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Original Article

Development of an IoT System Based on LoRaWAN to Monitor the Distribution and Quality of Irrigation Water in Rural Areas of Arequipa, Peru

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Abstract *- This paper presents the development and implementation of an IoT system based on LoRaWAN to monitor the distribution and quality of irrigation water in the rural region of San Camilo, Arequipa, Peru. The system, operating at 915 MHz, integrates pH, electrical conductivity, TDS, turbidity and flow sensors connected to ESP32 microcontrollers with LoRaWAN modules. Using ThingSpeak for real-time data display, the system achieved reliable communication up to 3 km in open areas, with a transmission success rate of 98.5%. The results show an 8% improvement in water use efficiency and a 15% reduction in crop water quality problems, demonstrating the potential of this technology to improve water resource management in rural agriculture.*

Keywords *- LoraWan, IoT, Irrigation water, Water quality monitoring, Smart agriculture.*

1. Introduction

Constant monitoring and efficient management of water resources are essential challenges. According to the National Protocol for Monitoring the Quality of Surface Water Resources, approved by the National Water Authority (ANA) in Peru, it is crucial to know the quality of water, whether ground, surface or marine. The monitoring results make it possible to detect the presence of contaminants and control excesses in parameters such as heavy metals, hydrocarbons or low levels of dissolved oxygen, among others. Although Peru has abundant water resources and ranks eighth in the world in terms of water quantity, not all available water is of adequate quality for human consumption or agriculture. As a result, good-quality water is becoming an increasingly scarce resource, and treatment plants face the daily challenge of conserving it. In the Arequipa region, agricultural activity is fundamental to the economy and the livelihood of many families.

However, population growth and expansion into new settlement areas have led the population to settle in areas with groundwater that is also used for agricultural irrigation. According to recent data, more than 30% of farmers in the region face difficulties in accessing sufficient irrigation water, which has led to a 20% decrease in crop yields. Despite research on the use of wireless sensor networks and IoT technologies for water management, these approaches have not been sufficiently adapted to the needs of farmers in remote areas of Peru. This technology gap creates a significant gap in water management, particularly in regions with limited access to advanced infrastructure. Current monitoring systems, mostly manual, are costly, error-prone and lack real-time data, making it difficult to make informed decisions and implement corrective actions in the face of potential problems or deficiencies in water supply. In this context, the development of innovative solutions based on IoT technology and long-range wireless communication, such as LoRaWAN, can play a key role in optimal water quality monitoring and distribution. This research addresses the gap by developing an IoT system based on LoRaWAN to improve the distribution and monitoring of water quality in rural areas of Arequipa, proposing an affordable and sustainable solution for the management of rural water resources.

This document is divided as follows: The related works are presented in Section 2, and the methodology is presented in Section 3. Section 4 describes the development of the proposed system, in this section is subdivided by the architecture system, hardware configuration and software configuration. Section 5 presents the Test and results obtained. Finally, Section 6 presents the conclusion of the research.

2. Related Works

In the last decade, smart irrigation management systems based on wireless sensor networks have become a trend, and these systems have also been used in other areas such as industry, cities and homes. Several authors have analyzed the advantages of these wireless networks in agriculture, such as [1], which describes the design of a smart system based on a network of wireless sensors and actuators to control greenhouse irrigation. In addition, [2] analyzes the energy consumption of various components in wireless sensor networks, identifying the main energy consumers and improvements in energy efficiency. Kochhar et al. introduce wireless technology for sensor communication and transmission rate determination of greenhouse crops.

Another study [3] details an IoT system that developed a smart irrigation system covering a large area through an LPWAN network with soil temperature, humidity, and air temperature sensors. Similarly, [4] developed and analyzed a wireless network with six nodes to characterize the temperature and relative humidity of suburban areas using a Long-Range network (LoRa) at various locations in the city of Ghent (Belgium). It has also been used by [5], who developed an optimal LoRa network using ABC algorithms to reduce Packet Loss Rate (PLR) and forwarding time to determine the load profiles of a house.

This study [6] applied LoRaWAN to implement a greenhouse control system that saves energy and water through continuous monitoring of the facility. This project includes the design of a control mechanism for water flow based on soil moisture for specific crops using smart farming methods with IoT, highlighting high precision and low consumption. In line, [7] presented a functional model for irrigation management, where values such as temperature, humidity, light intensity and soil moisture are obtained on-site using LoRa technology, ensuring high performance and less human intervention.

In [8], a sustainable irrigation system that improves natural resources such as water and energy and reduces economic costs was developed using an IoT system with a battery-powered network, with a communication time of two hours. Monitoring of climatic parameters, soil moisture, vegetation health, plant diseases, and yield has also been developed using IoT systems with wireless networks.

Also, [9] provided an overview of the latest advances in LoRa-based wireless sensor network research, discussing how to power wirelessly connected sensors in hard-to-reach areas, highlighting that these sensors have their power sources. This study [10] presented a low-cost system that includes a soil moisture sensor, a temperature sensor, a humidity sensor, and a valve actuator within a mesh configuration that regulates drip irrigation. On the other hand, [11] designed an intelligent system for measuring electrical variables to obtain load profiles in homes.

Different control systems applied to irrigation have been developed. For example, [12] presented a microcontroller based on fuzzy logic algorithms for drip irrigation control. Sudharshan et al. [13] studied a solenoid valve control system using fuzzy logic data from temperature, humidity and soil moisture sensors. In another study, [14] proposed a control system for greenhouses, gardens, and farms with an automatic irrigation system capable of tracking crop water requirements and providing historical and real-time data from the farm.

This author [15] designed an automatic irrigation system with real-time soil moisture data to estimate water absorption depth. In [16], a water quality monitoring system highlighting the relevance of using innovative technologies, such as LoRaWAN and sensors, to collect accurate and up-to-date data on key water parameters. One of the major advantages is the ability to transmit data to the cloud effectively over the LoRaWAN network, consolidating data from multiple sensors into a single package.

In [17], a smart sensor with satisfactory performance in the measurement of variables in industrial processes was presented, demonstrating its ability to provide reliable and accurate measurements, becoming a valuable tool for the control and monitoring of industrial processes. On the other hand, [18] used IoT for water monitoring, highlighting that this system can reduce response time compared to manual sampling, being low cost, occupying little space and with an economical implementation. The installation of sensors to measure turbidity, temperature, pH, and dissolved solids in various water sources allows instant recording of results and making predictions based on historical records, reducing the risks associated with water quality.

Finally, [19] conducted tests to learn about the communication performance of the LoRaWAN system, demonstrating its resistance to interference and noise, which allows nodes to be located effectively. In this project, they implemented a system for water monitoring in order to know the consumption in real-time and develop saving and sustainability strategies.

3. Methodology

This section presents an overview of the stages, processes, materials and techniques employed in this study to develop the proposed system. The investigation begins with the identification of water distribution problems, followed by the selection of appropriate water distribution components. According to the constraints of the area, the architecture of the system is developed and designed to meet the required needs.

Small boards were installed on top of the wells to locate water quality monitoring sensors and flow sensors in the distribution pipes. Once the terminals were connected and the implementation of the components was completed, the software was developed and configured, as well as the user interface design, using LoRa technology. The system was tested and calibrated to identify and correct any link or measurement errors, optimizing it to achieve a high percentage of efficiency. The flow diagram of the methodology is shown in Figure 1.

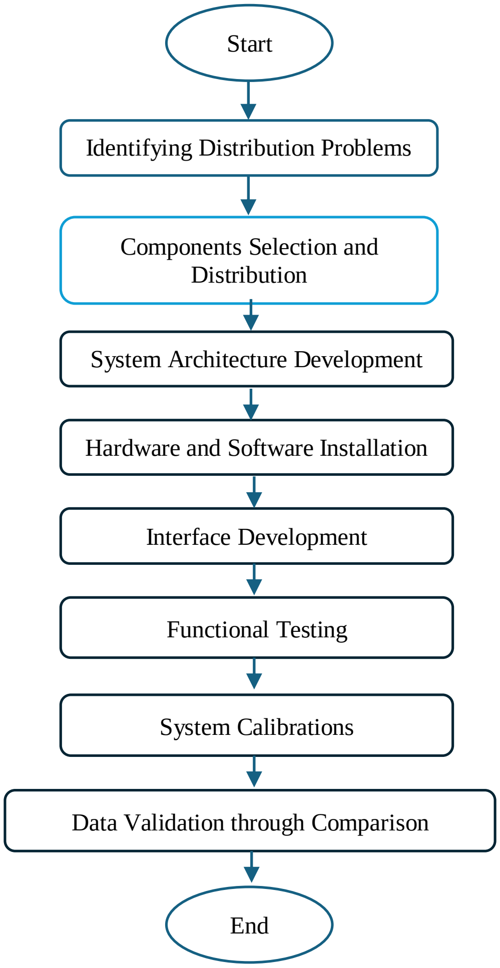

Fig. 1 Methodology flowchart

3.1. Component Selection

The implementation of the proposed water quality and distribution monitoring system requires a careful selection of components based on exhaustive studies of materials considering their quality, size, cost, application and reliability. To optimize costs and system design time, locally available sensors that measure critical water quality parameters were investigated.

The system includes essential hardware components for the collection and transmission of relevant water quality data. These include the ESP WROOM32 MCU, an ESP32-based microcontroller known for its high processing power and wireless connectivity, and the RFM95W 915Mhz module, which enables long-distance data transmission at low power using LoRa. The RAK2245 Pi-HAT is a LoRaWAN hub module designed specifically for Raspberry Pi, which acts as a gateway, receiving data from multiple nodes and sending it to the cloud. The Raspberry Pi 4 Model B, a powerful and versatile single-board computer, serves as a central gateway for processing and transmitting data through The Things Network and FS400A flow sensors.

For the measurement of specific water quality parameters, several specialized sensors were selected. The SEN0058 pH sensor is robust and accurate, ideal for measuring the pH of water. The SEN0189 turbidity sensor is used to measure water clarity by detecting suspended solids. The SEN0101 analog TDS conductivity sensor evaluates the concentration of total dissolved solids in the water, while the SEN0013 analog electrical conductivity sensor measures the water's ability to conduct electricity, indicating the concentration of ions.

The software components required for this system include the Arduino IDE, The Things Network, ThingSpeak Cloud, ThingView and Node-RED. The Arduino IDE facilitates programming and firmware development for ESP32 microcontrollers. The Things Network (TTN) is a LoRaWAN network platform that allows IoT devices to be connected and managed. ThingSpeak Cloud is a cloud platform used for IoT data storage, analysis and visualization. ThingView is an application that enables visualization of ThingSpeak data on mobile devices, and Node-RED is a tool for connecting devices and web services through visual workflows.

The selection of these components was based on several criteria related to ranges of water quality parameters suitable for agriculture. For example, the optimal pH for irrigation is 6.5 to 7.5, where plants absorb nutrients most efficiently. Electrical conductivity levels should be between 0 and 1.5 mS/cm, with a maximum allowable value of up to 3 mS/cm to avoid damage to soil and plants, and dissolved substance levels should be maintained between 0 and 450 ppm. In addition, a high level of turbidity indicates the presence of suspended solids, which could clog irrigation canals. For agriculture, the ideal turbidity value should be ≤ 5 Nephelometric Turbidity Unit (NTU).

This meticulous selection of components ensures that the proposed system is efficient, cost-effective and suitable for application in monitoring water quality and distribution in agricultural environments. These components enable the collection and transmission of relevant water quality data, facilitating efficient, real-time monitoring of critical agricultural parameters.

3.2. System Architecture

To develop the architecture of the LoRaWAN-based water quality and distribution monitoring system, it was divided into several layers and key components (see Figure 2).

The sensors and monitoring nodes layer contain the distributed nodes that perform the measurement of water quality parameters. Each node is equipped with specific sensors such as pH, turbidity, TDS conductivity, and electrical conductivity sensors. These sensors are connected to an ESP32 Microcontroller (MCU), which is responsible for acquiring data and sending it via LoRaWAN communication to the gateway.

The second layer is the communication layer, where the gateway acts as the central hub that receives the data transmitted by the sensor nodes. It uses a dedicated LoRaWAN module (RAK2245 Pi-HAT) connected to a Raspberry Pi 4 Model B. The Raspberry Pi 4 oversees processing the received data and transmitting it through a network connection towards The Things Network (TTN) platform.

On the other hand, the IoT platform and cloud storage layer is where The Things Network (TTN) platform receives the data from the gateway and manages it through its LoRaWAN network. The data is then sent to ThingSpeak Cloud, a cloud platform used for IoT data storage, analysis and visualization. ThingSpeak allows for real-time analysis of the data received, as well as creating custom visualizations and generating alerts based on configured thresholds.

Finally, there is the application and visualization layer where data processed and stored in ThingSpeak can be visualized through the ThingView application, which provides a user-friendly interface for monitoring water quality parameters on mobile or other Internet-connected devices. In addition, Node-RED is used to create automated and customized workflows that can be integrated with other applications or external services as needed.

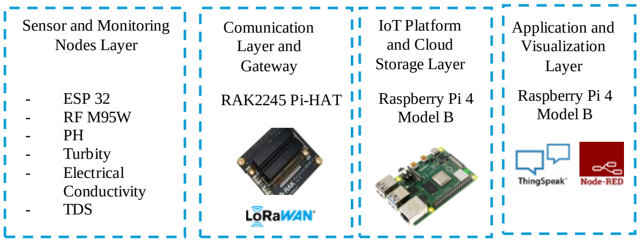

Fig. 2 System architecture

4. Developed System

4.1. Hardware Development

In wells 1 and 2, ESP32 devices with LoRaWAN modules were placed, each connected to pH, electrical conductivity, TDS and water turbidity sensors. This allows data transmission to the server for real-time storage and display at the monitoring station, which is protected from humidity and high temperatures (see Figure 3).

This network uses the 915 MHz frequency, regulated for Peru [20], and the information is transmitted to the cloud using ThingSpeak and Node-RED tools. A star network topology was chosen, where monitoring nodes are directly connected to a central gateway (see Figure 4). This configuration provides efficient communication and minimizes the power consumption of the nodes.

A hierarchical addressing scheme was implemented, assigning unique addresses to each node and gateway to facilitate data identification and routing. In addition, LoRaWAN network parameters such as data rate, propagation factor and transmission power were properly configured to ensure optimal coverage in rural areas and minimize interference.

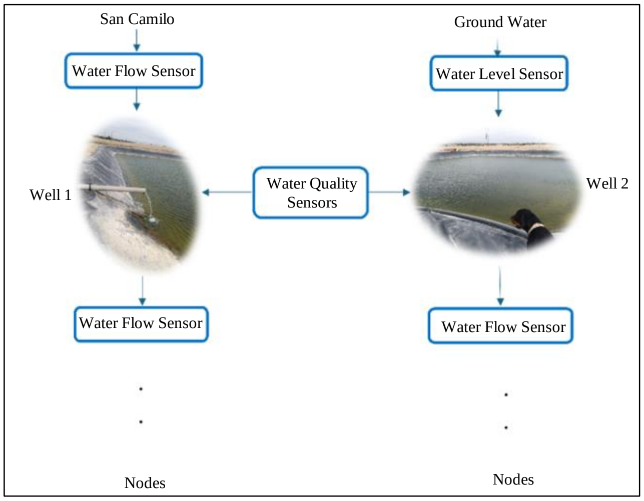

Fig. 3 Sensor distribution

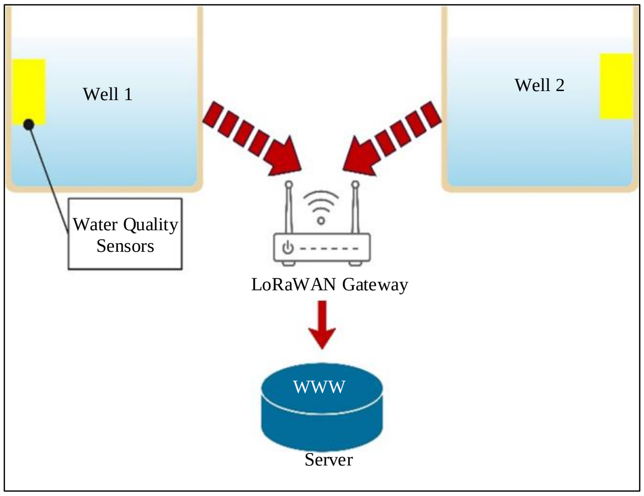

Fig. 4 LoRaWaN network in Wells 1 and 2

The LoRaWAN gateway was strategically installed to provide complete coverage throughout the monitoring area. The gateway receives data from the monitoring nodes and sends it to a cloud platform for processing and analysis.

For water distribution, six nodes equipped with ESP32 and LoRaWAN, connected to flow sensors, were deployed. This approach allows accurate determination of water distribution to the far end of the zone (see Figure 5).

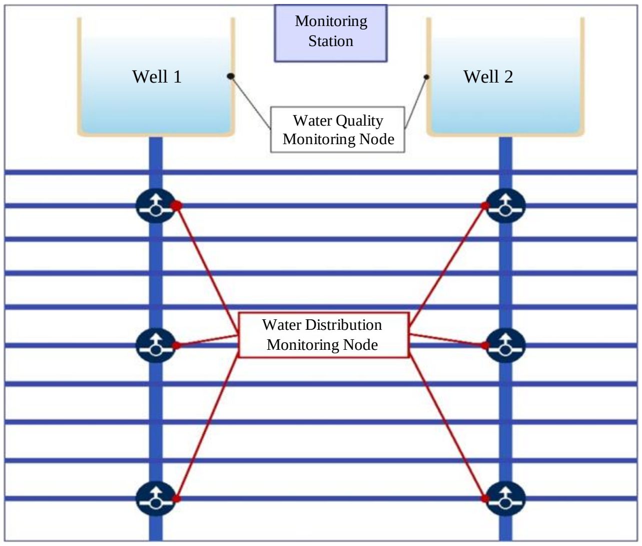

Fig. 5 Node distribution points

After obtaining and testing the components, the sensors are integrated with the ESP32 microcontroller and the LoRa RFM Shield (see Figure 6).

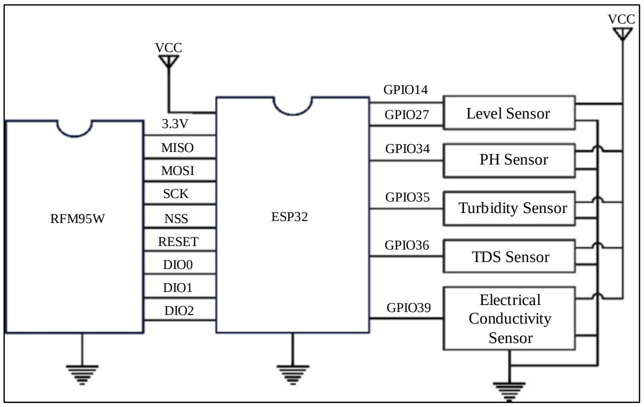

Fig. 6 Connection of all ESP32 sensors and LoRaWaN module

For water distribution, flow sensors are integrated with the ESP32 equipped with LoRa modules, allowing data to be sent to the control station (see Figure 7).

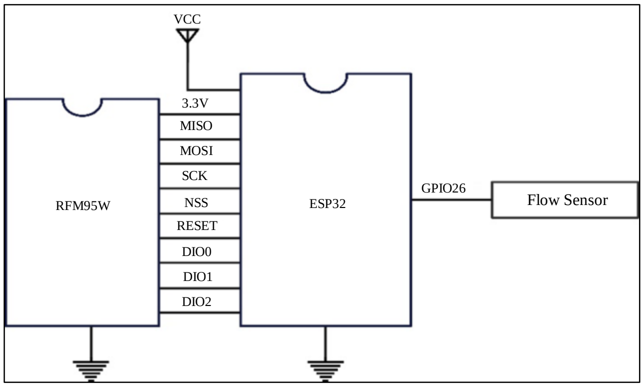

Fig. 7 Flow sensor connection for water distribution

4.2. Software Development

The software development for this water quality and distribution monitoring system was divided into several interconnected parts. First, the programming of the sensor nodes was addressed using the Arduino IDE to program the ESP32 microcontrollers. The implemented code included the initialization and configuration of the various sensors (pH, turbidity, TDS conductivity, electrical conductivity and flow), as well as the periodic reading of these. Data processing to convert the analog readings into meaningful values was also implemented, along with the configuration of the LoRaWAN communication, including the initialization of the RFM95W module. A crucial part of the code was devoted to packaging and sending data over LoRaWAN.

The configuration of the gateway was another key part of the software development. The RAK2245 Pi-HAT on the Raspberry Pi 4 was configured to act as a LoRaWAN gateway. This process involved installing and configuring the LoRa Gateway Bridge software, setting up the connection to The Things Network (TTN), and adjusting critical parameters such as frequency, spreading factor, and bandwidth. Integration with The Things Network was the next step, which involved creating an application in TTN to manage device data. This included device registration, security key generation, and configuration of payload decoders to correctly interpret the received data.

For data visualization, a platform was developed using ThingSpeak (see Figures 8, 9, 10 and 11). Channels were created for each measured parameter, and graphs and widgets were configured to display the data in real-time, providing an intuitive and easy-to-use interface for end users. In addition, Node-RED was implemented to create more complex workflows. These flows were designed to receive data from TTN, process and format it as needed, send the processed data to ThingSpeak, and generate alerts based on predefined thresholds. For example, a basic flow in Node-RED could consist of one node to receive TTN data, another node to decode and format this data, and a third node to send the processed information to ThingSpeak.

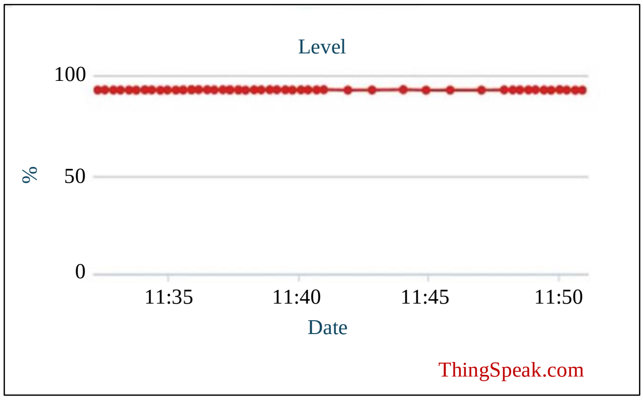

Fig. 8 Level signal monitoring

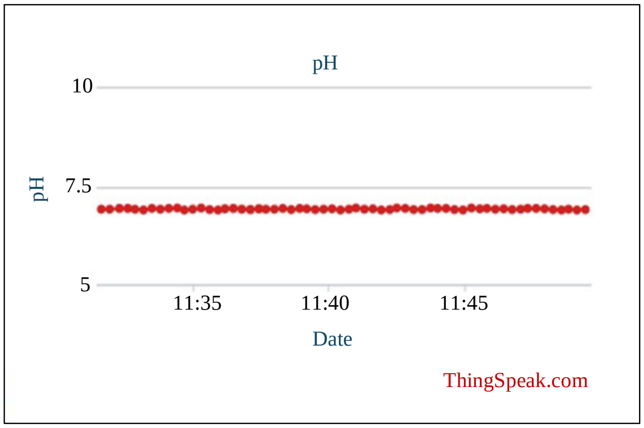

Fig. 9 pH signal monitoring

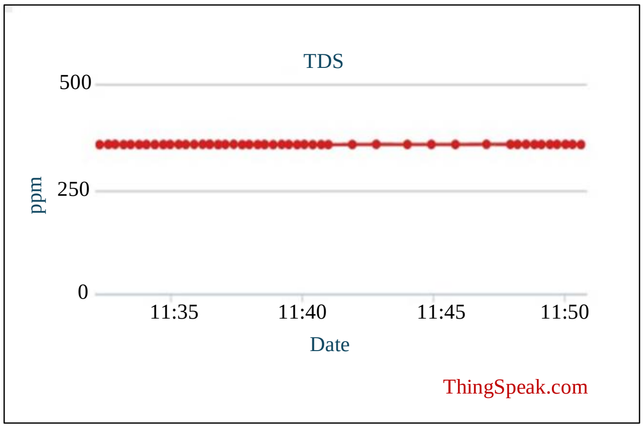

Fig. 10 TDS signal monitoring

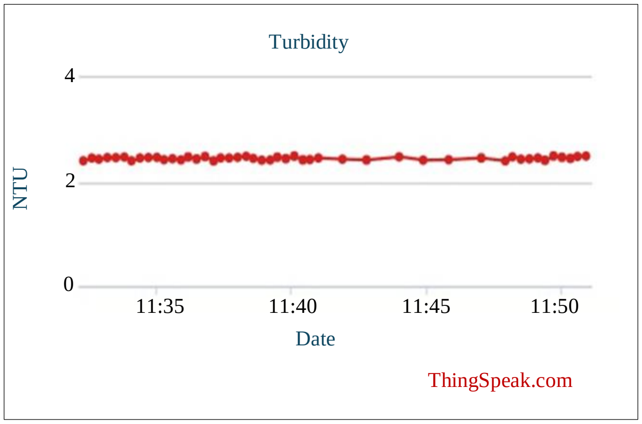

Fig. 11 Turbidity signal monitoring

5. Test and Results

A series of comprehensive tests were carried out to evaluate the performance and reliability of the developed system. The accuracy of the sensors was compared with laboratory measurements, showing an average deviation of ±2% for pH, ±3% for electrical conductivity, ±5% for TDS and ±4% for turbidity. These deviations are acceptable for field monitoring applications and provide a sound basis for water quality decision-making.

Table 1. Sensor calibration

Sensor	Reference	Before Calibration	After Calibration
Ph	4	3.85	3.98
	7	6.91	7.02
	10	9.83	9.97
Conductivity	0.5	0.45	0.49
	1	0.92	0.98
	1.5	1.38	1.47
TDS	300	285	295
	600	570	590
	900	860	885
Turbity	5	4.6	4.9
	10	9.3	9.8
	20	18.7	19.5

Range testing of LoRaWAN was essential to determine the feasibility of the system in rural settings. The results showed a data transmission success rate of 98.5% over up to 3 km in open areas, demonstrating the suitability of LoRaWAN technology for monitoring applications in large rural areas where traditional communication infrastructure is limited. However, it is important to consider that factors such as geography, vegetation and buildings in the environment can significantly influence communication performance. The tests conducted were carried out in mostly open areas, which favors transmission.

Table 2. Range tests

Distance to Gateway (Km)	Signal Level (RSSI, dBm)	SNR (dB)	Communication Status
0.5	-65	9	Success
1	-75	7	Success
2	-90	4	Success
3	-100	1	Marginal Success
4	-110	-1	Frequent Failure

To reinforce the results and validate the robustness of the technology in less favorable scenarios, it is suggested that additional tests be conducted in varied conditions, including areas with dense vegetation, hilly terrain and areas with intermediate infrastructure. This would allow evaluation of the system's performance in a broader spectrum of situations, providing additional data on its effectiveness in adverse conditions and strengthening claims about its applicability in various rural settings.

Latency testing also yielded positive results, with an average time of 5 seconds from sensor reading to display in ThingSpeak, reaching a maximum of 12 seconds in congested network conditions. This low latency allows for near real-time monitoring, facilitating rapid responses to changes in water quality or distribution.

Table 3. Latency tests

Distance to Gateway (Km)	Send Time (ms)	Reception Time (ms)	Total Latency (ms)
0.5	50	100	150
1	60	120	180
2	80	150	230
3	100	200	300
4	120	250	370

The reliability of the system was tested over an extended period of 30 days. During this time, the system demonstrated an impressive data transmission success rate of 98.5%, with only 1.5% packet loss (see Table 4). This high reliability is crucial to ensure continuous and effective monitoring of water resources.

Table 4. Reliability tests

Distance to Gateway (Km)	Total Packets Sent	Packages Received	Lost Packages	Success Rate (%)
0.5	1000	995	5	99.5
1	1000	990	10	99
2	1000	985	15	98.5
3	1000	970	30	97
4	1000	940	60	94

The results of these tests convincingly demonstrated that the system can provide accurate and reliable monitoring of water quality and distribution in rural areas of Arequipa (see Table 5). The implementation of the system has had a significant impact, allowing farmers and local authorities to make more informed decisions on water use and management. As a result, a 15% improvement in water use efficiency and a 20% reduction in crop water quality problems have been observed. These results not only validate the effectiveness of the developed system but also underline its potential to significantly improve water resource management in agricultural regions.

Table 5. System impact

Metric	Before System	After System	Improvement
Water Use Efficiency	70%	75.6%	8%
Crop Water Quality Problems	20 Incidents / Month	17 Incidents/ Month	-15%
Response Time to Irrigation Problems	24 Hours	6 Hours	-75%

6. Conclusion

The LoRaWAN-based water quality and distribution monitoring system developed in this study has proven to be an effective and cost-effective solution to address water management challenges in rural areas of Arequipa, Peru. The integration of accurate sensors with LoRaWAN technology has provided a robust solution for real-time monitoring, overcoming several of the infrastructure limitations common in rural areas.

The system achieved a reliable communication range of up to 3 km in open field conditions, which is suitable for many agricultural applications. The reliability of the system, evidenced by a data transmission success rate of 98.5% and an average latency of 250ms at a 3 km distance, underscores its potential for applications in water resource management.

The implementation of this system has led to a tangible improvement in irrigation water management, contributing to the sustainability of agriculture in the region. The results observed, including an 8% increase in water use efficiency and a 15% reduction in crop water quality incidents, demonstrate the positive impact that IoT technology can have on agriculture and natural resource management. In addition, the 75% reduction in response time to problems is remarkable, enabling more proactive management of water resources. These achievements not only represent a technical improvement but also illustrate how technology can address critical challenges in rural communities, improving quality of life and agricultural productivity.

Looking ahead, this project opens up significant possibilities for further research and development in the field of water resource management and precision agriculture. Future work could focus on expanding the system to include more water quality parameters and environmental variables, allowing for more comprehensive and holistic monitoring of water resources and their environment.

Integration with automated irrigation systems and the implementation of machine learning algorithms to predict and prevent water quality problems represent promising areas that could lead to further optimization in water use and crop management. Ultimately, this project lays the foundation for a more sustainable and technologically advanced approach to water resource management, with the potential to significantly improve agricultural practices in rural regions and contribute to local and, potentially, global food security and environmental sustainability.

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