

From Manual to Automated: Development of a Distributed Sensor System for Water Data Collection in Rural Regions of Eswatini

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1 Abstract

Access to reliable water quality monitoring remains a pressing challenge in resource constrained regions, where limited infrastructure and variable connectivity restrict the deployment of conventional solutions. This thesis develops a system architecture that addresses these challenges by combining wireless communication technologies within a modular edge-cloud framework. The design explicitly considers topographical and technical constraints in Eswatini and proposes a hybrid approach that leverages existing infrastructure rather than relying on entirely new deployments.

The contribution of this work is threefold. First, it provides a structured analysis of how geographic and infrastructural conditions shape the feasibility of distributed monitoring. Second, it outlines a hybrid communication strategy that balances reliability, scalability, and cost-awareness given these constraints. Third, it situates the design within broader discussions of sustainable infrastructure, highlighting its potential relevance for researchers, local operators, and development agencies.

As a theoretical study, the system is not implemented in practice but serves as a blueprint for future development, illustrating how existing infrastructure can be leveraged under these constraints to enable scalable and cost-aware water quality monitoring.

2 Abstract (german)

Der Zugang zu verlässlicher Wasserqualitätsüberwachung stellt in ressourcenbeschränkten Regionen weiterhin eine zentrale Herausforderung dar, da begrenzte Infrastruktur und variable Konnektivität den Einsatz konventioneller Lösungen erschweren. Diese Arbeit entwickelt eine Systemarchitektur, die diesen Herausforderungen begegnet, indem sie drahtlose Kommunikationstechnologien in einem modularen Edge-Cloud-Framework kombiniert. Das Design berücksichtigt ausdrücklich die topographischen und technischen Rahmenbedingungen in Eswatini und schlägt einen hybriden Ansatz vor, der bestehende Infrastruktur nutzt, anstatt vollständig neue Strukturen aufzubauen.

Der Beitrag dieser Arbeit ist dreifach. Erstens bietet sie eine strukturierte Analyse darüber, wie geografische und infrastrukturelle Bedingungen die Machbarkeit verteilter Überwachungs systeme prägen. Zweitens skizziert sie eine hybride Kommunikationsstrategie, die unter diesen Rahmenbedingungen Zuverlässigkeit, Skalierbarkeit und Kostenbewusstsein ausbalanciert. Drittens verortet sie das Design in breiteren Diskussionen über nachhaltige Infrastruktur und hebt seine potenzielle Relevanz für Forschende, lokale Betreiber und Entwicklungsorganisationen hervor.

Als theoretische Studie wird das System nicht praktisch implementiert, sondern dient als Blaupause für zukünftige Entwicklungen. Es illustriert, wie bestehende Infrastruktur unter diesen Rahmenbedingungen genutzt werden kann, um skalierbare und kosteneffiziente Was serqualitätsüberwachung zu ermöglichen.

3 Introduction

Access to clean and safe water is not only a fundamental human right but also a critical determinant of public health and socio-economic development. In rural Eswatini, many communities still depend on unprotected water sources such as rivers, springs, and shallow wells, which are highly vulnerable to contamination. This exposes residents to waterborne diseases like cholera, typhoid, and diarrhea-conditions that disproportionately affect children and other vulnerable groups.

According to the World Bank, large portions of Eswatini's rural population remain underserved by formal water infrastructure, prompting targeted interventions such as the Water Supply and Sanitation Access Project, which aims to expand potable water coverage in regions like Shiselweni [1]. However, the effectiveness of such initiatives is often limited by a lack of real-time data on water quality, which is essential for timely responses and sustainable resource management.

In this context, developing a robust, autonomous, and scalable water monitoring system tailored to Eswatini's rural conditions is not just a technical challenge, but it is a public health necessity.

3.1 Problem Statement

In rural Eswatini, outdated infrastructure and difficult terrain hinder continuous water quality monitoring. Although several wells and boreholes exist, the sensors in use are often obsolete and require manual data collection, an inefficient and time-consuming process that delays responses to contamination. The high cost of modern sensor systems further limits access to reliable, real-time data for local authorities and researchers.

Traditional monitoring methods are infrequent and labor-intensive, leading to data gaps and reduced effectiveness. However, emerging technologies such as distributed sensor networks and wireless communication systems offer a promising alternative. There is a need for a scalable, low-maintenance monitoring solution tailored to Eswatini's rural context. One that enables automated data collection and reliable transmission to centralized platforms for timely analysis and decision-making.

3.2 Research Questions

In order to develop a suitable solution, this study focuses on the following research questions:

1. To what extent is the combination of wireless transmission technologies (e.g. LoRaWAN (Long Range Wide Area Network) , ZigBee, GSM (Global System for Mobile Communications) and existing infrastructure elements (such as cell towers, power supply, local network operators) suitable for reliable, regular, and cost-efficient transmission of water quality data in Eswatini?

2. What would a modular end-to-end architecture look like that combines cloud services (e.g. AWS IoT (Internet of Things) Core, databases, analytics and visualization tools) with edge components to enable scalable, secure, and cost-optimized collection, storage, analysis, and visualization of water quality data in Eswatini?

3.3 Objectives

The primary objective of this thesis is to design a sound, scalable, and cost-efficient system architecture for automated water quality monitoring in rural Eswatini. To achieve this, the following sub-objectives are defined:

1. **Assessment of the Current Situation**
   Identify the number, type, and distribution of existing water quality sensors in Eswatini. Analyze the topographical features (e.g. mountains, forests, ravines) that may affect sensor placement and data transmission.

2. **Infrastructure Evaluation**
   Investigate the availability and coverage of existing communication infrastructure using sources such as OpenCelliD. Determine which existing cell towers and power sources can be leveraged for data transmission.

3. **Technology Feasability Analysis**
   Evaluate wireless transmission technologies (e.g. LoRaWAN, ZigBee, GSM, NB-IoT (Narrowband IoT) for their applicability in Eswatini's rural context. Propose a suitable mix of technologies based on coverage, costs, energy efficiency, and reliability.

4. **Gateway and Network Planning**
   Identify optimal locations for gateways based on sensor distribution, terrain, and infrastructure. Assess whether additional towers or antennas are needed and recommend sustainable, vandalism-resistant solutions.

5. **System Architecture Design**
   Develop a modular end-to-end architecture that integrates edge devices with cloud services (e.g. AWS IoT Core, databases, analytics, and visualization tools). Ensure the architecture supports scalability, security, and low maintenance.

3.4 Structure of the Thesis

This thesis is structured as follows. To begin with, Chapter 2 introduces the motivation, problem statement, research questions, and objectives of the work. Subsequently, Chapter 3 provides background information on water monitoring in Eswatini, including current practices, challenges in data collection, and an overview of sensor network technologies. Building on this, Chapter 4 presents a requirements analysis, focusing on topographical and environmental factors, data transmission requirements, energy and autonomy considerations, and stakeholder needs. In the next step, Chapter 5 evaluates various wireless transmission technologies and hybrid approaches, assessing their suitability for Eswatini's rural context and comparing their integration potential. Following this, Chapter 6 analyzes the existing infrastructure, including mobile network coverage and integration possibilities, and identifies potential obstacles and solutions. On this basis, Chapter 7 proposes a modular system architecture, detailing the end-to-end data flow from sensors to the cloud, including communication layers, cloud integration, and security and scalability considerations. Afterwards, Chapter 8 discusses the results, comparing them with related work and outlining their implications. Finally, Chapter 9 concludes the thesis and provides an outlook for future work, while the Appendix contains supplementary figures, tables, and additional material supporting the main text.

4 Context

Water monitoring in Eswatini is primarily managed by the Department for Water Affairs (DWA) under the Ministry of Natural Resources and Energy. While the country has made progress in expanding access to water, especially through initiatives like the World Bank's Water Supply and Sanitation Access Project, rural areas still face significant challenges. Many communities rely on boreholes and wells, but the monitoring infrastructure is often outdated and lacks real-time capabilities [1].

4.1 Challenges in Data Collection

Current water quality monitoring in rural Eswatini is largely manual. Field personnel must travel long distances to collect data from remote sites, which is time-consuming, labor-intensive, and prone to delays. This limits the frequency and responsiveness of monitoring efforts and increases operational costs.

A challenge to the delpoyment of modern automated monitoring systems are th high equipment costs and limited infrastructure. For example, commercial LoRaWAN-based water quality monitoring kits such as the Libelium Smart Water Xtreme can cost more than $2,500 per node, excluding gateway and cloud integration costs [2]. GSM-enabled sensor systems like the Eijkelkamp Smart Sensoring platform can exceed $3,000 per unit [3], while NB-IoT-based solutions such as those offered by Sensoterra or Ayyeka typically range from $1,500 to $2,500 per sensor, depending on configuration and connectivity [4].

These systems often rely on cellular or low-power wide-area network (LPWAN) infrastructure, which is not uniformly available across Eswatini. Remote areas, particularly in mountainous or forested regions, may lack reliable GSM or NB-IoT coverage, making real-time data transmission inpossible without additional infrastructure investments. This technological gap further limits the feasibility of deploying advanced monitoring systems in the areas where they are most needed [5].

4.2 Overview of Sensor Networks for Water Quality

Sensor networks for water quality monitoring have evolved significantly in recent years, offering new possibilities for real-time, distributed environmental data collection. These systems typically consist of multiple sensor nodes deployed across various locations, each capable of measuring parameters such as pH, turbidity, temperature, electrical conductivity, and dissolved oxygen. The data collected is transmitted to a central gateway, which then forwards it to cloud-based platforms for storage, analysis, and visualization.

A typical water quality sensor network includes three main components:

- **Sensor Nodes** are equipped with water quality sensors and microcontrollers. They are often battery-powered and designed for low energy consumption.
- **Gateways** act as intermediaries between the sensor nodes and the cloud, aggregating data and handling communication protocols.

- **Cloud Infrastructure** includes databases, analytics tools, and dashboards for real-time monitoring and long-term trend analysis.

In developing regions, wireless sensor networks (WSNs) are particularly promising due to their scalability, low maintenance requirements, and ability to operate in off-grid environments. They reduce the need for manual data collection and enable early detection of contamination events, which is critical for public health and resource management [6].

The choice of wireless transmission technology-such as LoRaWAN, ZigBee, GSM, or NB-IoT-plays a crucial role in the performance and feasibility of such systems. These technologies differ in terms of range, power consumption, data rate, and infrastructure requirements. A detailed comparison and evaluation of these technologies will be presented in Chapter 6, where their suitability for Eswatini's rural context will be assessed.

5 Requirements Analysis

This chapter presents a comprehensive analysis of the requirements for designing and deploying an automated water quality monitoring system in rural Eswatini. It examines the topographical and environmental factors that influence sensor placement and communication reliability, outlines the data transmission and energy autonomy needs, and identifies key stakeholders and their roles. The insights gained here form the foundation for the subsequent evaluation of suitable technologies, infrastructure integration, and system architecture.

5.1 Topographical and Environmental Factors

Motivation

Topographical and environmental conditions play a critical role in the design and deployment of distributed water quality monitoring systems. In rural regions like Eswatini, factors such as mountainous terrain, dense vegetation, and seasonal weather patterns can significantly impact both the physical placement of sensors and the reliability of data transmission.

Understanding the landscape is essential for several reasons. First, elevation changes and natural barriers such as hills or ravines can obstruct wireless signals, especially for line-of-sight (LoS) technologies like LoRaWAN or ZigBee. Second, environmental conditions such as humidity, flooding, or extreme temperatures may affect sensor durability and maintenance cycles. Third, accessibility to remote sites is often limited, making it crucial to plan for autonomous operation and minimal physical intervention.

In addition, environmental factors directly influence the choice and reliability of energy sources for sensor nodes and gateways. In off-grid areas, solar energy is often the most viable option, but its effectiveness depends on local sunlight availability, which may be reduced in forested or mountainous regions. Wind energy may be considered in elevated or open areas, while battery-only systems require regular maintenance, which is challenging in remote locations. These constraints must be considered when designing a resilient and low-maintenance monitoring network.

Elevation Ranges

Eswatini's highest point is *Emlembe* in the northwest, reaching an elevation of 1,862 meters above sea level. In contrast, the lowest point lies along the *Great Usutu River* near the eastern border with Mozambique, at approximately 21 meters. This significant elevation gradient introduces challenges for LoS communication and infrastructure access. The following section discusses the different types of terrain.

Terrain Zones:

- **Highveld:** Located in the west, this region is characterized by mountainous terrain and high plateaus. It includes the capital Mbabane and is prone to steep slopes and dense vegetation.
- **Middleveld:** The central region features rolling hills and valleys. It presents moderate elevation changes and is often used for agriculture and settlements.
- **Lowveld:** Found in the east, this area consists of flat plains and low hills. It is more arid and generally easier to access, but may lack natural elevation for signal propagation.
- **Lubombo Range:** A narrow mountain range along the eastern border with Mozambique. It presents both topographical barriers and opportunities for elevated sensor or gateway placement.

This topographical diversity must be carefully considered when selecting communication technologies, planning network coverage, and ensuring long-term system reliability. To address these challenges, the following section analyzes representative groundwater monitoring sites across Eswatini, as shown in Figure 1. These sites span different terrain zones, including the Highveld, Middleveld, and Lowveld and reflect the country's varied elevations and environmental conditions.

The analysis focuses on key factors such as elevation, slope, vegetation cover, and accessibility, which directly influence sensor deployment, wireless communication, and energy autonomy. By systematically evaluating these constraints, the study identifies potential obstacles and provides insights that inform the design of a robust, context-aware monitoring architecture.

5.2 Topographic and Vegetation Analysis Example

Reliable data transmission is a critical component in the deployment of distributed sensor systems for water monitoring. In rural and topographically diverse regions such as Eswatini, the feasibility of LoS communication is influenced by elevation, terrain features, and vegetation density. These environmental factors can significantly affect the performance of wireless communication technologies such as LoRa, Wi-Fi, or cellular networks.

To explore these challenges in practice, five representative borehole sites were selected from different ecological and topographic regions across Eswatini. The selection includes locations in the Highveld, Middleveld, Lowveld, and transboundary zones, ensuring a diverse range of environmental conditions. Each site is analyzed with respect to its surrounding terrain and vegetation, with a particular focus on potential obstacles to LoS communication such as ridgelines, valleys, and dense forest cover.

The analysis was conducted using Google Earth[7], which provided high-resolution satellite imagery and 3D terrain visualization. For consistency, all images were captured with an approximate camera height of 1km above ground level. This perspective allows for a clear assessment of the surrounding landscape and potential signal obstructions. The following subsections present each site individually, accompanied by satellite imagery and a discussion of its communication-related advantages and limitations.

An overview of the selected groundwater monitoring sites in Eswatini is shown in Figure 1, where the five sites chosen for detailed analysis are marked in blue.

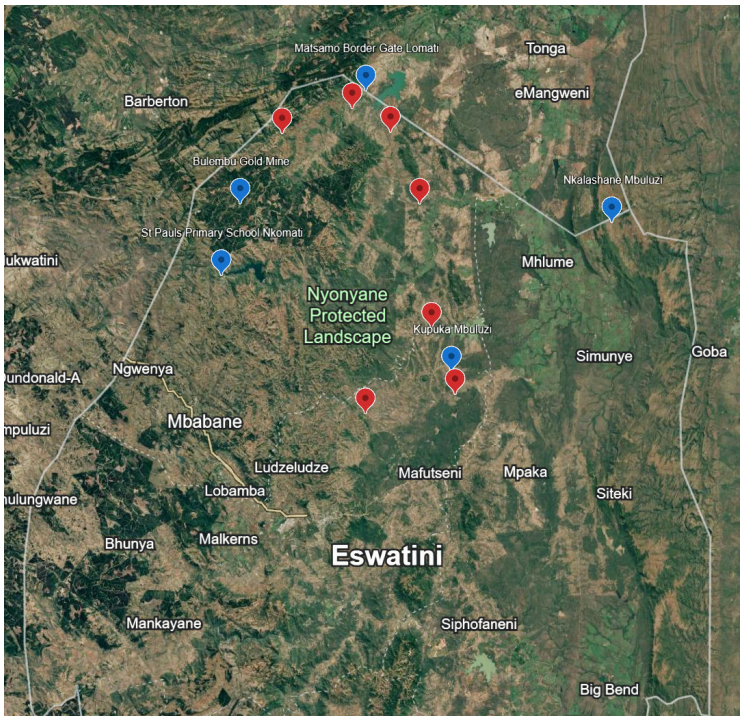


Figure 1: Current groundwater monitoring boreholes in Eswatini blue and red [7]

Bulembu Gold Mine (Highveld - mountainous)

Bulembu is located in the Highveld region near the South African border, at an elevation of approximately 1,500 meters above sea (asl). The area is defined by steep ridges, deep valleys, and extensive montane forest, as can be seen in Figure 2, all of which present significant challenges for LoS communication. These natural features can obstruct radio signals and reduce transmission reliability, particularly for LPWANs such as LoRa.

Although Bulembu is not situated near a major urban center, it is accessible via several roads. The nearest town is Piggs Peak, located roughly 18-20 kilometers to the southeast. The combination of rugged terrain and dense vegetation makes this site one of the more complex environments for wireless data transmission. Elevated antenna placement or the use of strategically positioned relay nodes may be required to ensure connectivity.

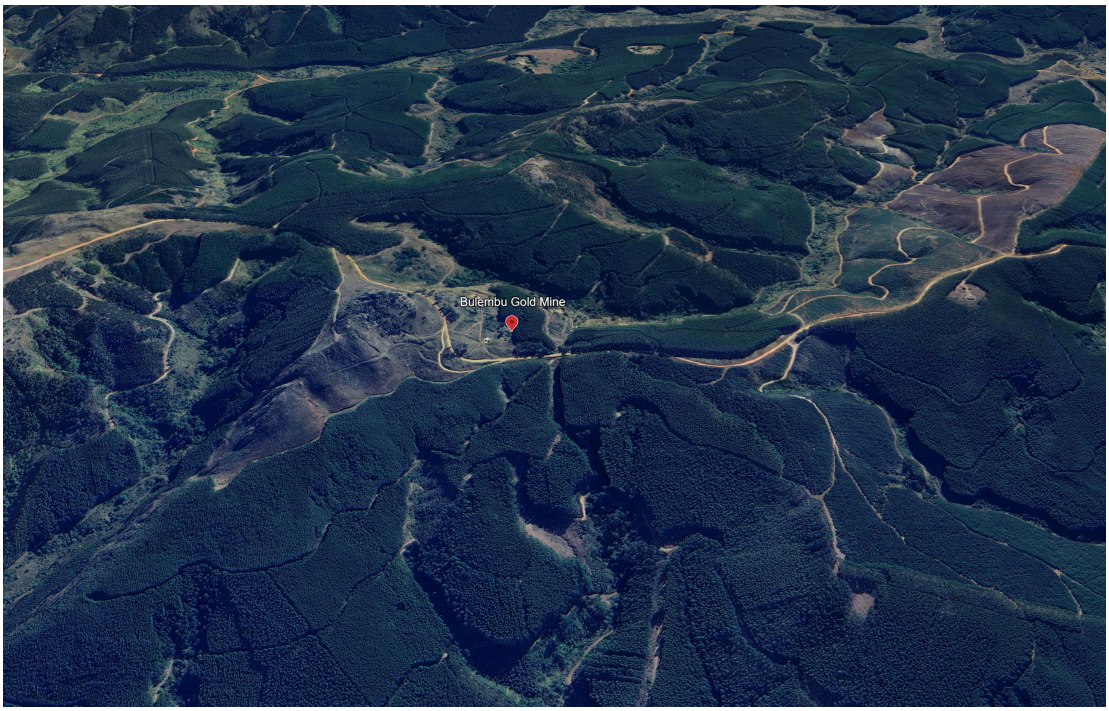


Figure 2: Satellite view of Bulembu Gold Mine and surrounding terrain [7].

St Pauls Primary School (Middleveld - rolling hills)

Situated in the Middleveld, St Pauls Primary School lies at an elevation of approximately 1,200 meters (asl). The terrain consists of gently rolling hills with moderate vegetation, including scattered trees and cultivated fields. These conditions are generally favorable for LoS communication. Minor terrain undulations may exist, but they are unlikely to significantly obstruct signal paths. Antennas mounted on rooftops or poles can further improve connectivity.

The site is located near a main road, which increases the likelihood of existing communication infrastructure such as mobile towers or utility poles that could be leveraged for data transmission. This accessibility, combined with the relatively open terrain, makes the site well-suited for wireless sensor deployment.



Figure 3: Satellite view of St Pauls Primary School and surrounding terrain [7].

Kupuka (Lowveld - flat and arid)

Kupuka is located in the Lowveld, a flat and semi-arid region with minimal vegetation and few natural obstructions. The site's low elevation of 450 meters (asl) and open terrain make it ideal for LoS communication. Signals can propagate over long distances with minimal attenuation, and the sparse vegetation further enhances signal clarity. This site is highly suitable for long-range wireless technologies such as LoRaWAN or point-to-point Wi-Fi.

Although the population in the area is present, it is relatively low in density. This suggests limited urban infrastructure but also implies reduced interference and fewer competing signals. The presence of a local community increases the likelihood of basic services and potentially existing communication towers or utility poles that could be repurposed for sensor data transmission. Overall, Kupuka is highly suitable for long-range wireless technologies such as LoRaWAN or point-to-point Wi-Fi.



Figure 4: Satellite view of Kupuka site in the Lowveld region [7].

Matsamo Border Gate (Lomati Basin - transboundary zone)

Located near the Eswatini-South Africa border, this site lies in a relatively flat area with moderate elevation of around 850 meters (asl). The terrain is semi-urban, with existing infrastructure such as roads and buildings. While these structures may introduce some localized signal reflections, the overall topography is favorable for LoS communication. The presence of infrastructure may also facilitate antenna mounting.



Figure 5: Satellite view of Matsamo Border Gate and surrounding area [7].

Nkalashane (Eastern Mbuluzi - near Lubombo Range)

Nkalashane is located near the Lubombo mountain range at an elevation of approximately 600-700 meters (asl). The surrounding terrain includes a mix of flat areas and rising foothills, which can obstruct LoS paths depending on the relative position of other nodes. These terrain features can cause signal shadowing, where hills or ridges block the direct path between transmitter and receiver. This is particularly problematic for LoS-dependent technologies such as LoRa, as even partial obstructions can lead to significant signal degradation or complete loss of connectivity.

Vegetation in the area is moderate, consisting of scattered trees and grassland. While not as dense as in forested regions, this vegetation can still contribute to signal attenuation, especially when combined with uneven terrain.

Compared to more accessible sites like Matsamo Border Gate, Nkalashane is situated in a distinctly rural setting with limited infrastructure. The absence of nearby urban centers or major roads reduces the likelihood of existing communication towers or utility poles that could be repurposed for sensor data transmission. As a result, achieving reliable connectivity at this site may require the installation of dedicated relay nodes or elevated antennas to overcome both natural and infrastructural limitations.

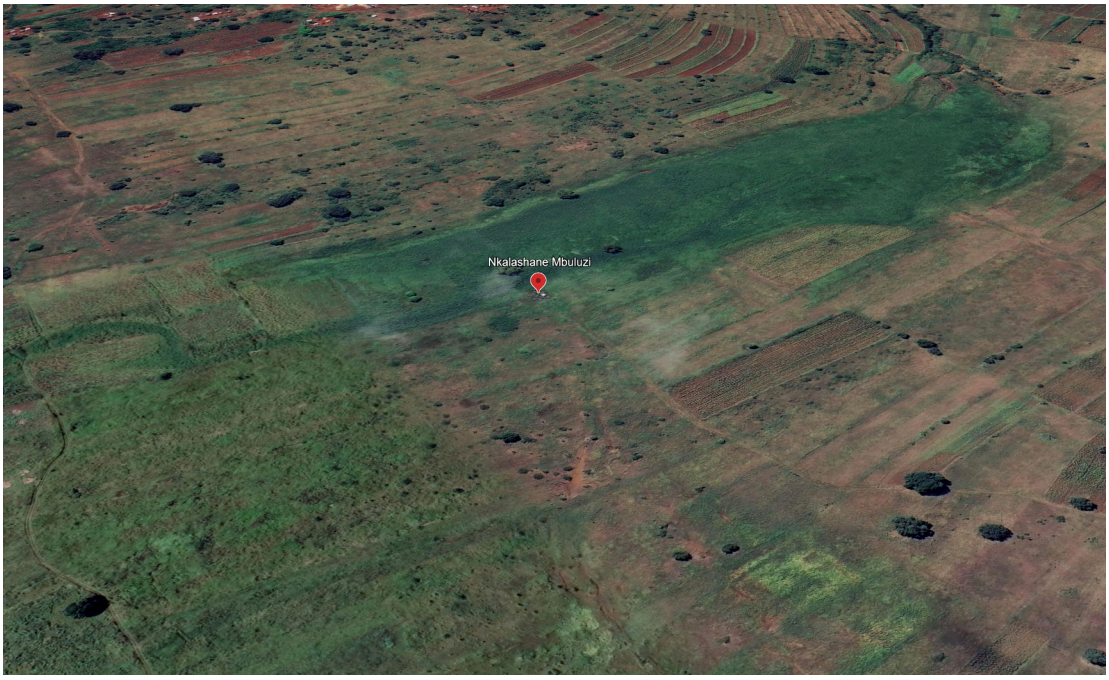


Figure 6: Satellite view of Nkalashane near the Lubombo foothills [7].

5.3 Data Transmission Requirements

The successful deployment of a distributed sensor system for groundwater monitoring depends not only on the physical placement of sensors but also on the reliability of data transmission between remote sites and central collection points. In rural and topographically diverse regions like Eswatini, several environmental and infrastructural factors must be considered when designing the communication layer of the system.

Line-of-Sight (LoS) Considerations

As established in the site analyses, terrain features such as mountains, ridges, and valleys can obstruct direct LoS paths, which are essential for many wireless communication technologies. Sites like Bulembu and Nkalashane, located in or near mountainous regions, are particularly affected by terrain-induced shadowing. In such cases, elevated antenna placement or the use of intermediate relay nodes may be necessary to maintain connectivity.

Vegetation and Signal Attenuation

Dense vegetation, especially in montane or forested areas like with Bulembu Gold Mine, can significantly attenuate radio signals. This is particularly relevant for LPWAN technologies such as LoRa, which rely on clear signal paths to achieve long-range communication. In such environments, signal degradation can be mitigated by increasing antenna height, using directional antennas, or deploying additional relay nodes to bypass dense forest zones.

Environmental Resilience

Environmental conditions such as heavy rainfall, high temperatures, or dust can impact the performance and longevity of communication hardware. In Eswatini's varied climate zones, equipment may be exposed to intense sun in the Lowveld or high humidity in forested regions. These factors can degrade antenna performance, corrode connectors, or cause power fluctuations. To ensure reliable data transmission, all communication components should be weatherproof, temperature-tolerant, and, where possible, equipped with surge protection or environmental shielding.

Infrastructure Availability

The presence of existing infrastructure, such as mobile towers, utility poles, or school buildings can greatly facilitate the deployment of communication equipment. Sites located near main roads or within semi-urban areas, such as St Pauls Primary School and Matsamo Border Gate, are more likely to benefit from such infrastructure. In contrast, more remote locations like Nkalashane may require the installation of dedicated communication hardware. A more detailed assessment of infrastructure availability will be presented in Section 7.

Data Volume and Frequency

The volume and frequency of data transmission directly influence the choice of communication technology and the energy requirements of the system. In the context of groundwater monitoring, typical sensor payloads may include parameters such as water level, temperature, and conductivity. These values are generally small in size (on the order of tens to hundreds of bytes per reading), allowing for efficient transmission even over LPWANs.

Given the long-term nature of the monitoring system, high-frequency data transmission is generally not required. For most applications, hourly or even daily updates are sufficient to capture meaningful trends. However, the system should remain flexible enough to support more frequent transmissions in the future, for example in the case of early warning systems or dynamic environmental events.

Latency Requirements

Latency, the delay between data collection and reception, is typically not a critical factor in long-term groundwater monitoring. Delays of several minutes to hours are acceptable, as the primary objective is to observe gradual changes over time. However, if the system is later extended to include real-time alerts (e.g. for contamination or flooding), lower latency may become necessary. The communication protocol and network design should therefore be adaptable to both low-frequency and near-real-time transmission scenarios.

Redundancy and Reliability

In rural and remote environments, communication links are inherently less stable due to environmental interference, power fluctuations, or hardware failure. To ensure data integrity and system robustness, redundancy mechanisms should be considered. These may include local data buffering on the sensor node, retransmission protocols in case of failed delivery, and fallback communication paths where possible.

The network architecture should also be designed to tolerate node failures without compromising the entire system. This can be achieved through mesh networking, multi-hop routing, or the strategic placement of relay nodes to maintain connectivity even if individual links are disrupted.

Scalability

As the sensor network expands-either by adding more borehole sites or integrating additional environmental parameters-the communication system must be able to scale accordingly. Technologies such as LoRaWAN are well-suited for scalable deployments, as they support a large number of nodes with minimal infrastructure. However, increased network size can lead to congestion, especially if many nodes transmit simultaneously. To maintain performance, the system should implement strategies such as time-synchronized transmissions, adaptive data rates, or hierarchical network structures with regional gateways.

5.4 Energy and Autonomy Requirements

Energy autonomy is a critical consideration for distributed water quality monitoring systems, especially in rural and off-grid environments like Eswatini. Reliable, long-term operation requires sensor nodes and gateways to function independently of frequent maintenance or grid power. This section examines the energy requirements of typical sensor deployments, reviews common power supply strategies such as solar and battery-based solutions, and analyzes the feasibility of different configurations. The goal is to identify approaches that maximize system autonomy, minimize maintenance, and ensure sustainable operation under local environmental conditions.

Common Power Supply Options in Related Work

In similar deployments, especially in rural or off-grid regions, the following power supply strategies are commonly used:

- **Solar + Battery:** This is the most prevalent solution for long-term, autonomous sensor systems. A typical setup includes a small solar panel (5–10 Watt (W) paired with a rechargeable battery (e.g. Li-ion (Lithium-ion battery) or $LiFePO_4$ (Lithium-iron-accumulator)). For example, a study on remote water quality monitoring in rural India used a 10 W solar panel with a 6600 mAh (milli ampere hours) Li-ion battery to power a LoRa-based sensor node, achieving over 90% (percent) uptime across a 6-month deployment [8].
- **Battery-Only:** Battery-powered systems are often used for short-term deployments or in locations with limited solar exposure (e.g. dense forests or shaded riverbanks). These systems require larger battery capacities and more frequent maintenance. For instance, a deployment in the Amazon basin used high-capacity Li-ion packs to power turbidity sensors for 30-day intervals [9].
- **Energy Harvesting:** Though less common, energy harvesting from environmental sources such as vibration, wind, or thermal gradients has been explored in research. A notable example is a prototype system in Kenya that used thermoelectric generators (TEGs) placed in riverbeds to harvest temperature differentials between water and air, powering low-duty-cycle sensors [10].

A further approach to achieving energy autonomy in distributed water quality monitoring systems is the use of flat-plate solar thermal collectors coupled with thermoelectric generators. This method relies on a simple but effective principle: a black absorber plate is exposed to sunlight, where it efficiently captures and converts solar radiation into heat. The absorbed heat creates a temperature gradient between the hot plate and the cooler surrounding environment. By attaching thermoelectric modules to the plate, this thermal gradient can be directly converted into electricity through the Seebeck effect. In essence, the system works as the reverse of a refrigerator: instead of expelling heat to maintain a cold interior, it deliberately accumulates heat to generate usable energy. Flat-plate collectors are relatively

inexpensive to construct, require minimal maintenance, and can operate even under diffuse sunlight conditions, making them suitable for rural or off-grid environments. While their electrical conversion efficiency is lower than that of photovoltaic panels, they offer the advantage of hybridization, as they can complement PV modules by harvesting solar energy in both thermal and electrical forms. Recent reviews of flat-plate collector technology highlight their ability to reach absorber temperatures between 30 °C (celsius) and 80 °C under typical conditions, with advanced coatings pushing this range higher, thereby improving the potential for thermoelectric conversion. This makes them a promising supplementary energy source for low-duty-cycle sensor nodes in distributed monitoring networks [11].

These approaches balance autonomy, cost, and maintenance effort. Among them, solar-powered systems are favored for long-term, low-maintenance deployments in rural regions due to their reliability and scalability. The examples presented here are chosen at random, as the systems are broadly similar in design and performance.

Power Consumption Analysis

To estimate the energy requirements of the sensor node, we analyze the power consumption of its main components: the sensor, microcontroller, and communication module. The goal is to minimize or eliminate the need for internal batteries by using solar energy for daytime charging and energy-efficient hardware.

Sensor: Keller Series 36XW CTD The *Keller Series 36XW CTD* is a multi-parameter probe for water level, temperature, and conductivity. It includes an internal 3.6 V (volt) lithium battery and is optimized for low-power operation. During measurement, it draws 5–10 mA (milli ampere) for a few seconds, while standby current is less than 10 μA (micro ampere). At one measurement per hour, the internal battery can last up to 10 years [12]. However, to extend lifetime or eliminate battery use, external solar power is considered.

Communication Module (technology-agnostic) Since the exact transmission technology (e.g. LoRa, NB-IoT, GSM) is not yet finalized, average values for low-power communication modules are used. Typical transmit current is 100–150 mA for 0.2–0.5 s (seconds), receive current is 10–20 mA, and sleep current is below 1 μA. Assuming one transmission per hour with 0.3 s duration:

$$E_{\text{comm}} = 0.15\,\text{A} \times 0.3\,\text{s} \times 24 = 1.08\,\text{As} = 0.3\,\text{mAh}$$

Microcontroller (optional) If a microcontroller is used for control or preprocessing (e.g. STM32L series), active current is 5–10 mA, and sleep current is below 1 μA. With deep sleep and short wake-up periods, average consumption can be kept below 0.5 mA.

Estimated Total Consumption Assuming 5 seconds of activity per hour and deep sleep otherwise:

$$I_{\text{avg}} \approx 0.5\,\text{mA} \quad \Rightarrow \quad E_{\text{daily}} = 0.5\,\text{mA} \times 24\,\text{h} = 12\,\text{mAh}$$

This value serves as a baseline for sizing the energy storage and harvesting components.

Battery Life Estimation

Battery life depends on average current draw, battery capacity, and charging strategy. For example, with a 6600 mAh battery and 0.5 mA average draw:

$$\text{Battery Life} = \frac{6600\,\text{mAh}}{0.5\,\text{mA}} = 13200\,\text{h} \approx 550\,\text{days}$$

This estimate assumes no recharging. With solar charging, autonomy can be extended indefinitely under favorable conditions.

Feasibility of Power Supply Modifications

Adapting the system to different power supply configurations involves trade-offs:

- **Adding Solar:** Increases autonomy and sustainability but requires additional components such as a charge controller, energy storage (e.g. Li-ion or $LiFePO_4$ battery), and weatherproof housing. The required solar panel size depends on the daily energy consumption and local solar irradiance. For example, with an estimated daily consumption of 12 mAh and an average of 4 h of effective sunlight per day, a 0.1–0.5 W panel would be sufficient. However, to account for inefficiencies, cloudy days, and battery charging losses, a panel in the range of 1–2 W is recommended. The physical size of such panels typically ranges from 10 cm (centimeter) x 10 cm to 15 cm x 20 cm.
- **Battery-Only:** Simplifies design and reduces component count but limits deployment duration and increases maintenance frequency. For example, a 6600 mAh battery would last approximately 550 days at 0.5 mA average current draw, assuming no recharging. However, battery degradation and environmental factors (e.g. temperature) can reduce effective capacity over time.
- **Hybrid Systems:** Offer flexibility and redundancy by combining solar, battery, and possibly energy harvesting (e.g. micro-hydro or thermoelectric). These systems are more resilient but require more complex power management and increase cost, size, and integration effort.

The feasibility of each option will be evaluated based on deployment location (e.g. solar exposure, accessibility), cost constraints, and required autonomy. In remote or hard-to-reach areas, solar-powered or hybrid systems are often preferred due to their low maintenance requirements and long-term sustainability.

5.5 Stakeholder Analysis

The development and deployment of a distributed water data collection system in rural Eswatini involves a diverse set of stakeholders, each with distinct interests, responsibilities, and levels of engagement. Local communities rely on surface and groundwater sources for drinking, agriculture, and livestock, while local authorities and water boards such as the Eswatini Water Services Corporation (EWSC) oversee water management and enforce policy. Non-governmental organizations (NGOs) contribute through rural development initiatives and environmental monitoring, and academic and research institutions are engaged in studying environmental data and system performance. In addition, technical partners and developers are responsible for designing and maintaining the sensor network, whereas funding agencies and donors provide financial support and expect transparent reporting.

Stakeholder Roles and Interactions

Each stakeholder group interacts with the system in distinct ways. Local communities benefit from reliable access to clean water and early warnings about water quality or availability, and they often host sensor nodes while reporting issues. Local authorities depend on accurate, timely data for resource management and infrastructure planning, and they may also oversee maintenance and data governance. Non-governmental organizations (NGOs) use the data to evaluate project impact, advocate for policy changes, and coordinate interventions, frequently serving as intermediaries between communities and authorities. Academic institutions leverage the system for research, training, and environmental modeling, while also contributing to system design and data analysis. Technical partners take responsibility for hardware and software development, deployment logistics, and long-term technical support. Finally, funding agencies expect measurable outcomes and clear sustainability planning to ensure the long-term success of the system.

Infrastructure and Engagement

The effectiveness of stakeholder engagement is closely linked to the availability and quality of local infrastructure. A reliable power supply, often solar, based in off-grid areas is essential to ensure continuous data collection and transmission. Equally important is connectivity, whether provided through mobile networks or LoRa gateways, since limited coverage can restrict real-time access to information. Transport infrastructure, such as road networks, influences the ability to install, maintain, and monitor sensor nodes, particularly during the rainy season when accessibility is reduced. Finally, digital infrastructure in the form of dashboards, mobile applications, or SMS alerts enables stakeholders to interact directly with the system and make informed decisions.

Collaboration and Governance

Collaboration and governance are critical for long-term success. Clear agreements on data ownership and access, well-defined maintenance responsibilities (potentially involving local technicians or trained community members), and inclusive decision-making processes such as joint planning meetings and community consultations help ensure the system remains relevant and trusted. Capacity building through training programs for local users and authorities further strengthens sustainability and promotes local ownership.

6 Technology Analysis

In this section, various wireless transmission technologies are analyzed with respect to their applicability in a distributed sensor system for water data collection in rural regions of Eswatini. The focus lies on low-power, long-range communication methods that can operate reliably in areas with limited infrastructure. Each technology is evaluated based on its technical characteristics, energy efficiency, scalability, and suitability for deployment in remote environments. The analysis aims to identify the most appropriate communication solutions for ensuring robust and sustainable data transmission within the proposed system architecture. The presented technologies constitute the most common low-power, long-range, and scalable communication technologies for evaluating sensor networks.

6.1 Wireless Transmission Technologies

The selection of appropriate wireless transmission technologies is a critical component in the design of distributed sensor systems, particularly in rural and infrastructure-limited regions such as Eswatini. These technologies must balance energy efficiency, cost, scalability, and reliability under challenging environmental conditions.

LoRaWAN is a LPWAN protocol that enables long-range communication with minimal energy consumption. It is particularly suitable for battery-powered sensors in remote areas, as it does not rely on cellular infrastructure. LoRaWAN operates via gateways that forward data to centralized servers, making it ideal for applications with low data throughput and infrequent transmissions. However, its limited data rate and dependency on gateway placement can pose challenges in dynamic or high-density deployments. Security aspects of LoRaWAN, including encryption and authentication mechanisms, are discussed in Silva and Pereira (2025) [13].

ZigBee is a short-range wireless protocol based on IEEE (Institute of Electrical and Electronics Engineers) 802.15.4, designed for low-power mesh networks. It supports self-healing topologies and is well-suited for local communication between sensors. Despite its robustness in mesh configurations, ZigBee's limited range per node and susceptibility to interference in the 2.4 GHz (gigahertz) band restrict its applicability in large-scale outdoor deployments. A comprehensive review of ZigBee and backscatter communication technologies is provided by Khan and Zhang (2025) [14].

Cellular technologies such as GSM, 3G, 4G, and LTE (long term evolution) Cat 1 offer high data rates and broad coverage, making them suitable for real-time applications and high-volume data transmission. However, they are energy-intensive and often cost-prohibitive, especially in regions with limited network infrastructure. Ericsson Research (2025) outlines the role of cellular networks in enabling massive IoT deployments, emphasizing the trade-offs between performance and power consumption [15].

NB-IoT is a cellular LPWAN standard optimized for stationary, low-bandwidth IoT devices. It offers excellent indoor penetration and long battery life, but its reliance on mobile network availability limits its deployment in underserved areas. Recent industry trends indicate a

decline in global NB-IoT adoption, as highlighted by Eseye Ltd. (2025) [16], although it remains relevant in specific markets.

Sigfox is another LPWAN technology characterized by ultra-low power consumption and minimal data rates. It is particularly effective in dense sensor environments where collision avoidance and simplicity are prioritized. Comparative performance evaluations between Sigfox and LoRa in such contexts are presented by Alshammari and Alotaibi (2025) [17].

Finally, **LTE-M (Cat M1)** bridges the gap between traditional cellular and LPWAN technologies. It supports mobility, voice services, and moderate data rates while maintaining low power consumption. LTE-M is increasingly viewed as a successor to NB-IoT in many regions, as discussed by 5G Americas (2025) [18].

Figure 7 provides a comparative overview of several wireless transmission technologies commonly used in IoT applications. The visualization highlights key parameters including cost, data rate, power consumption, and communication range. It illustrates the trade-offs inherent in each technology: for example, LoRaWAN and Sigfox offer low power consumption and long range but limited data rates, while cellular technologies such as 4G provide high throughput at the expense of energy efficiency and cost. This comparison supports the selection process by clarifying which technologies align best with the constraints and requirements of rural deployments.

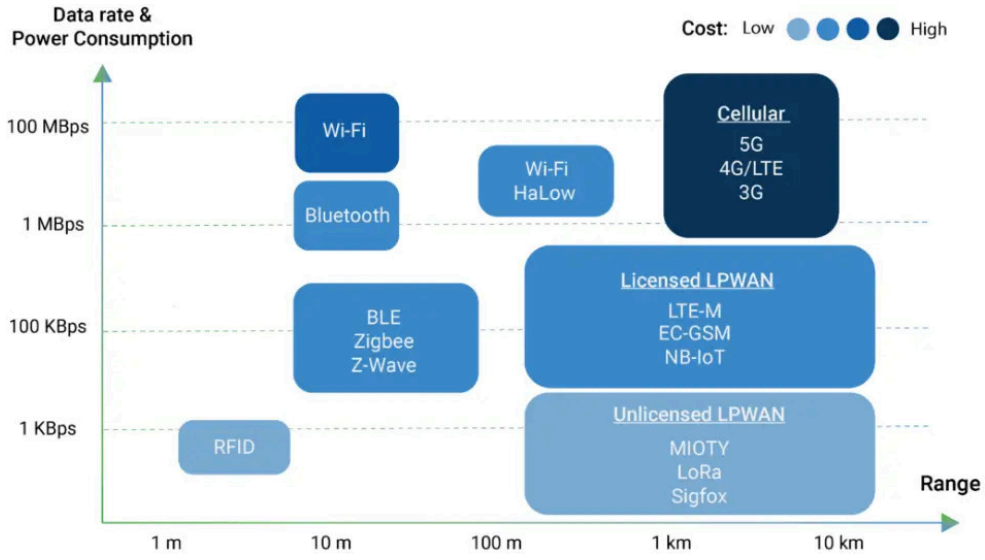


Figure 7: Comparison of wireless transmission technologies [19]

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6.2 Hybrid Approaches

In distributed sensor systems deployed in rural regions, relying on a single communication technology often proves insufficient due to varying environmental conditions, infrastructure availability, and application-specific requirements. Hybrid communication architectures offer a flexible and resilient solution by combining multiple wireless technologies such as ZigBee, LoRaWAN, GSM, and NB-IoT into a unified system.

Hybrid IoT networks typically follow a tiered structure. Short-range protocols like ZigBee or Bluetooth are used for local communication between sensor nodes, while long-range technologies such as LoRaWAN or GSM serve as backhaul links to transmit aggregated data to cloud platforms. This layered approach allows for energy-efficient local data exchange and reliable long-distance transmission. Gateways equipped with multi-protocol capabilities act as intermediaries, translating and forwarding data between heterogeneous networks. These gateways often support protocol conversion and edge computing, enabling real-time processing and adaptive routing decisions [20].

An example of such a hybrid communication architecture is illustrated in Figure 8, which shows how ZigBee can be used for local sensor communication, LoRaWAN for regional aggregation, and GSM/NB-IoT for cloud connectivity. The diagram highlights the tiered nature of the system and the role of gateways in bridging different protocols.

The implementation of hybrid systems introduces certain complexities. Hardware costs increase due to the need for multi-radio gateways, and software integration requires robust middleware capable of handling protocol translation, data synchronization, and fault tolerance. Nonetheless, modern IoT platforms and edge intelligence frameworks have significantly reduced the barrier to entry. For example, Židek et al. (2020) demonstrated a switchable hybrid system combining GSM, LoRaWAN, and Sigfox, which dynamically selects the most suitable protocol based on signal quality and environmental conditions [21].

Hybrid architectures are particularly strong in logistics, agriculture, and environmental monitoring, where devices operate across diverse terrains and connectivity conditions. They offer improved coverage, fault tolerance, and scalability, making them well-suited for Eswatini's rural deployment scenario. However, they also require careful planning in terms of network topology, energy budgeting, and maintenance strategies [22].

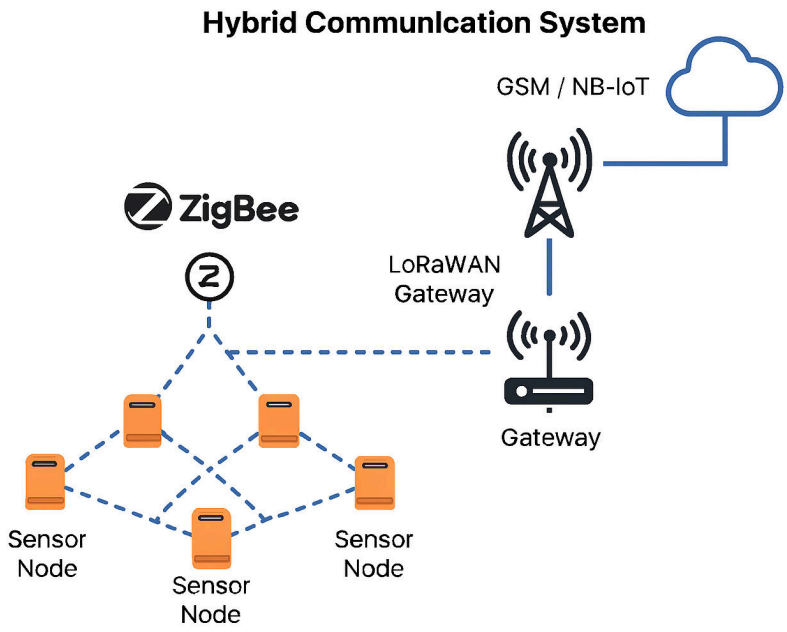


Figure 8: Hybrid communication architecture for distributed sensor systems A.

6.3 Technology Evaluation

This subsection presents a detailed evaluation of selected wireless communication technologies, focusing on their operational principles, advantages, limitations, and contextual relevance for deployment in Eswatini. The goal is to identify the most appropriate solutions for a distributed sensor network in rural environments.

LoRaWAN

A key strength of LoRaWAN lies in its energy efficiency. Devices spend most of their time in sleep mode and only activate to transmit data, allowing for battery lifespans of several years. Adaptive data rate mechanisms further optimize energy use by adjusting transmission parameters based on proximity to the gateway. These features make LoRaWAN ideal for low-maintenance deployments in hard-to-reach areas.

From an economic perspective, LoRaWAN is attractive due to its low operational costs. Although initial investments in gateways and sensor nodes are required, the absence of licensing fees and the long service life of devices contribute to a favorable total cost of ownership. Its scalability and cost-effectiveness have led to widespread adoption in energy and environmental monitoring applications [15].

Nevertheless, LoRaWAN has limitations. Its relatively low data rate (0.3-50 kbps) restricts its use to applications with small, infrequent data transmissions. The protocol is also vulnerable to interference and packet collisions in dense deployments, and its limited downlink capacity can hinder bidirectional communication. Network performance is highly dependent on the strategic placement of gateways.

Security is another important consideration. While LoRaWAN includes AES-128 encryption, its lightweight design can expose it to vulnerabilities if not properly configured. Silva and Pereira (2025) provide a comprehensive analysis of these challenges, including issues related to key management and authentication in distributed sensor networks [13].

Despite these constraints, LoRaWAN remains a compelling option for rural sensing applications where energy efficiency, scalability, and independence from cellular infrastructure are critical.

ZigBee

Energy efficiency is a defining feature of ZigBee. Devices operate in low-duty cycles, waking only to transmit or receive data, which significantly extends battery life. Research has shown that routing protocols such as AOMDV can improve throughput and energy distribution, thereby increasing the longevity of ZigBee-based systems [23].

In terms of implementation, ZigBee is cost-effective. Modules are inexpensive, and the protocol does not require spectrum licensing. However, its limited range-typically 10 to 100 meters-and operation in the crowded 2.4 GHz band make it susceptible to interference from other wireless technologies. These constraints limit its scalability in outdoor or large-area

deployments. Nonetheless, ZigBee remains a robust solution for localized networks where low power consumption and mesh networking are advantageous [24].

GSM/3G/4G

Cellular technologies such as GSM, 3G, and 4G offer high data rates and extensive coverage, making them suitable for real-time applications and large data volumes. Their ability to provide direct internet access and seamless cloud integration simplifies remote monitoring and data management.

However, these benefits come at the cost of high energy consumption. Cellular modules require constant network registration and signaling, which significantly increases power usage compared to LPWAN alternatives. According to 3GPP, mobile telecommunications are a major contributor to ICT-related energy consumption, prompting the development of more energy-efficient standards [25].

Cost is another consideration. Cellular deployments involve recurring expenses such as SIM cards, data plans, and network access fees. These costs can be prohibitive in large-scale or rural deployments. Despite this, cellular networks remain indispensable for applications requiring high reliability and bandwidth [26].

NB-IoT

NB-IoT offers strong indoor penetration, long battery life, and secure communication. It is particularly well-suited for applications such as smart metering, environmental monitoring, and infrastructure tracking.

From a cost perspective, NB-IoT presents a nuanced picture. While hardware modules are relatively affordable, total deployment costs, including network access and infrastructure, can vary widely depending on the region and operator. Comparative studies suggest that NB-IoT may be less cost-effective than LoRaWAN in areas with limited cellular coverage [27].

Technically, NB-IoT faces challenges such as low data rates, energy-intensive channel coding, and limited scalability. Ongoing research focuses on improving resource allocation and modulation efficiency. Migabo et al. (2020) emphasize the need for better scheduling and energy optimization to enhance NB-IoT performance in large-scale deployments [28].

Despite these challenges, NB-IoT remains a strong candidate for secure, licensed spectrum communication in urban and semi-urban environments where cellular infrastructure is already in place.

6.4 Comparison and Suitability for Eswatini

The selection of an appropriate wireless transmission technology for a distributed sensor system in Eswatini must consider the region's geographic, infrastructural, and economic constraints. Eswatini's rural areas often lack reliable cellular coverage and power infrastructure,

which places a premium on energy-efficient, long-range, and low-cost communication solutions.

Given these considerations, a hybrid communication architecture presents the most balanced and resilient solution. By combining ZigBee for local mesh communication, LoRaWAN for regional data aggregation, and GSM or NB-IoT for cloud uplink, the system can adapt to varying connectivity conditions and optimize energy usage. This layered approach ensures reliable data transmission across diverse terrains while minimizing operational costs and infrastructure dependency.

Such a hybrid model also enhances fault tolerance: if one communication layer fails, data can be rerouted through alternative paths. This flexibility is particularly valuable in Eswatini's rural context, where environmental and infrastructural unpredictability is common. Therefore, the hybrid approach not only aligns with technical requirements but also supports long-term sustainability and scalability of the sensor network.

6.5 Inter-Technology Communication and Integration

Effective communication between different wireless technologies within a hybrid sensor network is essential for ensuring seamless data flow and system reliability. In the proposed architecture for Eswatini, each technology, ZigBee, LoRaWAN, and GSM/NB-IoT-serves a distinct role and their integration must be carefully orchestrated to avoid data bottlenecks and ensure synchronization.

Gateway Bridging and Protocol Translation At the heart of inter-technology communication lies the gateway, which acts as a bridge between local ZigBee mesh networks and regional LoRaWAN infrastructure. These gateways must support multi-protocol communication stacks and perform real-time protocol translation. For example, data packets from ZigBee nodes are aggregated and reformatted into LoRaWAN-compatible payloads before transmission to regional collectors or cloud uplinks.

Data Aggregation and Buffering To accommodate differences in data rates and transmission intervals, intermediate nodes or gateways should implement buffering and aggregation mechanisms. ZigBee nodes may transmit frequently in short bursts, while LoRaWAN and GSM/NB-IoT links operate on scheduled intervals to conserve energy. Aggregation ensures that data is not lost during these transitions and allows for efficient batch transmission.

Synchronization and Time Stamping Accurate time stamping is crucial for correlating data across technologies. A lightweight synchronization protocol, such as the Network Time Protocol (NTP) or a GPS-based time source, can be used to align timestamps across ZigBee, LoRaWAN, and cellular modules. This ensures temporal consistency in datasets and supports reliable analysis.

Fault Detection and Routing Logic Hybrid systems benefit from intelligent routing logic that can detect faults or connectivity issues and reroute data accordingly. For instance, if LoRaWAN connectivity is disrupted due to terrain interference, the system can temporarily switch to GSM uplink or buffer data locally until transmission is restored. This dynamic routing enhances fault tolerance and system resilience.

By enabling robust communication between technologies, the hybrid architecture not only ensures reliable data transmission but also supports scalability and adaptability in diverse rural environments. This integration is key to maintaining system performance under varying operational conditions and aligns with the long-term sustainability goals of the sensor network.

7 Infrastructure Assessment

This section evaluates the infrastructural conditions relevant to deploying a distributed sensor system in Eswatini, with a focus on rural regions. It begins by analyzing the existing technological landscape, including cellular network availability, using data from OpenCelliD, a global, crowdsourced database of cell tower locations. This enables a realistic assessment of uplink communication feasibility via GSM or NB-IoT.

Eswatini is characterized by marked disparities between urban hubs, such as Mbabane and Manzini, and widespread, sparsely populated rural areas. The Ministry of ICT and the Eswatini Communications Commission (ESCCOM) anchor regulatory oversight, driving digital readiness and expansion [29][30]. While the state has prioritized digital transformation as a vector for economic growth, infrastructure rollouts remain uneven, with pronounced coverage and quality-of-service gaps outside major centers [31].

7.1 Existing Infrastructure in Eswatini

In Eswatini, mobile network operators (MNOs), notably MTN Eswatini and Eswatini Mobile, dominate the telecommunications sector, offering GSM services (2G/3G/4G) and, more recently, 5G in select areas. Fixed broadband and fiber connections remain limited, particularly outside urban centers, which further reinforces the central role of mobile networks in providing rural connectivity [32].

OpenCelliD is the world's largest open database of cell tower locations, offering detailed, crowdsourced cell site data via API and downloadable datasets [33]. As of 2025, the aggregated data from OpenCelliD indicate the following:

Region	**Towers**	**Technologies**	**Operators**	**Coverage Quality**
Urban Centers (Mbabane, Manzini)	∼90	2G/3G/4G/5G	MTN, Eswatini Mobile	Excellent, 95%+ population
Major Towns	∼60	2G/3G/4G	MTN, Eswatini Mobile	Good, 85–90% population
Rural Lowlands	∼50	2G/3G	MTN, Eswatini Mobile	Moderate, patchy
Rural Highlands	∼30	2G	MTN	Poor, dead zones

Table 1: Mobile Network Coverage in Eswatini by Region [33][34][35]

The table 1 reveals a clear concentration of cellular infrastructure in and around urbanized zones, with a sharp drop-off as population density declines into Eswatini's highland and low-

land rural districts. While the high-priority corridors and economic centers are well-served, rural communities face fragmented and often unreliable cellular access. The imbalance in cell tower coverage stems from economic and logistical constraints: infrastructure costs rise as population density falls, and challenging terrain exacerbates deployment difficulties. In practice, rural towers are spaced further apart, operate at lower capacity, and may be subject to intermittent power and maintenance interruptions.

LoRaWAN coverage does not exist in Eswatini, and this absence is largely due to infrastructural and economic priorities. The country's telecommunications landscape is dominated by mobile network operators like MTN and Eswatini Mobile, who focus almost exclusively on expanding cellular technologies, namely: 2G, 3G, 4G, and increasingly 5G. These technologies serve the majority of the population and are prioritized for both urban and rural connectivity efforts.

7.2 Integration Possibilities

This section will analyze possible integration methods for five specific stations: Bulembu Gold Mine, St Pauls Primary School Nkomati, Kupuka, Matsamo Border Gate Lomati, and Nkalashane. It will leverage the strengths of Zigbee, LoRa, and GSM technologies to craft robust architectures tailored to each site's unique geographic and infrastructure considerations. The ongoing digital transformation in Eswatini, including government ambitions to extend coverage and digital inclusivity, underpins feasibility considerations. The approximate distances to the nearest GSM towers were obtained by querying the OpenCellID database via Copilot's API interface [33][36]. To validate these values, approximate air-line distances were cross-checked using Google Maps. This combined approach ensures that the values presented are sufficiently accurate for feasibility analysis, while acknowledging that exact coverage conditions may vary in practice.

This table 2 provides a synthesized overview, but detailed consideration of each site is vital. For each location, the recommended integration approach addresses proximity to infrastructure, local environment, and available power sources, with a focus on maximizing rural connectivity reliability and minimizing deployment costs.

Bulembu Gold Mine is situated near Eswatini's mountainous northwest border, in a region characterized by challenging topography and sparse settlements. OpenCelliD data indicates that the nearest registered GSM towers are likely 7–15 km away, with the hilly terrain further increasing signal path losses. Under these conditions, direct GSM sensor deployment would risk coverage inconsistencies and elevated power consumption. A more suitable architecture involves placing a LoRa gateway on a promontory with LoS to a GSM-connected site, thereby bridging the LoRaWAN uplink from the mine to the GSM backhaul for onward data transmission. Within the mine itself, a local Zigbee mesh network can efficiently aggregate sensor data at very low power and cost, as Zigbee performs particularly well in dense, localized deployments where obstacles are metallic or structural and mesh formation remains stable.

Station	**Coordinates**	**Distance to Nearest GSM Tower**	**Expected Key Challenges**
Bulembu Gold Mine	25°56'54"S 31°12'57"E	7–15 km	Hilly terrain, power connection, GSM gaps
St Pauls Primary Nkomati	26°04'22"S 31°10'43"E	5–10 km	Variable GSM, school infrastructure
Kupuka	26°14'32"S 31°37'37"E	10–20 km	Remote, power, unpredictable coverage
Matsamo Border Gate Lomati	25°44'57"S 31°27'38"E	1–5 km	Cross-border interference, congestion
Nkalashane	25°58'48"S 31°56'27"E	15–25 km	Isolation, weak GSM, infrastructure gaps

Table 2: Recommended Integration Methods and Challenges for Selected Monitoring Stations in Eswatini

The primary integration tasks here include: site surveying for best LoRa gateway placement, directional antenna use to optimize GSM connectivity, and establishing a robust, battery- or solar-powered power supply for the electronics. Given the 7-15 km distance to the nearest GSM towers, a single elevated LoRa gateway with a high-gain antenna is likely sufficient-provided line-of-sight and Fresnel clearance can be achieved. If terrain obstructs the path, a relay node or repositioned backhaul may be required. The mine's operational presence may facilitate installation and regular maintenance of both Zigbee nodes and the gateway, but careful environmental hardening against dust and vibration will be necessary.

St Pauls Primary School in Nkomati benefits from its status as a community hub, often representing a priority for educational connectivity initiatives. OpenCelliD-based estimates suggest 5-10 km to the nearest GSM tower, making direct GSM connectivity plausible but potentially unreliable inside solid school buildings or during network congestion. The mixed structure of the school allows the aggregation of local sensor data via Zigbee within classrooms or between buildings, ensuring that low-cost, low-power nodes efficiently gather environmental, energy, and usage statistics.

A small LoRaWAN gateway, preferably placed on a school rooftop or mast, can bridge Zigbee sensor clusters to GSM backhaul. The school may already have access to grid power or a community-level solar system, simplifying gateway powering. Integration should prioritize ensuring that the LoRa gateway is both physically secure and electrically protected, since school sites are subject to greater human activity and potential interference than isolated mining areas.

Kupuka Kupuka presents a typical rural connectivity challenge: a remote settlement with minimal infrastructure and an estimated 10-20 km distance to the nearest GSM tower, based on OpenCelliD mapping. In this context, deploying a dedicated LoRaWAN gateway powered by a small off-grid solar PV system would be an option to enable low-power sensor communication. Where LoRa cannot reliably bridge the full distance to a GSM-connected site, a directional LoRa backhaul or multi-hop relay configuration, using elevated terrain points, could be considered to extend coverage.

Due to the site's isolation, minimizing the need for physical maintenance is critical. All gateway and relay components should be weather-resistant, wildlife-proof, and serviceable using locally available tools. Where possible, community-based monitoring and basic training in fault identification could support long-term sustainability. To accommodate intermittent GSM availability, the data backhaul should emphasize bandwidth efficiency, with edge-level preprocessing to reduce transmission volume.

Matsamo Border Gate Lomati Serving as both a national border post and transport hub, Matsamo Border Gate offers the best proximity to established infrastructure, with the closest GSM towers only about 1-5 km away and robust trans-border road and utility links. In this context, direct GSM integration for sensors is practical and cost-effective. For sensor-rich installations (such as for environmental monitoring of the border perimeter), a Zigbee mesh within the compound feeds into a GSM-connected coordinator node.

Because border areas may experience congestion, signal interference, or policy-driven network filtering from neighboring South African networks, the deployment should use multi-network SIMs for redundancy and configure fallback routines into the network protocol. Further, cross-border interference may necessitate coordination with spectrum regulators on both sides, reinforcing the importance of using license-exempt frequencies aligned with Eswatini's published spectrum usage guidelines

Nkalashane is characterized by its isolation and difficult terrain, with estimated distances to GSM infrastructure stretching up to 15-25 km. Here, LoRaWAN is the most practical backbone, with a gateway situated at the best possible local elevation and equipped with directional antennas. Multiple relay devices may be needed to bridge to any GSM gateway for uplink. Sensor clusters using Zigbee connect within manageable range and relay to the local LoRaWAN node, then onward via LoRaWAN's substantial rural coverage potential, especially when properly oriented and interference is minimal.

The critical task is identifying high-ground points and preparing robust power solutions. Solar energy, as commonly deployed in rural Sub-Saharan Africa, is the best option. Data may be batched for infrequent GSM transmission, or mesh-linked with other remote sites to relay data to wherever GSM contact is most reliable on a given day. Edge computing for data filtering and compression at the local gateway is crucial to ensure efficient use of limited uplink bandwidth.

This tiered approach of using Zigbee for local collection, LoRa for regional aggregation, and GSM for global relay ensures full connectivity across diverse terrain while minimizing hardware, energy, and maintenance overhead. It aligns with best practices for rural African deployments, where resource constraints demand resilient and scalable network design.

To minimize operational costs and ensure ease of data management, sensor data should be preprocessed locally, at the LoRa gateway or even the Zigbee mesh coordinator, before transmission. Edge computing enables data filtering, aggregation, compression, and prioritized batch transmission, significantly reducing the dependency on high-cost or limited GSM bandwidth. Many successful agricultural and environmental monitoring projects in rural Africa demonstrate this strategy's value [37]. In addition, LoRaWAN's support for adaptive data rates and duty cycle control can be leveraged to conserve energy and optimize transmission success rates without sacrificing essential monitoring fidelity.

7.3 Potential Obstacles and Solutions

While the theoretical framework for integrating distributed sensors via Zigbee, LoRa, and GSM appears straightforward, the reality on the ground is far more complex. Terrain irregularities, inconsistent power supply, sparse cellular coverage, and limited technical maintenance capacity in rural Eswatini introduce significant challenges. These factors can disrupt even well-planned deployments, making reliability and scalability harder to guarantee without substantial infrastructural support. These are some of the key obstacles and potential mitigation strategies:

Power Supply Challenges: Almost all rural deployments in Eswatini must contend with unreliable or entirely absent grid electricity, especially acute in Kupuka and remote parts of Nkalashane. Even where grid power is present, unpredictability during storms or brownouts jeopardizes continuous sensor operation. The most effective countermeasure is to use proven solar PV/battery hybrid systems sized according to local insolation patterns, sensor and gateway load profiles, and forecasted days without sunlight. Studies show that even modest systems (e.g., 20-40W PV panel plus 30-60Ah battery) can sustain low to moderate sensor and gateway loads for up to a week of poor weather [38][39]. An added benefit is easier installation (no need for utility connection) and the opportunity for students or local staff to participate in basic maintenance. Complementary solutions include supercapacitor banks for rapid cycling, efficient deep-sleep regimes for all devices, and periodic diagnostics preventing outright drain.

Vandalism, Theft, and Wildlife Risks: Solar arrays, batteries, and exposed radio units may face vandalism, casual theft, or animal damage-issues reported in multiple rural network case studies and echoed in Sub-Saharan project lessons. Especially for unmanned sites like Kupuka or isolated border sensors, infrastructure hardening is essential. Mitigation steps range from simple (metal cages, tamper-proof bolts, ground-mounted panels at odd angles to reduce visibility) to complex (remote tamper detection, sensor health reporting, and even integrating community 'ownership' models for protection). Local hiring for periodic cleaning and inspection encourages community buy-in and fosters long-term sustainability.

Weather and Extreme Conditions: Most terrain-induced barriers have been addressed through careful topographical planning and adaptive antenna configurations, allowing reliable signal propagation even in Eswatini's more rugged zones. However, weather-related challenges remain a persistent threat. Seasonal extremes-particularly heavy rainfall and dust storms, continue to compromise sensor integrity and radio performance. These environmental stressors demand ongoing mitigation through robust hardware design, predictive diagnostics, and maintenance protocols tailored to local climatic conditions. Deployment must use weatherproof enclosures (rated to at least IP65 or IP67), conformal coating on sensitive PCBs, and all cable entries should be downward-facing or double-gasketed. Sensors with built-in diagnostics that can flag early signs of water ingress or dust buildup are advantageous, providing early warning before data loss or outright failure.

Spectrum Licencing and Interference: Despite recent progress by Eswatini's regulatory authorities to open up license-exempt spectrum for IoT and sensor network use, deployment planners must remain vigilant to both regulatory shifts and interference risk from neighboring countries or commercial operators [15]. In border zones (e.g., Matsamo), overlapping coverage and conflicting channel plans could induce interference or even intentional jamming from competing systems. Best practice involves continuous regulatory engagement, use of standards-compliant equipment with flexible channel setting, and the ability to coordinate with South African spectrum managers in places where channel overlap is likely. All deployed devices should be swiftly reconfigurable in the field to adapt to new mandates or emergent interference without requiring entire hardware replacement.

Skills Availability and Community support: In rural Eswatini, local capacity for supporting digital systems is mixed, often requiring either regular training or partnership with regional universities, technical high schools, or NGOs to ensure rapid diagnosis and response to network problems. Integration plans should include structured training for local users, teachers, health workers, or mine operators on basic fault finding, panel cleaning, and data network rebooting. Capacity building paired with simple, visual diagnostics on key assets minimizes need for costly expert intervention, embedding sustainability and local digital expertise as part of Eswatini's national goals.

Data Security and Network Longevity: With increasing exposure to networked IoT, Eswatini will face rising risks of data interception, unauthorized access, and sensor spoofing or jamming attacks. Rural sites may be slower to patch vulnerabilities or respond to breaches. Security measures begin with using only authenticated and encrypted protocols (Zigbee AES-128 [40], LoRaWAN end-to-end encryption [41]), strong physical security for all access points, and geofenced or anomaly-flagging network management tools.

Deploying a distributed sensor system across rural Eswatini's diverse landscape presents significant but surmountable challenges. Careful integration of Zigbee, LoRaWAN, and GSM-tailored to the specific conditions of each of the five target stations, offers one possible pathway toward robust, scalable, and cost-efficient monitoring that can survive and adapt to variability in coverage, power, and environment. Key obstacles including network and power gaps, security risks, and maintenance capacity must be systematically addressed with hybrid technical designs, thorough site engagement, and strong community partnerships.

8 System Architecture

This section outlines a proposed end-to-end architecture for a distributed water monitoring system in Eswatini. It highlights the intended data flow, sensor-to-gateway and gateway-to-cloud communication, cloud integration, as well as security and scalability considerations that should be taken into account during system design and deployment.

8.1 End-to-End Data Flow

The proposed system could follow a structured end-to-end pipeline that supports reliable acquisition, transmission, and utilization of environmental and hydraulic data from distributed field sites in Eswatini. Each stage of the pipeline should be designed with the constraints of remote deployments in mind, including limited power availability, intermittent connectivity, and the need for reproducibility and scalability.

Sensing: At the field level, low-power sensor nodes will continuously monitor critical parameters such as water level, electrical conductivity, temperature, and device health indicators (e.g. battery voltage). These measurements should be timestamped using a gateway-synchronized real-time clock to ensure temporal consistency across the network. The sensing strategy could be adaptive: under normal conditions, nodes might report at low frequency to conserve energy, while threshold violations (e.g. sudden water level rise) should trigger higher-frequency sampling windows. This approach would balance energy efficiency with responsiveness to hydrological events [8].

Local preprocessing: Before transmission, the gateway will perform lightweight preprocessing to reduce noise and data volume. This might include calibration correction, outlier filtering, and normalization of timestamps. Where multiple sensors are co-located, the gateway could aggregate readings into compact batches, applying delta encoding to minimize payload size. Such preprocessing would not only reduce bandwidth requirements but also ensure that downstream cloud services receive structured, validated input.

Transport: The gateway will be responsible for securely forwarding telemetry to the cloud. Data will be batched and signed using device-specific private keys, ensuring authenticity and integrity. Depending on network availability, the gateway might select between the *Message Queuing Telemetry Transport (MQTT)* protocol over *Transport Layer Security (TLS)* (for persistent, lightweight connections) and HTTPS POST (for intermittent or mobile connections). Retransmission strategies with exponential backoff and jitter could be employed to handle unreliable mobile coverage, which is a known challenge in Eswatini's rural regions [34]. To prevent data loss during outages, the gateway should maintain a persistent local queue with configurable retention.

Ingestion: Upon arrival at the cloud endpoint, telemetry could undergo authentication and validation. Each batch should be verified against the gateway's certificate, and malformed or replayed packets would be discarded. Validated data could then be routed through a message bus (e.g. AWS Kinesis or Simple Notification Service, SNS) to multiple consumers. The primary consumer might persist the data in a time-series database (e.g. Amazon Timestream), while secondary consumers could trigger anomaly detection functions and generate event notifications. Instead of distributing messages directly to individual stakeholders, the system could integrate with a dedicated front-end platform, *ES-MIS* [42], which would provide a unified interface for data visualization and analysis. This approach should ensure that all users access consistent, validated information through dashboards and reports, rather than receiving fragmented or ad-hoc notifications. The modular ingestion design could further allow the system to scale horizontally as the number of monitored sites increases.

Presentation: The final stage of the pipeline could be implemented as a modular presentation layer that transforms raw telemetry into actionable insights. A dashboard interface, potentially built on Grafana or integrated into the custom ES-MIS front end would allow operators to visualize real-time trends in water levels, conductivity, and system health metrics. Historical data could be retained in a time-series database to support long-term analysis and seasonal comparisons. While alerting mechanisms such as email, (short message service), or webhook integrations are not currently active, they could be added to notify stakeholders of anomalies including sensor failures, data gaps, or threshold exceedances. Additionally, export endpoints might be provided to support integration with external research workflows, enabling both operational monitoring and academic analysis through reproducible data access.

In summary, the end-to-end data flow should be modular, resilient, and reproducible. Each stage, from sensing to visualization and could contribute to a robust monitoring pipeline that would operate under the constraints of remote deployments while remaining extensible for future scaling and integration.

8.2 Sensor-to-Gateway Communication

The communication between sensor nodes and the gateway could be structured to balance energy efficiency, reliability, and maintainability under the constraints of remote deployments in Eswatini. Informed by the Infrastructure Assessment, each site might follow a *star topology*, where multiple sensor nodes connect wirelessly to a single gateway. This approach should minimize the number of gateways required, simplify maintenance, and reduce overall system cost, which is particularly important in rural areas where technical support capacity is limited.

For the wireless link, different technologies could be employed depending on deployment density, terrain, and range requirements. In dispersed rural sites with weak or distant GSM

coverage, communication should be considered due to its low-power, wide-area characteristics and ability to bridge several kilometers when line-of-sight is available. In contrast, for clustered deployments such as schools or border posts, Zigbee could be more suitable for short-range, low-power aggregation. This flexibility would allow the system to adapt to heterogeneous field conditions, from mountainous mining areas to community hubs with partial GSM access.

The sampling strategy could be adaptive: under normal conditions, nodes might report at low frequency to conserve energy, while threshold violations or rapid environmental changes should trigger higher-rate sampling windows. This would ensure responsiveness to hydrological events without compromising long-term autonomy of solar-powered nodes. Given the unreliable grid power in many rural sites, energy-aware sampling and duty cycling should be prioritized to extend operational lifetime.

To improve local reliability, each sensor node could maintain sequence numbers and a small non-volatile buffer, allowing data to survive transient gateway outages or weak GSM backhaul. Packets should include per-frame cyclic redundancy checks (CRC) and lightweight acknowledgement (ACK/NACK) mechanisms to ensure integrity and retransmission when necessary. In areas with extended outages, buffering at the node level would be essential to prevent data loss [43].

Message Format Example: Sensor messages are transmitted as compact binary frames that include fields for node identification, sequence tracking, timestamping, sensor readings, battery voltage, and a CRC16 checksum for integrity verification. For diagnostics and cloud ingestion, these frames are decoded into structured JSON objects. The following template illustrates the typical format of a decoded sensor message:

```
{
  "node_id": "node-012",
  "seq": 12345,
  "ts": "2025-08-21T10:15:00Z",
  "sensors": {
    "level_cm": 215,
    "temp_C": 23.4,
    "cond_uS": 520
  },
  "bat_V": 3.71
}
```

This format ensures consistent parsing across gateway and cloud components, supports schema validation during ingestion, and enables seamless integration with the ES-MIS dashboard for visualization and analysis. A typical message of this structure occupies approximately **220–260 bytes** when serialized as UTF-8 JSON, depending on field precision and formatting. When batched and compressed at the gateway, multiple messages can be reduced to under **100 bytes per reading**, significantly optimizing bandwidth and storage [44].

8.3 Gateway-to-Cloud Communication

The gateway could serve as the critical bridge between local sensor networks and the cloud infrastructure. It should not only forward telemetry but also perform selective preprocessing and buffering to reduce dependency on continuous uplink. This division of responsibilities would allow the system to operate autonomously under rural Eswatini's intermittent connectivity, while still leveraging the scalability of cloud services for long-term storage and analytics.

Gateway responsibilities: The gateway could aggregate and compress sensor frames into batches, applying optional delta encoding to reduce payload size. Each batch should be enriched with metadata such as device health metrics and a monotonic batch sequence number to support traceability and replay protection. To guarantee authenticity and integrity, batches could be signed with a device-specific private key using the Elliptic Curve Digital Signature Algorithm (ECDSA), with the corresponding certificate thumbprint included for verification in the cloud. For transport, the gateway might adopt an adaptive strategy using the MQTT protocol over TLS for persistent connections where available, and falling back to HTTPS POST with retries in more constrained or mobile network environments. In sites with weak GSM coverage, the gateway could also delay transmissions until sufficient signal strength is available, or opportunistically forward data through multi-hop LoRa backhaul, where feasible.

Reliability and backoff: To maintain robustness under intermittent connectivity, the gateway should implement exponential backoff with jitter for reconnect attempts, thereby avoiding synchronized retry storms. A local persistent queue with a configurable time-to-live (TTL) could buffer telemetry during extended outages, ensuring eventual delivery without overwhelming storage. Given the power constraints identified in the infrastructure assessment, queue management should be optimized for energy efficiency, with edge-level filtering and compression to minimize uplink volume. In addition, a lightweight heartbeat channel might be maintained to support remote device management commands and over-the-air configuration updates, enabling operators to adjust system parameters without requiring physical access to the gateway.

Hybrid system considerations: The hybrid design implies that part of the processing pipeline could remain at the edge (e.g. filtering, aggregation, anomaly pre-detection), while more resource-intensive analytics and long-term storage should be handled in the cloud. This approach would allow the system to continue functioning even during extended GSM outages, while still benefiting from the elasticity and integration capabilities of cloud platforms. Such a division of responsibilities directly addresses the infrastructural challenges highlighted in the assessment, including patchy rural coverage, power limitations, and the absence of LoRaWAN backbone infrastructure.

8.4 Cloud Integration, AWS, Databases, Visualization

The cloud layer will provide the scalable backbone for long-term storage, analytics, and visualization of water monitoring data. It will complement edge processing at the gateways by handling resource-intensive tasks that cannot be reliably executed in rural Eswatini due to power and connectivity constraints.

Integration with cloud services: A public cloud platform such as Amazon Web Services (AWS) could be employed to host the system's data ingestion, storage, and analytics pipelines. Gateways would forward authenticated and signed batches of telemetry to an IoT ingestion service (e.g. AWS IoT Core) which could then route messages into a managed data stream for further processing. This architecture would allow the system to elastically scale with the number of deployed sites while maintaining secure, verifiable data flows.

Database design: For structured sensor data, a time-series optimized database (e.g. Amazon Timestream or an equivalent open-source alternative) could be used to store high-frequency telemetry efficiently. Metadata such as device health, site identifiers, and batch sequence numbers should be indexed to support traceability and anomaly detection. To ensure resilience, data could be replicated across multiple availability zones, with retention policies balancing cost and long-term research needs.

Visualization and dashboards. The cloud layer could expose validated data to a visualization platform, enabling stakeholders in Eswatini to access real-time and historical insights. A web-based dashboard (e.g. built on Grafana or AWS QuickSight) might provide interactive charts, geospatial overlays, and alerting mechanisms. Integration with the ES-MIS [42] front end would ensure that water monitoring data is accessible alongside other environmental and socio-economic indicators, supporting unified decision-making.

Hybrid system considerations: Given the patchy GSM coverage and intermittent uplinks identified in the infrastructure assessment, the cloud should be designed to tolerate delayed or batched uploads. Data pipelines must handle out-of-order arrivals gracefully, ensuring that late-arriving telemetry is still incorporated into the time series without duplication. Security should be enforced end-to-end, with TLS encryption in transit, ECDSA signature verification at ingestion, and role-based access control for visualization and analytics tools.

8.5 Security and Scalability Considerations

The proposed distributed water monitoring system must be designed with both security and scalability in mind. Given the sensitivity of environmental data and the long-term ambition to expand deployments across Eswatini, the architecture should ensure confidentiality, integrity, and availability while remaining adaptable to future growth.

Security considerations: End-to-end security should be enforced across all communication layers:

- **Encryption in transit:** All sensor-to-gateway and gateway-to-cloud links could use authenticated encryption (e.g. AES-128 for Zigbee, LoRaWAN's built-in end-to-end encryption, and TLS 1.3 for MQTT/HTTPS uplinks) [43].
- **Authentication and integrity:** Gateways should sign batches with device-specific private keys (ECDSA), including certificate thumbprints for cloud-side verification. This ensures that only trusted devices can inject data into the system [45].
- **Access control:** Role-based access policies in the cloud should restrict data visibility to authorized stakeholders (e.g. researchers, government agencies), with audit logging to track access and configuration changes [46].
- **Physical security:** Given risks of vandalism, theft, or tampering in rural deployments, gateways and solar power systems should be housed in tamper-resistant enclosures, with optional intrusion detection (e.g. tamper switches or anomaly reporting).
- **Resilience to interference:** Border sites such as Matsamo may face cross-border spectrum interference. Flexible channel assignment and standards-compliant radios should be used to mitigate jamming or congestion.

Scalability considerations: The system should be designed to scale from a handful of pilot sites to a nationwide deployment:

- **Horizontal scaling:** The cloud ingestion pipeline (e.g. AWS IoT Core or equivalent) should elastically scale with the number of gateways, ensuring that additional sites can be added without re-architecting the system.
- **Database scalability:** Time-series databases should support partitioning and retention policies, allowing high-frequency data to be stored cost-effectively while archiving or downsampling older records.
- **Adaptive data rates:** LoRaWAN's adaptive data rate (ADR) and duty-cycle control could be leveraged to optimize spectrum use as node density increases, conserving energy while maintaining reliability.
- **Batching and compression:** As deployments expand, gateways should continue to batch and compress data to minimize bandwidth costs, especially in rural areas with constrained GSM backhaul.
- **Modular expansion:** The architecture should allow new sensor types (e.g. water quality, soil moisture, weather) to be integrated without disrupting existing deployments, using standardized data schemas and APIs.

Hybrid system implications: The hybrid edge–cloud design directly supports both security and scalability. By performing preprocessing, filtering, and anomaly detection at the gateway, the system reduces the volume of data transmitted over costly or unreliable GSM links. At the same time, the cloud provides elastic resources for long-term storage, visualization, and advanced analytics. This division of responsibilities ensures that the system can grow sustainably while maintaining robust security guarantees [46].

In summary, the security and scalability of the proposed system depend on a layered approach: strong cryptographic protections and physical safeguards at the edge, combined with elastic cloud services and modular design principles. This ensures that the monitoring network can expand across Eswatini while remaining resilient to both technical and environmental challenges.

8.6 Example Flow

Component Diagram: The component diagram below provides a structural view of the system, showing the main building blocks and their interactions. At the sensing layer, multiple water sensors transmit data to a LoRa Gateway, which acts as the first aggregation point. The gateway forwards data via a Cell Tower (Base Station) into the wider network infrastructure, where it is relayed to the cloud platform. Within the cloud, data is stored, verified, and made available to the front-end service, which provides dashboards and user interaction.

This diagram 9 illustrates the modular responsibilities of each component and the transition from physical devices to digital services. Rather than detailing specific protocols, it highlights the logical dependencies that structure interactions between system parts.

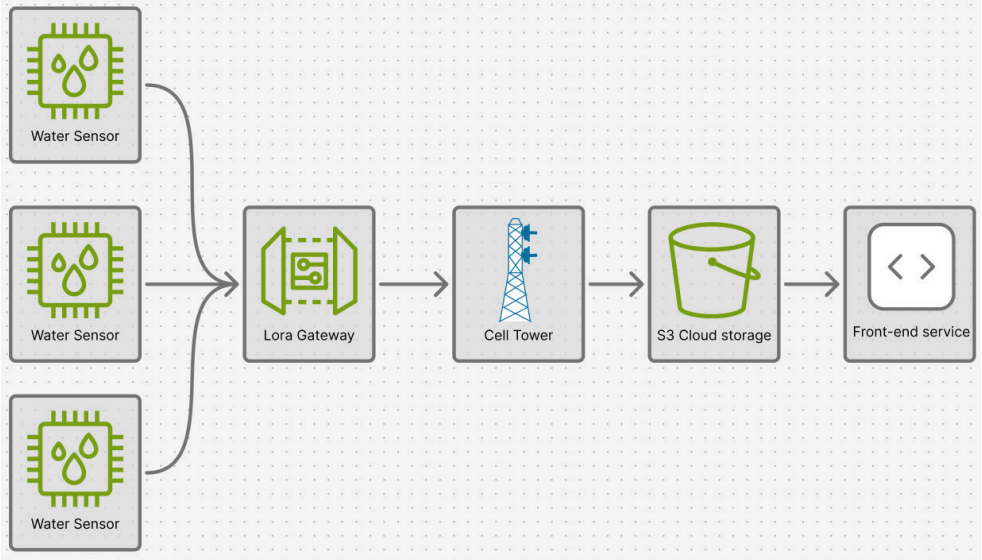


Figure 9: Core Components of the Monitoring System [created by Maximilian Mirnik]

Flow Diagram: To complement the structural view, the following flow diagram illustrates the dynamic behavior of the system. It traces how data moves step by step, beginning with periodic sampling at the sensor level, continuing through gateway aggregation and signing, passing through network infrastructure, and finally reaching the cloud for verification, storage, and anomaly detection. If anomalies are detected, alerts are generated and surfaced in the front end.

The flow diagram 10 thus provides a process-oriented perspective, showing how decision points and data handling logic are distributed across the five stages: Sensor, Gateway, Network Infrastructure, Cloud, and Front End.

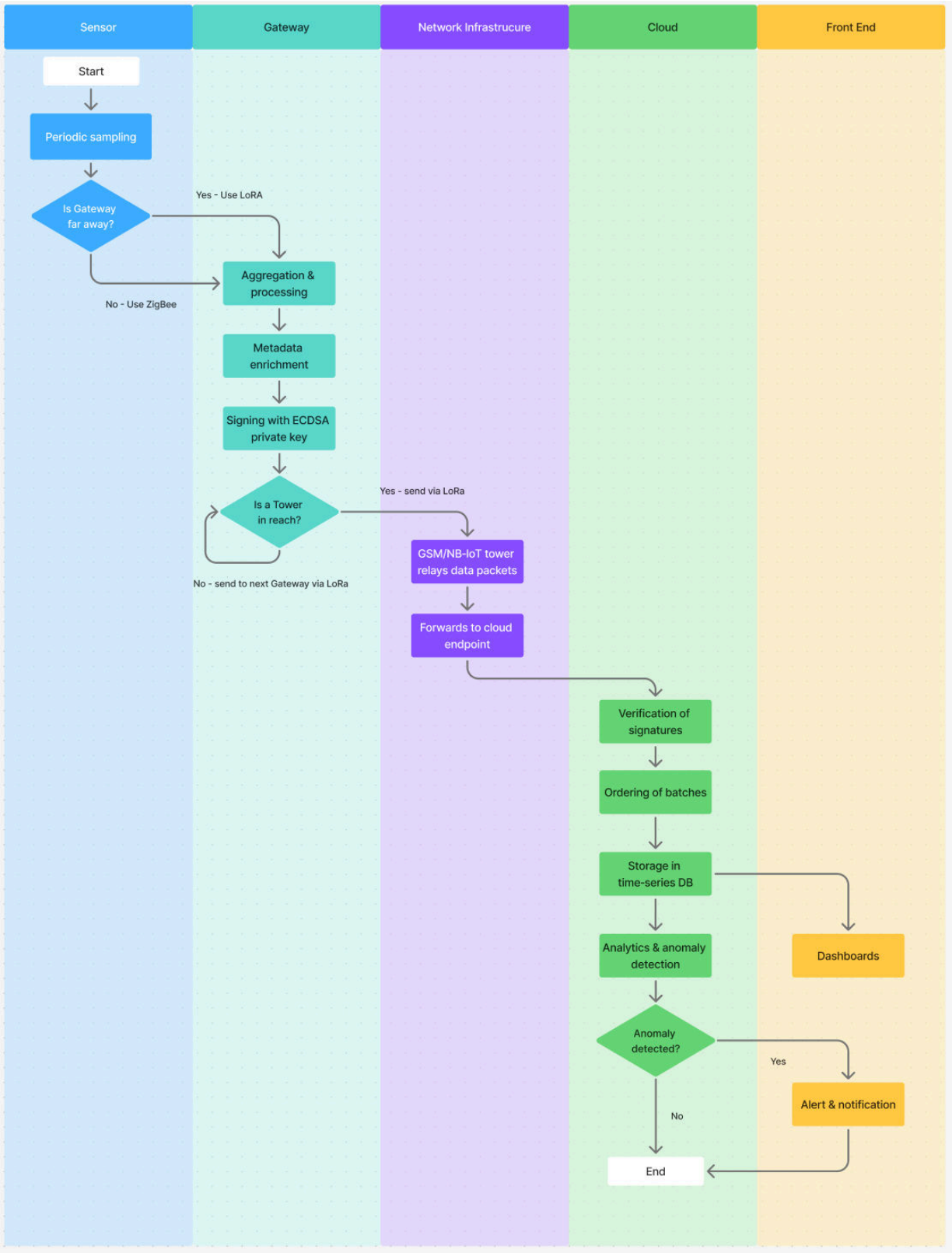


Figure 10: End-to-End Data Flow [created by Maximilian Mirnik]

9 Discussion

The preceding chapters have outlined the design and implementation of the proposed system architecture for distributed water monitoring. While the architecture chapter focused on describing the technical components and their integration, the following discussion shifts the perspective towards interpretation and reflection. The aim is to critically evaluate how well the architecture addresses the initial research problem, to situate the design within the context of related work, and to highlight both its strengths and limitations. Beyond this evaluation, the discussion also considers the broader implications of the system and outlines potential directions for future development.

9.1 Interpretation of Results

The first research question examined the suitability of combining multiple wireless transmission technologies with existing infrastructure for reliable and cost-efficient data transfer in Eswatini. The results support a hybrid strategy that leverages short-range, low-power protocols (e.g. LoRaWAN, ZigBee) for sensor-to-gateway links and long-range cellular connectivity (e.g. GSM) for backhaul where coverage exists. This layered design aligns well with heterogeneous terrain and intermittent connectivity, and when gateways are placed to match topography and infrastructure, can achieve regular data delivery without excessive energy or monetary costs.

This suitability depends on specific conditions. Coverage gaps, variable signal quality, and terrain-induced line-of-sight constraints limit long-range reliability. In contrast, reliable short-range links require careful attention to gateway density, antenna positioning, and interference control within shared spectrum. Power reliability and maintenance capacity directly affect uptime, while heterogeneity across devices and local operator policies introduces configuration overhead. Cost-effectiveness varies with local tariffs, data plans, and operational support: the architecture minimizes overhead by buffering and compressing at the edge but total cost of ownership ultimately depends on organizational practices (e.g. monitoring routines, spares, training). In sum, the hybrid approach is suitable under the identified constraints and demonstrates a pragmatic balance, yet its reliability and cost profile remain sensitive to site-specific deployment choices and ongoing operational discipline.

The second research question concerns whether a modular end-to-end architecture that combines cloud services with edge components can enable scalable, secure, and cost-optimized collection, storage, analysis, and visualization. The proposed design establishes a clear separation of concerns: gateways perform local aggregation, preprocessing, and buffering to bridge connectivity gaps, while the cloud layer provides managed ingestion, durable storage, analytics, and visualization via ES-MIS. This division is technically sound, supports resilience and incremental scaling from pilot to multi-site deployments, and allows components to be replaced without redesigning the entire system.

A concrete view highlights that scalability is reasoned from architectural principles (managed services, modularity) rather than stress-tested benchmarks across high node counts

or multi-region scenarios. Security controls are specified, including segmentation, managed identities, and encryption at rest and in transit, while comprehensive validation of operational posture, key lifecycle management, access governance, and incident response remains beyond the present scope. Cost optimization is addressed through edge preprocessing and selective use of managed services. However, long-term costs depend on data retention policies, cellular pricing dynamics, egress charges, and local support capacity, which have been analyzed conceptually rather than modeled longitudinally. These gaps are practical and expected for this level of implementation, and they define clear targets for future trials and audits.

Overall, the thesis answers the two questions to the extent that it (1) demonstrates a context-appropriate hybrid transmission strategy that is reliable and cost-aware when aligned with local infrastructure and disciplined operations, and (2) provides a coherent end-to-end blueprint whose modular edge–cloud separation supports scalability, security, and cost-consciousness in principle. Full confirmation requires extended field deployments, performance and cost benchmarking under load, and structured security assessment, which are proposed as next steps.

Potential weaknesses and risks: Beyond addressing the core research questions, the architecture exhibits several strengths that reinforce its suitability under Eswatini's constraints. Its modular interfaces-spanning data schemas, messaging protocols, and API boundaries enable gradual integration of heterogeneous sensors and gateways without redesigning core components, supporting evolution and vendor diversity as deployments expand. Fault tolerance is strengthened at the edge through local buffering, retry logic, and preprocessing, which together mitigate outages and bandwidth limitations and thereby sustain regular data delivery across intermittent links. The clear separation of layers fosters operational observability, allowing targeted monitoring of gateway health, link quality, and ingestion pipelines. This accelerates incident detection and root cause analysis, translating architectural clarity into actionable operations. Maintainability and reproducibility are enhanced by standardized configurations and layered deployment templates which reduce configuration drift and enable controlled updates across sites, a practical foundation for scaling beyond pilot contexts outlined by the second research question. Security benefits from segmentation across sensor, gateway, and cloud boundaries. This segmentation simplifies the application of least privilege, scoped credentials, and encryption in transit and at rest. Although it is not a substitute for formal audits, the resulting structure provides a defensible baseline that aligns with the thesis' security goals.

Cost-awareness is embedded through edge-side filtering and compression, as well as tiered storage lifecycles (from hot to archive), limiting unnecessary data volumes and egress charges without sacrificing analytical fidelity. The ES-MIS dashboard consolidates stakeholder needs into a unified interface, reducing ad-hoc tooling and clarifying roles between operators, analysts, and decision-makers this strengthens the practical utility emphasized in the first research question's focus on regular, reliable transmission. Finally, context-aware

deployment-mapping power availability, coverage, and terrain to inform antenna selection and gateway density avoids overengineering, while elevating performance where it matters. All in all, these strengths demonstrate that a hybrid, layered design can be both adaptable and operationally grounded: it not only aligns with the research questions requirements for reliability, scalability, and cost-consciousness, but also provides concrete mechanism-interoperability, edge resilience, observability, and governance through which those requirements can be sustained over time.

Despite its strengths, the proposed architecture carries several practical risks that temper its theoretical promise. Environmental robustness is a primary concern: sensors and gateways exposed to heat, humidity, dust, or vandalism will suffer degraded accuracy and reduced uptime, and the protective enclosures and maintenance cycles required to mitigate these effects increase capital and operational costs. Closely related is the challenge of calibration and data quality, sensor drift, biofouling, and inconsistent calibration procedures can introduce bias and noise into the dataset, undermining downstream analytics unless routine QA/QC (quality assurance / control) workflows and spare part strategies are institutionalized. Time synchronization and latency variability further complicate the analysis as inconsistent clocks and intermittent transmission delays hinder temporal alignment, event correlation, and reliable anomaly detection across distributed sites.

Operational risks stem from limited local capacity and skills: successful installation, troubleshooting, and governance require trained personnel, clear documentation, and sustained support, all of which represent recurring investments that affect long-term viability. Governance and data stewardship are equally important. Without explicit policies for access control, data retention, provenance tracking, and incident handling, the system risks compliance gaps, fractured ownership, and eroded stakeholder trust. Architectural choices can also create vendor lock-in and portability challenges reliance on specific managed services simplifies operations but may impede migration or hybrid strategies unless open formats, containerization, and infrastructure-as-code practices are enforced.

Financial sustainability is uncertain because cost variability, cellular tariffs, egress fees, and long-term storage charges can change over time. Budgets must therefore include allowances for growth, spares, and maintenance to avoid hidden total cost of ownership escalation. The very modularity that enables extensibility also introduces complexity: more components mean more interfaces to secure and maintain, increasing integration overhead and dependency management burdens that can overwhelm small teams. Regulatory and data sovereignty constraints may further restrict deployment options.

Finally, scalability and resilience assumptions deserve scrutiny. High-frequency sampling, bursty events such as storms or contamination spikes, and multi-region expansion can reveal ingestion and processing bottlenecks if not stress-tested. Local buffering and retry logic depend on sufficient storage and power stability, and prolonged outages can still produce backlogs, clock skew, or data loss if bounded recovery strategies are absent. These weaknesses do not invalidate the architecture but identify concrete limitations: addressing them requires targeted design hardening, explicit operational playbooks, field validation under representative conditions, and ongoing investment in local capacity and governance.

9.2 Comparison with Related Work

Existing monitoring architectures typically follow one of three patterns: centralized systems that rely on a monolithic backend and heavy upstream connectivity, purely cloud-native approaches that assume persistent high-bandwidth links, or local-first designs that prioritise edge autonomy at the expense of centralized analytics [47]. Each approach targets different trade-offs between reliability, cost, and operational complexity.

The architecture proposed in this thesis aligns with established best practices in several respects. Like hybrid gateway patterns described in the literature, it uses modular gateways to aggregate and preprocess sensor data, reducing bandwidth needs and enabling incremental rollouts [48]. The introduction of a unified visualization layer mirrors trends toward dashboard-centric stakeholder engagement, consolidating operational telemetry and analytical outputs into a single interface that supports both on-site operators and remote decision-makers [49]. These points of alignment show that the design adopts proven architectural primitives while adapting them to the domain-specific constraints identified for Eswatini.

Where the design diverges is in its explicit, proposal-oriented treatment of site-specific constraints and its combination of multiple wireless technologies with managed cloud services. Rather than prescribing a single dominant layer, the thesis argues for a context-driven layering: short-range, low-power protocols for sensor-to-gateway links and cellular backhaul for long-range transport where feasible, combined with edge buffering and cloud-managed ingestion [50]. The ES-MIS integration is presented not merely as a visualization add-on but as the unifying operational layer that codifies stakeholder roles, access patterns, and data provenance. This divergence emphasises practical deployability in heterogeneous, resource-constrained settings rather than idealised network assumptions.

The unique contributions of this work are therefore twofold. First, it provides a disciplined, site-aware hybrid design that explicitly maps infrastructural realities (power, coverage, terrain) to technology choices, producing a repeatable decision framework rather than a one-size-fits-all blueprint [48]. Second, it frames modularity and reproducibility as first-class concerns by combining deployment templates, interface contracts, and a concrete dashboard integration path (ES-MIS) which, together, lower the barrier for iterative pilots and staged scale-up [49]. These contributions position the thesis between strictly academic architectures and ad-hoc field solutions, offering a middle ground that is both theoretically grounded and operationally pragmatic.

Finally, compared to related deployments reported in similar contexts, this architecture foregrounds governance, operational observability, and QA/QC workflows as integral elements rather than afterthoughts [47][50]. While other works may prioritise either cloud scale or maximal edge autonomy, this thesis synthesises those priorities into a balanced approach designed to be actionable for stakeholders with limited technical capacity and variable infrastructure, making it particularly relevant for translational projects in developing-country contexts [48].

9.3 Implications

The proposed architecture carries several implications that extend beyond the immediate research questions. On a **practical level**, the system provides stakeholders such as researchers, local operators, and NGOs with a reproducible and transparent framework for water quality monitoring. Researchers benefit from standardized data collection and modular interfaces that facilitate comparative studies and integration with existing datasets. Local operators gain a resilient tool that continues to function under intermittent connectivity, while NGOs and development agencies can rely on the ES-MIS dashboard to access validated information for programmatic decision-making and community engagement.

From a **theoretical perspective**, the work contributes to the broader field of distributed monitoring by demonstrating how hybrid communication strategies and modular edge–cloud integration can be adapted to resource-constrained environments. The design illustrates that scalability and reproducibility are not limited to high-resource contexts but can be achieved through careful layering of technologies and separation of concerns. This adds to the literature by framing modularity not only as a technical convenience but as a principle for ensuring long-term adaptability and generalizability across diverse infrastructural settings.

In terms of **policy and development**, the architecture highlights the potential role of distributed monitoring systems in sustainable infrastructure planning. By aligning technical design with local constraints, the system provides a blueprint for cost-aware, resilient deployments that can inform national water management strategies and donor-funded initiatives. The emphasis on modularity and reproducibility ensures that investments made at pilot level can be expanded incrementally, reducing the risk of stranded assets and supporting long-term capacity building. In this way, the thesis contributes not only to academic discourse but also to the practical and policy-oriented pathways through which water quality monitoring can be embedded into sustainable development agendas world wide.

10 Conclusion and Outlook

This thesis has demonstrated that a hybrid combination of wireless technologies and a modular edge–cloud architecture can address the infrastructural constraints of Eswatini while supporting scalable and cost-aware water quality monitoring. The design balances reliability, modularity, and reproducibility, offering both a concrete blueprint for implementation and a generalizable framework for distributed monitoring in similar contexts.

The implications of this work extend across practice, theory, and policy. Practically, the system provides stakeholders with a transparent and resilient tool for data collection and decision-making. Theoretically, it contributes to the literature on distributed monitoring by showing how modularity and hybrid communication can be adapted to resource-constrained environments. From a policy perspective, it highlights the role of such architectures in sustainable infrastructure planning and capacity building.

Looking ahead, several steps are required to transform this conceptual design into a robust, field-ready system. Extended field trials across multiple sites and seasons are essential to validate assumptions about scalability, resilience, and cost-efficiency under real-world conditions. Existing logger hardware will need to be adapted to support hybrid communication protocols, local buffering, and preprocessing functions. This may involve upgrading memory and storage capacity, integrating low-power modules such as LoRaWAN or ZigBee, and improving environmental robustness through protective enclosures and reliable power management. In parallel, structured QA/QC routines and calibration protocols should be developed with local operators to ensure long-term data quality. Comparative cost modelling over extended time horizons would further clarify the total cost of ownership and inform sustainable funding strategies. Finally, integration with national water management frameworks and regional development initiatives could position the system as a scalable reference model for distributed monitoring in resource-constrained contexts.

In this way, the thesis not only addresses its immediate research problem but also lays the foundation for future work that can extend its technical, operational, and policy relevance. By aligning design principles with local realities, it provides a pathway from pilot deployments toward sustainable, scalable monitoring infrastructures that support long-term water resource management.

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Acronym Glossary

ACK/NACK	Acknowledgement / Negative Acknowledgement
AES-128	Advanced Encryption Standard, 128-bit
AOMDV	Ad hoc On-Demand Multipath Distance Vector
asl	Above Seal Level
API	Application Programming Interface
AWS	Amazon Web Services
AWS IoT Core	Amazon Web Services Internet of Things Core
CRC	Cyclic Redundancy Check
CRC16	16-bit Cyclic Redundancy Check
DWA	Department of Water Affairs (Eswatini)
ECDSA	Elliptic Curve Digital Signature Algorithm
ESCCOM	Eswatini Communications Commission
EWSC	Eswatini Water Services Corporation
GSM	Global System for Mobile Communications
HTTPS	Hypertext Transfer Protocol Secure
ICT	Information and Communication Technology
JSON	JavaScript Object Notation
Li-ion	Lithium-ion battery
LiFePO4	Lithium Iron Phosphate battery
LoRaWAN	Long Range Wide Area Network
LoS	Line of Sight
LPWAN	Low Power Wide Area Network
LTE-M	Long Term Evolution for Machines
MQTT	Message Queuing Telemetry Transport
MTN Eswatini	Mobile Telephone Network Eswatini
NB-IoT	Narrowband Internet of Things
NGOs	Non-Governmental Organizations
PV panel	Photovoltaic panel
QA/QC	Quality Assurance / Quality Control
SNS	Simple Notification Service (AWS)
SMS	Short Message Service
TEGs	Thermoelectric Generators
TLS	Transport Layer Security
WSNs	Wireless Sensor Networks
ZigBee	IEEE 802.15.4-based wireless mesh protocol

Symbol Glossary

Symbol	Meaning	Unit
A	Ampere (electric current)	A
As	Ampere-second (charge)	As
cm	Centimeter	cm
E_{comm}	Energy consumption per communication event	As or mAh
E_{daily}	Daily energy consumption	mAh
GHz	Gigahertz	
h	Hour	h
I_{avg}	Average current draw	mA
kbps	Kilobits per second	
mA	Milliampere	mA
μA	Microampere	µA
s	Second	s
V	Volt	V
W	Watt (power)	W
$^{\circ}$C	Degree Celsius (temperature)	℃

A Copilot

All Microsoft Copilot Prompts will be listed below.

A.1 Hybrid Communication System image

Prompt:

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    {"from": "Cell Tower", "to": "Cloud Platform", "protocol": "Internet"}
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        GSM/NB-IoT (backhaul).",
    "Designed for distributed water quality monitoring in rural areas."
  ]
}
```

Generated: 05-08-2025

A.2 Finding Distance Between Stations and Nearest GSM Tower

Prompt:

```
using opencellid find out how far these five stations are from the nearest
    gsm tower:
Bulembu Gold Mine - 2556’54"S 3112’57"E
St Pauls Primary School Nkomati - 2604’22"S 3110’43"E
Kupuka - 2614’32"S 3137’37"E
Matsamo Border Gate Lomati - 2544’57"S 3127’38"E
Nkalashane - 2558’48"S 3156’27"E
```

Generated: 17-08-2025

A.3 Help in Structuring the Thesis Example

Prompt:

```
for my bachelor thesis help me structure the Discussion part. Give me an
    example structure in Latex with a few bullet-points what belongs into
    which section.
```

Generated: 09-10-2025