disparity, Halubanza et al. [3] developed a low-cost IoT-based locust monitoring system in Kazungula, Zambia. Their approach integrated spatial data acquisition with mobile phone alerts, demonstrating the potential of hybrid GIS-sensor solutions in under-resourced ecological contexts. In a related study, Halubanza and colleagues applied quantized MobileNet V2 neural networks to detect Locusta migratoria using geolocated sensor imagery, further proving the utility of localized spatial intelligence for real-time monitoring [4].

Other regional studies have proposed digital frameworks for event-based early warning systems using spatially aware data mining [5]. These systems, initially built for entomological or agricultural threats, highlight the transferability of GIS and buffer-based techniques to other domains like weather monitoring. Furthermore, mobile applications have emerged as effective tools for bridging accessibility gaps in remote sensing. A recent system developed by Chembe and Halubanza [6] used Flutter to build a waste management monitoring tool with embedded location tracking, illustrating cross-domain applicability of mobile GIS.

From a policy standpoint, Zambia's weather services have acknowledged the need for spatial planning in meteorological infrastructure. However, most existing tools are either paper-based or use static maps, lacking real-time interactivity or algorithm-driven coverage modeling. As such, there remains a gap in research and implementation around interactive, mobile-accessible, GIS-integrated tools specifically tailored for Zambia's weather station network.

This study fills that gap by combining buffer-based spatial analytics with a Flutter mobile frontend and dynamic map rendering to support decision-making around weather station deployment. It contributes to the growing body of literature emphasizing locally relevant, cost-effective, and digitally accessible climate technologies.

# METHODOLOGY

The methodology for this study comprises three main components: geospatial buffer analysis, spatial subtraction for gap detection, and mobile-based visualization. The goal is to identify underserved regions in Zambia's national weather monitoring network using spatial analytics and present the findings through a user-friendly mobile application.[3]

### *A. Geospatial Data Collection*

The spatial coordinates and metadata of existing weather stations were compiled from the Zambia Meteorological Department in CSV format, including longitude, latitude, station name, and administrative zone. The national boundary shapefile for Zambia was sourced from the Global Administrative Areas (GADM) database. These datasets were loaded into a GIS environment using QGIS and further processed via Python scripts (GeoPandas, Shapely).

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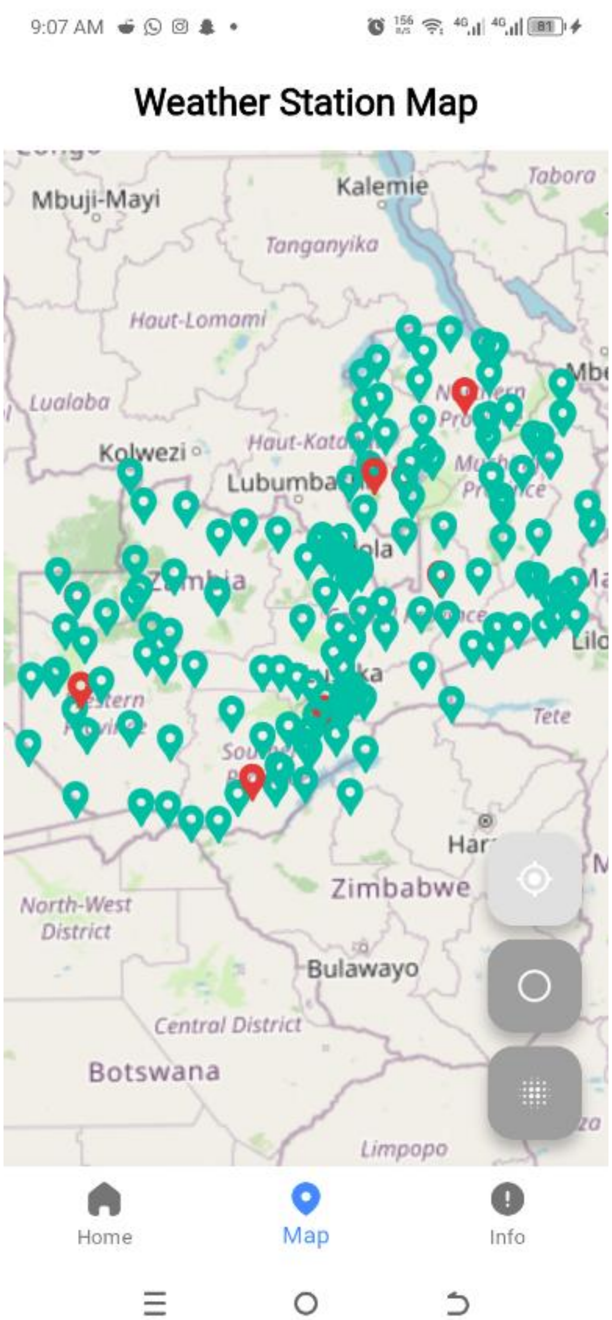


*Figure 1 Geospatial Distribution of Weather Stations in Zambia*

B. Buffer Analysis

Each weather station was assigned a buffer radius of 100 km, representing an ideal coverage area under typical synoptic observation guidelines [1]. The buffers were constructed as circular polygons around each station using Euclidean distance calculations.

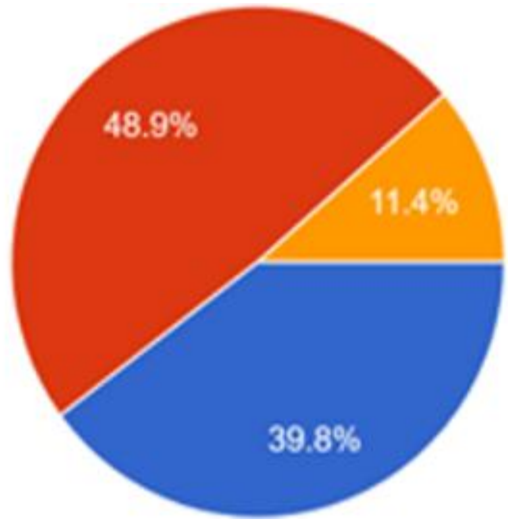


*Figure 2 Station Buffer Creation*

This approach is consistent with spatial modeling done in environmental and locust tracking systems by Halubanza et al. [2], who similarly employed buffer zones to estimate device coverage for IoT sensors.

*C. Subtraction Algorithm and Gap Extraction*

To identify unmonitored regions, the union of all buffer areas was subtracted from the national boundary polygon using topological difference functions. The resulting polygons represented geospatial coverage gaps, i.e., regions of Zambia not


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within 100 km of any weather station.

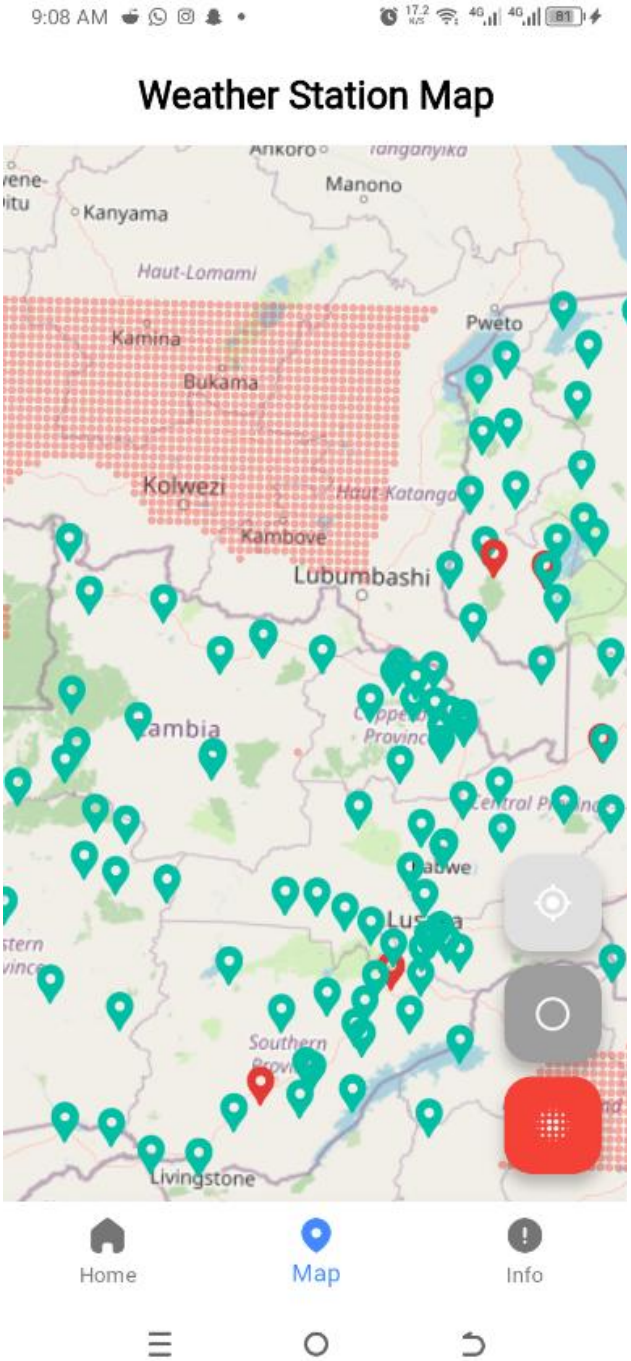


*Figure 3 highlights uncovered areas after buffer subtraction*

This subtraction method was inspired by similar implementations in early warning systems for vector-borne diseases [3] and locust detection in Zambia's Southern Province [4].[6]

*D. Visualization on Mobile App*

The final step involved overlaying the gap regions on a Flutter-based mobile application. The app integrates the Leaflet JS library and supports:

- Real-time weather station data display
- Interactive map browsing
- Station metadata popups
- Offline caching of geospatial layers

The application interface and backend were modeled after prior work by Chembe and Halubanza [5], who built a mobile waste monitoring dashboard with integrated spatial feeds.

*E. Diagram of Processing Pipeline*

The figure above illustrates the complete processing pipeline, from raw data input to mobile visualization. The modular design allows for scalability and integration with additional environmental or sensor layers in future iterations.

# IV. RESULTS AND DISCUSSION

*A. Spatial Coverage Analysis*

- The buffer analysis revealed that a significant portion of Zambia's landmass remains outside the optimal 100 km radius from any existing weather station. Specifically, under current infrastructure, only ~72% of the country's area is covered, with the remaining 28% considered spatially underserved. The most critically affected provinces include:

- North-Western Province – high rural density, low weather accessibility
- Western Province – prone to seasonal flooding, minimal sensor coverage
- Luapula and Northern Provinces – limited connectivity and logistical challenges

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The buffer subtraction algorithm allowed precise quantification of these coverage gaps. This technique builds on similar spatial logic applied in Halubanza's locust surveillance project in Kazungula, which identified tracking blind spots using IoT and GIS buffers [1].

*B. Interactive Mobile Visualization*

The spatial gap regions, once extracted, were rendered in the Flutter-based mobile application. Key features implemented include:

- Interactive Map Layer: Users can pan, zoom, and view station coverage
- Real-Time Station Metadata: Includes location, name, and coverage range
- Offline Accessibility: GeoTIFF map tiles are stored locally for offline users

This mobile-first approach ensures accessibility for rural extension officers, farmers, and disaster management units. It aligns with previous mobile GIS tools developed by Halubanza et al. for locust management and waste monitoring [2], [3].

*C. Cross-Comparison with Existing Systems*

Unlike traditional map-based coverage assessments, this system integrates real-time visual feedback and field accessibility, which has been lacking in Zambia's national weather infrastructure strategy. Internationally, similar mobile-linked systems have shown success in disaster-prone regions of India and Indonesia, though most use closed-source GIS frameworks with limited flexibility [4].

In contrast, this study's open-source geospatial framework can be extended to multimodal hazard data, such as floods, heatwaves, and vector-borne disease risk, aligning with Sustainable Development Goal 13 (Climate Action).

# CONCLUSION AND RECOMMENDATIONS

This study developed a geospatial buffer-based framework to assess the spatial coverage of weather stations in Zambia. By combining topological GIS operations with a mobile visualization platform, it revealed significant gaps in coverage especially in underdeveloped and climate-vulnerable regions such as North-Western and Western Provinces. The integration of the buffer subtraction algorithm with a mobile-friendly Flutter interface offers a low-cost, scalable tool for weather infrastructure planning and climate resilience building.

The system contributes to both national and academic goals. For Zambia's Meteorological Department, it serves as a decision-support system for station placement, sensor investment, and infrastructure prioritization. For academic and research stakeholders, it provides a methodological foundation for geospatial coverage studies in other sectors such as flood risk, disease monitoring, and smart agriculture.

*B. Recommendations*

Use machine learning models to predict future weather station needs based on population growth, rainfall variability, and extreme weather forecasts. Halubanza et al. [4] have demonstrated AI's applicability to ecological modeling and can inform this transition.

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