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RESEARCH ARTICLE OPEN ACCESS

MONITORING AND EVALUATION OF WATER QUALITY IN RURAL ANDEAN AREAS OF PERU USING WIRELESS SENSORS WITH LORA

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ABSTRACT

The objective of this research was to implement wireless sensors for remote monitoring and evaluation of water quality in five reservoirs in rural Andean communities in the district of Huancavelica-Peru, given the scarcity of information on water quality and its poor monitoring. It is important to monitor water quality for its safe management according to the sustainable development goals of the 2030 agenda, against natural or anthropogenic contaminants. The remote monitoring evaluated the performance of wireless sensors and water quality (temperature, pH and turbidity) for 10 days. The wireless sensors were calibrated with Hanna Instruments brand equipment achieving an R^2 of 98.98%, 96.81% and 89.82% for temperature, pH and turbidity respectively. The average amount of data received was 456/462, 8.73 km maximum communication distance, received signal strength RSSI (-93 to -122 dBm), signal to noise ratio SNR (9 to 13 dB), water temperature (-2.90 to 14.4 ºC), pH (6.60 to 8.24) and turbidity (0.34 to 4.98 NTU). The wireless sensors are highly effective in remote monitoring; the quality of the monitored water complies with Peruvian and World Health Organization regulations.

I. INTRODUCTION

Water is a fundamental resource for life and human health that is found in various sources such as rivers, springs, lagoons, dams, etc., whose accessibility and quality are important to monitor for an adequate sustainable management within the scope of the "Sustainable Development Goals" SDG 6 of the United Nations 2030 agenda [1]. Monitoring must be able to analyze water quality systematically for adequate and timely decision-making in the face of anomalies that arise; since, water is changing in space and time due to its own dynamics or due to anthropogenic activities in its environment that can ultimately affect the health and welfare of people [2-5].

Currently, water quality monitoring is commonly performed manually on site or by transferring samples to a laboratory; where, the execution of the procedure requires a long time according to the characteristics of its geographical area of study that make it impossible to develop continuous and real-time monitoring considering unforeseen situations in water change [6], [7]. In this regard, when reviewing the state of the art on water quality monitoring in rural areas of the Andes mountain range of

Peru in the province and district of Huancavelica, [8] identified that monitoring is precarious and that there is little information available on water quality due to various factors such as the manual procedure that takes a long time, the lack of nearby

laboratories, the high costs of monitoring and especially the geographical remoteness and difficult accessibility to the places where the sample that evaluates the water is taken, making it impossible to implement frequent monitoring programs recommended by [9]; also, due to the irregular way in which it is carried out, being temporarily limited to monitoring between one time or twice a year [10].

In response to poor water quality monitoring in different scenarios; different authors have proposed remote monitoring as an alternative for which different wireless prototypes have been developed such as [11-14] that have monitored water quality reaching distances up to 120 m; others such as [15-18] have improved monitoring reaching distances up to 2.0 km, with the particularity that these investigations have been developed and are limited to flat and low altitude geography less than 200 m above sea level.

However, the achievements are not sufficient for monitoring water quality in spaces with a greater range of distance and complex geography, such as the case of the rural Andean area of Huancavelica, where water sources are located between rugged mountain ranges and steep areas between 3,800 m and 4,000 m above sea level [19], which require continuous and real-time monitoring.

In response to this, this research work has proposed the implementation of wireless sensors for remote monitoring of water quality and its evaluation as an alternative to poor manual monitoring in the complex geographic conditions of the rural Andean area of the Huancavelica department; wireless sensors that monitor water quality continuously and in real-time.

In this regard, the contribution of this article is to present the results of remote monitoring of water quality based on wireless sensors with Long Range (LoRa) technology for its application in data management and quick decision-making on water quality in distant and complex geographic areas similar to the rural Andean area of Huancavelica among others; directly benefiting with information to the rural communities population, environmentalists, ecologists, among others who are interested in monitoring water quality for informed decision making.

II. MATERIALS AND METHODS

II.1 DESCRIPTION OF THE STUDY AREA

The research was carried out in five water reservoirs for human consumption in the high Andean rural communities of the province and district of Huancavelica-Peru (-12º 47.237, -74º 58.389) located in mountainous geographic areas of difficult access with altitudes of around 4000 m and located at distances of up to 16.9 km from the urban area of Huancavelica of difficult access by road and rough rural roads. The reservoirs belong to the communities of Sachapite, Antaccocha, Pampachacra, Huaylacucho, and San Gerónimo as detailed in Table 1.

Table 1: Location of reservoirs in rural communities for remote monitoring.

Community	Latitude	Length	Altitude (masl)	Distance km
S1 Sachapite	-12º 44.069	-74º 54.590	4196	16.9
S2 Antaccocha	-12º 44.697	-74º 54.948	4084	12.3
S3 Pampachacra	-12º 48.643	-74º 55.271	4072	10.2
S4 Huaylacucho	-12º 47.521	-74º 56.905	3823	4.7
S5 San Gerónimo	-12º 47.045	-74º 59.931	3885	1.2

Source: Authors, (2025).

Figure 1 presents the location map of the wireless sensors in the five identified communities (S1, S2, S3, S4, and S5), with which remote monitoring was carried out.

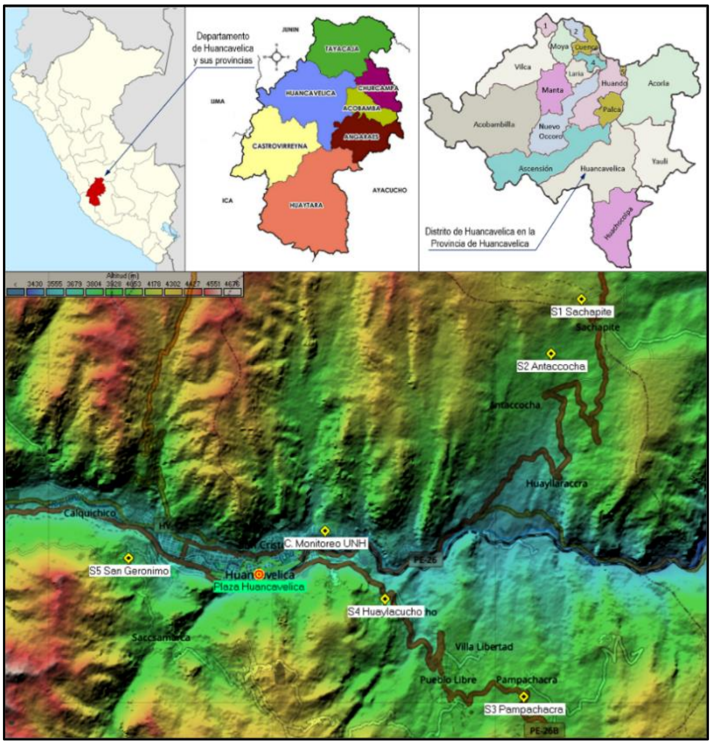

Figure 1: Location map of remote monitoring with wireless sensors.

Source: Authors, (2025).

II.2 SCOPE

The scope of the research was to evaluate water quality monitoring through wireless sensors with LoRa technology in the five communities that involved the implementation of the wireless sensors, the evaluation of the amount of data received from remote monitoring, the transmission distance, the intensity of the received signal RSSI and the signal-to-noise ratio SNR, according to the parameters indicated in Table 2.

Table 2: Remote monitoring data transmission/reception capability variables.

Variable	Unit	Range	Reference
Amount of data received	unit	<= 462	ThingSpeak
Transmission distance	km	< 10	[20] (Heltec Automation, 2023) [21] (Semtech, 2020)
RSSI, Received Signal Strength	dBm	> -135	
SNR, signal-to-noise ratio	dB	> -20	

Source: Authors, (2025).

Likewise, the results of remote monitoring corresponding to water temperature, pH, and turbidity corresponded to the ranges indicated in Table 3.

Table 3: Water quality parameters according to WHO and DIGESA-Peru.

Variable	Unit	Range	Reference
Temperature	º C	< 20	[22](WHO, 2011)
Hydrogen potential	pH	6.5 to 8.5	[23] (WHO, 1971) [24](DIGESA, 2010)
Turbidity	NTU	0 to 5	

Source: Authors, (2025).

II.3 SAMPLE COLLECTION AND DATA ANALYSIS

The sample size was directed with non-probabilistic sampling in a total of 462 daily samples of remote monitoring. Samples were collected digitally automated by the wireless sensors in time intervals of approximately three minutes in which the five sensors perform the process of acquiring, processing, transmitting and storing the information. The field tests were carried out between July and August 2024 for ten days of 24 hours each.

Data were grouped and tabulated according to the type of variable to be analyzed (transmission distance, received signal characteristics RSSI, SNR, and water quality measurements such as temperature, pH, and turbidity). Central tendency and dispersion statistics were used to describe the capacity of remote monitoring, and box plots were used to represent the distribution of the acquired data.

Calibration of the wireless sensors was performed in the laboratory during prototyping through comparisons between sensor measurements and Hanna Instruments contrast equipment, whose level of accuracy was verified with metrics such as coefficient of determination (R^2), root mean square error (MSE) and standard error of estimation (SEE).

II.4 REMOTE MONITORING MODEL ARCHITECTURE

The architecture is made up of three stages as shown in Figure 2. The first stage corresponds to the data acquisition and processing section of the physical phenomenon (water quality), the second corresponds to the stage of wireless data transmission within the Low Power Wide Area Network (LPWAN) and Wireless Fidelity (WIFI), and finally, the third stage of remote storage and dissemination of information.

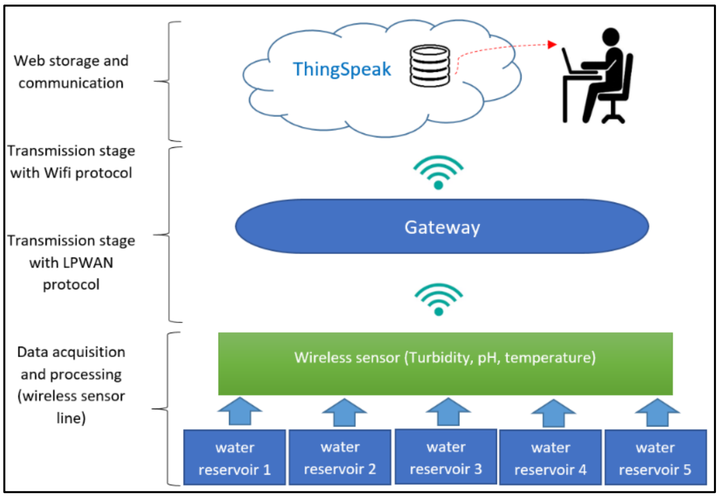

Figure 2: Architecture of remote water quality monitoring.
Source: Authors, (2025).

II.5 IMPLEMENTATION OF WIRELESS SENSORS

Wireless sensors have four electronic circuit blocks (see Figure 3). The first consists of the physical sensors, the second by data acquisition and processing block, the third by data transmission block, and finally the power supply block.

The sensor block consists of the DS18B20 temperature sensor that measures the temperature change with a probe-type electrode with a 12-bit resolution; the PH-4502C sensor that measures the acidity or alkalinity of the water through a potential difference between a glass electrode that is sensitive to H+ ions and another metal one that measures the electric potential that translates into pH; also, the LGZD V1.1 turbidity sensor that is an infrared light optoelectronic device with which the amount of turbidity is determined from the variability of the voltage of the receiving photodiode.

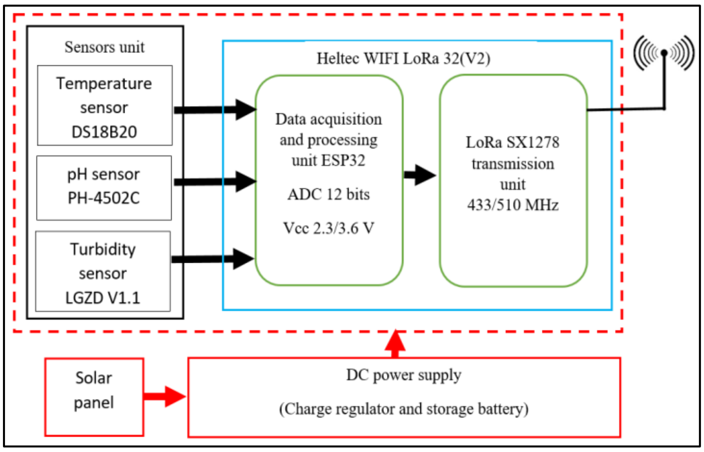

Figure 3: Structure of wireless sensors.
Source: Authors, (2025).

Table 4 presents the technical characteristics of each sensor.

Table 4: Characteristics of physical sensors and calibration instruments.

Variable	Unit	Model	Characteristics	Calibration instrument
Temperature	° C	DS18B20	Range: -10 to 85 ºC Accuracy: ± 0.5 ºC	Hanna HI98121 0 - 60 °C
Hydrogen potential	pH	PH-4502C	Range: 0 to 14 pH	Hanna HI98121 0 - 14 pH
Turbidity	NTU	LGZD V1.1	Voltage: 0V to 4.50V	Hanna HI93703 0 to 50 NTU

Source: Authors, (2025).

The data acquisition and processing block consists of the ESP32 microcontroller incorporated in the Heltec WIFI Lora 32(V2), to which the physical sensors are connected for sampling and 12-bit digital analog conversion of the water temperature, pH and turbidity variables. Figure 4. illustrates the calibration activity of the Hanna sensors and instruments.

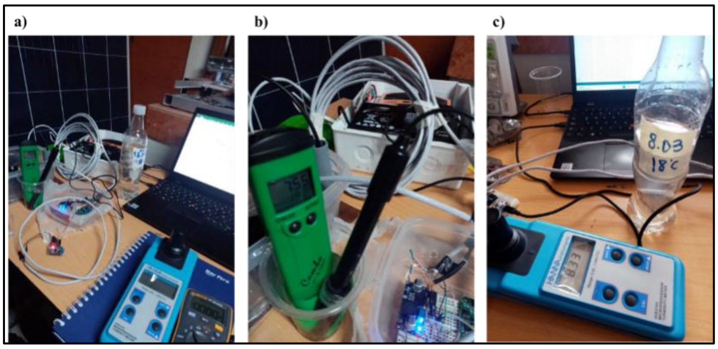

Figure 4: Calibration of, a) Wireless sensors with the multimeter, b) Temperature and pH with the Hanna multi-parameter HI98121, and c) Turbidity with the Hanna turbidimeter HI93703.
Source: Authors, (2025).

The DS18B20 temperature sensor and the PH-4502C hydrogen potential sensor were calibrated with the Hanna Instruments HI98121 multiparameter equipment under room temperature conditions of 15 ºC; the temperature was calibrated through the simultaneous immersion in water of the electrodes and the contrasting equipment at temperatures between 8.8 to 24.2 ºC, the sensor is of the 12-bit direct digital type whose precision oscillates in ± 0.5 ºC in the range of -10°C to +85°C [25]. From the correlation of measurements, a coefficient of determination R^2 of 98.98% ($p<0.001$) and averages of 8.36 ±0.12, 13.84 ±0.17, 14.76 ±0.51, 17.04 ±0.04, 20.25 ±0.06 and 24.25 ±0.13 were obtained for temperatures of 8.80, 13.90, 14.50, 16.90, 20.10 and 24.20 ºC respectively.

The pH calibration was also performed by simultaneous immersion of the electrodes in calibration solutions of Hanna HI7004L (4.01 pH), HI7007L (7.01 pH) and drinking water of 7.6 and 7.9 pH. The coefficient of determination of the calibration of the sensors was $R^2 = 96.81\%$ ($p<0.001$) and average values of 4.19 ±0.06, 7.09 ±0.08, 7.77 ±0.21, 7.98 ±0.18 for the 4.01, 7.01, 7.6 and 7.9 pH solutions, respectively. The PH-4502C sensor incorporates in its electronic design a temperature sensor for pH correction against temperature changes which has been considered in the implementation of the prototype taking as reference equation (1) [26] [27] where the variation of pH(end) ranges between 0 and 0.17 for temperatures of 15 and 0 ºC respectively.

$$pH_{(end)} = pH_{T1} + 0.0114\,(T_1 - T_2) \qquad (1)$$

Where, $pH_{(end)}$ is the temperature-corrected pH, pH_{T1} is the pH value at the measurement temperature T_1, T_2 is the reference temperature (15 ºC).

The LGZD V1.1 turbidity sensor was calibrated with the Hanna Instruments HI93703 turbidity meter by simultaneously measuring different water solutions in the range of 1 NTU to 12 NTU and temperature of 10 ºC. The sensor measures turbidity based on the transmittance of infrared light from the transmitter to the receiver at an angle of 180º generating an output voltage of 4.40V (10 ºC) for turbidity less than 0.5 NTU; the output voltage rises for low temperatures or low turbidity, and decreases with increasing water temperature or turbidity [28],[29]. Experimentally, equation (2) was obtained for the calculation of water turbidity from the correlation of the measurements of the contrast equipment and the turbidity sensor with a coefficient of determination of R^2 of 89. 82% and NTU averages of 1.17 ±1.38, 1.22 ±0.38, 3.42 ±0.34, 6.18 ±0.37, 6.79 ±0.57 and 8.99 ±068 for turbidity references of 1, 2, 5, 6, 9 and 12 NTU respectively with output voltages of between 4.397 V and 4.364 V. The accuracy obtained was accepted in the investigation because the sensor had a positive response and provided an acceptable reference approximation of turbidity despite being a low-cost device compared to the HI93703 contrast equipment, where the differences in measurements ranged around 1 NTU for values lower than 5 NTU, which we consider favorable in contrast to the non-existent monitoring of water turbidity in rural areas.

$$NTU = \frac{V_{T_b} - V_{T_a} + 0.0069(T_b - T_a)}{-0.003} \qquad (2)$$

Where, V_{Tb} is the sensor voltage at T_b (temperature of the water turbidity reading), V_{Ta} is the sensor voltage at T_a (reference temperature 10 ºC of the turbidity reading).

Table 5 describes the accuracy level metrics of the calibrated sensors concerning the coefficient of determination R^2, the root mean square error (MSE), and the standard error of estimation (SEE).

Table 5: Evaluating the accuracy level of wireless sensors.

Sensor	Calibration range	Accuracy Level Metrics		
		R^2	MSE	SEE
Temperature (DS18B20)	8.8 ºC to 24.2 ºC	0.9898	0.222	0.419
pH (PH-4502C)	4.01 pH, 7.01 pH, 7.6 pH, 7.9 pH,	0.9681	0.026	0.205
Turbidity (LGZD V1.1)	1 NTU to 12 NTU	0.8982	3.023	0.905

Source: Authors, (2025).

In Figure 5, the linear models of the calibration of the temperature, pH and turbidity sensors are presented.

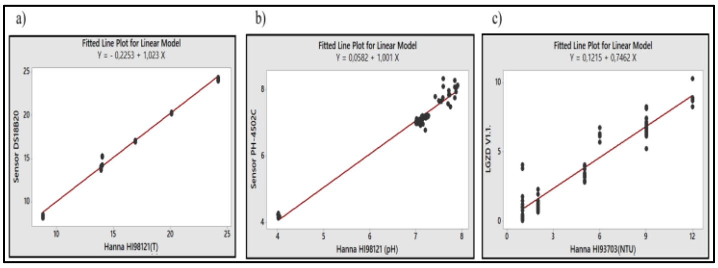

Figure 5: The linear model of the calibration level of wireless sensors, a) temperature b) hydrogen potential pH, and c) turbidity.
Source: Authors, (2025).

The data transmission unit is made up of two wireless communication systems. The first one is made up of the wireless sensors through Semtech LoRa SX1278 devices embedded in the Heltec Automation LoRa 32(V2) WiFi card and configured in an LPWAN network with a spreading factor (SF=12), transmission power of 13 dBm, in the frequency band for the industrial, scientific and medical (ISM) area of 433 MHz. The second communication system is made up of the Gateway that retransmits the signal from the wireless sensors to the Internet through the IEEE 802.11 b/g/n and TCP/IP WiFi protocol. The wireless sensors and the Gateway have an algorithm coded in C language and compiled in the LoRa32(V2) WiFi development boards through the Arduino IDE using the libraries "heltec.h", “OneWire.h” and “DallasTemperature.h” and the routines in Figure 6.

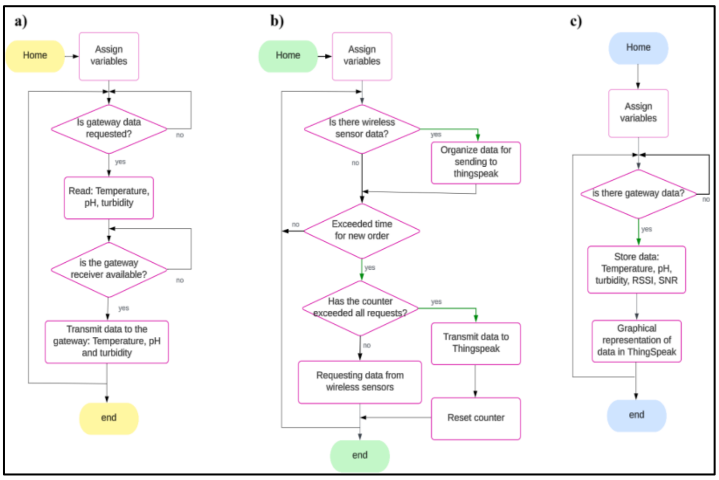

Figure 6. Flow diagrams of data transmission and reception routine, a) Wireless sensor with LPWAN protocol, b) Gateway with LPWAN/Wifi protocols, and c) ThingSpeak.
Source: Authors, (2025).

The Gateway starts the process by requesting data from the wireless sensors within the LPWAN network with their respective identifier code; on the wireless sensor network side, the requests are iteratively verified and data acquisition and processing are carried out to then transmit them to the Gateway; the Gateway receives and organizes all the data and sends it to ThingSpeak; finally, the data from the wireless sensors is stored and graphically represented on the ThingSpeak platform. The process is repeated iteratively from start to finish approximately every 3 minutes.

All sensor devices, the ESP32 microcontroller, and the SX1278 transmitters of the WiFi LoRa 32(V2) from Heltec Automation are connected to the power supply provided by a 12V/7Ah battery through a 12V/5V charge regulator.

II.6 INSTALLATION AND REMOTE MONITORING WITH WIRELESS SENSORS

The wireless sensors installed in the communities' reservoirs were identified as S1 Sachapite, S2 Antaccocha, S3 Pampachacra, S4 Huaylacucho, and S5 San Gerónimo; on the other hand, the Gateway is identified as "Monitoring Center (UNH) Huancavelica". Figure 7 illustrates the installation of the wireless sensors.

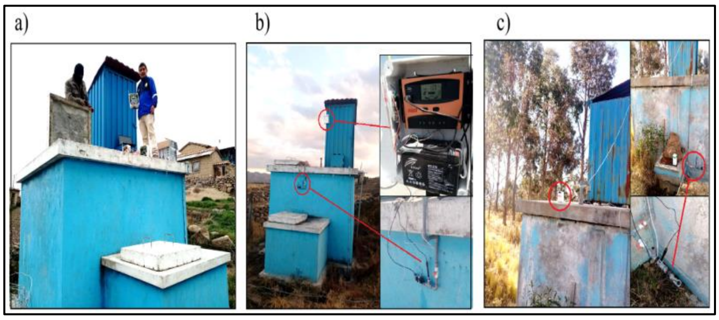

Figure 7: Water reservoirs in rural communities, a) prior to the installation of the wireless sensor, b) and c) with wireless sensors.
Source: Authors, (2025).

Table 6 describes the transmission paths of wireless sensors in remote monitoring.

Table 6: Transmission paths of wireless sensors in remote monitoring

Routes	Origin: Transmission	Location	Destination: Reception	Location
1	S1 Sachapite	-12º 44.069 -74º 54.590	S3 Pampachacra	-12º 48.643 -74º 55.271
2	S4 Huaylacucho	-12º 47.521 -74º 56.905	S2 Antaccocha	-12º 44.697 -74º 54.948
3	S2 Antaccocha	-12º 44.697 -74º 54.948	S3 Pampachacra	-12º 48.643 -74º 55.271
4	S3 Pampachacra	-12º 48.643 -74º 55.271	Monitoring Center (UNH) Huancavelica	-12º 46.733 -74º 57.617
5	S5 San Gerónimo	-12º 47.045 -74º 59.931		

Source: Authors, (2025).

Figure 8 graphically illustrates the transmission routes of wireless sensors within the mountainous rural Andean geography of Huancavelica.

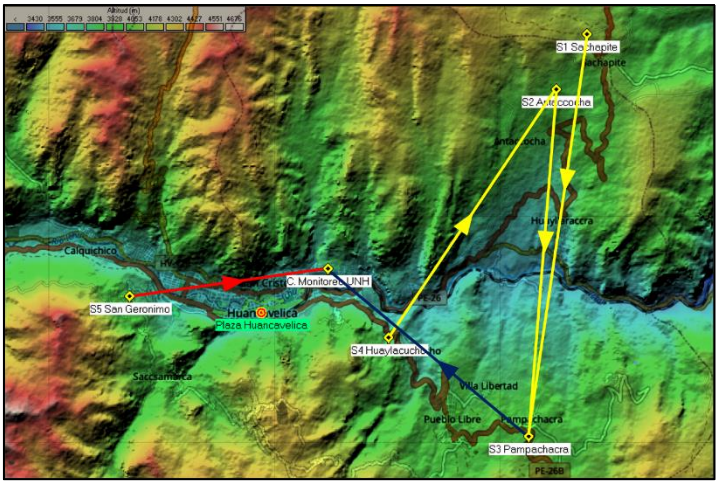

Figure 8: Transmission paths of wireless sensors in remote monitoring.
Source: Authors, (2025).

Figure 9 presents the data display panel for remote monitoring with wireless sensors.

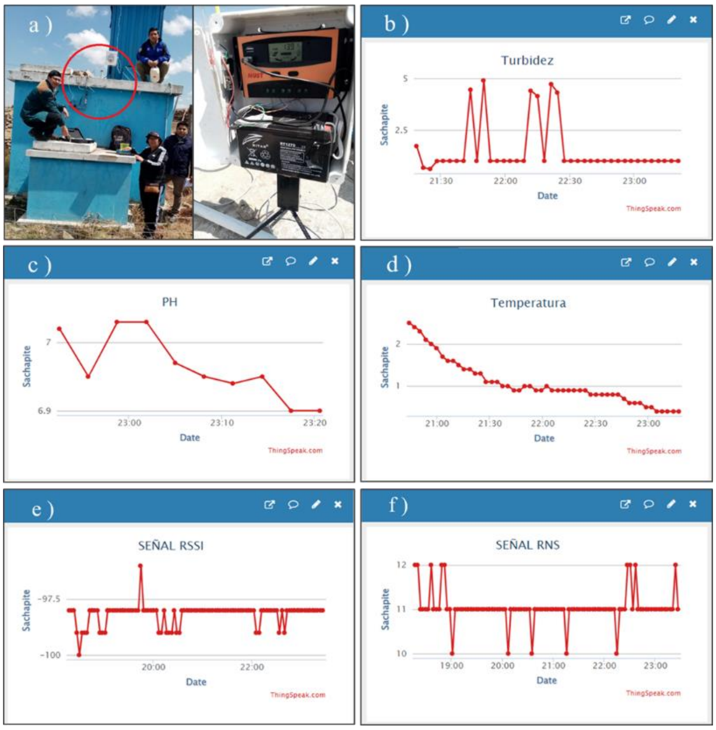

Figure 9: Remote monitoring of water quality; a) wireless sensor in the reservoir, b) turbidity monitoring, c) pH, d) temperature, e) RSSI, and f) RNS.
Source: Authors, (2025).

III. RESULTS AND DISCUSSIONS

Five wireless sensors have been implemented to facilitate real-time remote monitoring of water quality using wireless transceivers and temperature (DS18B20), pH (PH-4502C), and turbidity (LGZD V1.1) sensors, with an approximate accuracy of 98.98%, 96.81% and 89.82% respectively; the installation of the sensors makes up a low-power wide area network (LPWAN) distributed in five communities and a Gateway in charge of recording the information on the ThingSpeak Internet platform. LPWAN communication is carried out using the spread spectrum modulation technique through the LoRa 32 (V2) WiFi card with SX1278 transceiver, spreading factor (SF) of 12, and transmission power of 13 dBm in the 433 MHz ISM frequency band; the Gateway also uses the Wifi 802.11 b/g/n protocol.

In this regard, various studies state that monitoring water quality in rural areas is complex due to various factors such as geography, logistics, and manual procedures that make it difficult and impossible to develop frequent monitoring in favor of rural populations and the availability of information [8],[10],[30].

The results demonstrate the feasibility of monitoring water quality in rural, extensive, and mountainous geographic areas such as Huancavelica-Peru, based on the use of technologies such as LoRa [30],[31] with which the difficulties of monitoring are minimized; on the contrary, it enables remote monitoring of water quality, expanding the availability of information in favor of rural communities for water security and control actions according to the standard [32].

Table 7 shows the results of the data received during the transmission of the wireless sensors within the LPWAN network, where the overall average of the 5 reservoirs was 456 out of a total of 462 expected data, representing 98.7% effectiveness in the transmission and reception of data; a result similar to that recorded by [17] corresponding to 95.5% during the transmission of 600 data and much better than the 80% reported by [33] for a homogeneous LoRaWAN network. The research shows that wireless sensors ensure high effectiveness of data transmission and reception with LoRa transceivers in rural geographic spaces.

Table 7: Data received from the wireless sensors (S1 Sachapite, S2 Antaccocha, S3 Pampachacra, S4 Huaylacucho, S5 San Gerónimo)

Day	S1	S2	S3	S4	S5
1	459.00	459.00	456.00	456.00	455.00
2	458.00	457.00	456.00	455.00	454.00
3	458.00	455.00	460.00	456.00	457.00
4	458.00	460.00	458.00	458.00	456.00
5	456.00	458.00	458.00	458.00	454.00
6	458.00	457.00	457.00	457.00	455.00
7	457.00	456.00	456.00	454.00	457.00
8	457.00	456.00	458.00	457.00	453.00
9	454.00	456.00	458.00	455.00	455.00
10	456.00	451.00	457.00	456.00	457.00
General Average	457.10	456.50	457.40	456.20	455.30

Source: Authors, (2025).

On the other hand, Table 8 shows the distances and altitudes of signal transmission, as well as the maximum and minimum values of RSSI and SNR during data reception from the wireless sensors.

The maximum distance reached was 8.73 km between the S1 Sachapite and S3 Pampachacra positions located between 4196 and 4072 m of altitude respectively.

The results exceed the remote monitoring distances of research such as [11],[12],[14],[34], which reported monitoring at distances up to 120 m with Wifi systems and others up to 2.0 km with LoRa communication systems [15],[18],[35],[36] in flat and coastal geography.

However, despite the achievement, the challenge of improving the communication distance over 10 km recorded with technologies such as LoRa SX1272 or RN2483 still arises [37],[38].

Table 8: Results for RSSI and SNR considering transmission distances and altitudes.

Origin of transmission Location, altitude		Transmission destination Location, altitude		Distance (km)	RSSI dBm	SNR dB
S1 Sachapite	4196	S3 Pampachacra	4072	8.73	-95 to -104	10 to 12
S2 Antaccocha	4084	S3 Pampachacra	4072	6.43	-93 to -102	10 to 12
S4 Huaylacucho	3823	S2 Antaccocha	4084	5.45	-103 to -111	10 to 13
S3 Pampachacra	4072	Monitoring Center (UNH)	3723	5.60	-96 to -115	10 to 13
S5 San Gerónimo	3885		3723	4.29	-110 to -122	09 to 12

Source: Authors, (2025).

On the other hand, the RSSI received signal strength measurements were recorded in the range of -122 dBm to -93 dBm for different distances between 4.29 km to 8.73 km. These RSSI results are similar to the measurements of [39] and [40] whose achieved range was -120 dBm to -100 dBm for distances of 1560 m and 500 m respectively. It is evident that wireless sensors with the WiFi LoRa 32(V2) still have an adequate RSSI sensitivity at long distances, also having an approximate 9% tolerance margin with respect to the minimum limit of -135 dBm indicated by the manufacturer [20].

Regarding the results of the signal-to-noise ratio (SNR) of the communication, these were found in the range of 9 dB to 13 dB and according to [41], SNR values greater than 0 dB represent signals of good transmission quality with a minimum packet loss error rate. Therefore, the remarkable thing about the measured results of RSSI and SNR, is that they guarantee good communication of wireless sensors in far rural and mountainous scenarios where the quality of data transmission remains similar to those of short distances.

Table 9 presents the results of remote monitoring of water temperature, pH and turbidity for the five reservoirs.

Table 9. Results of remote monitoring of temperature, pH and turbidity in the rural Andean area of Huancavelica.

Ubication	Min	Quartile 1	Quartile 2	Quartile 3	Max
a) Temperature (°C)					
S1 Sachapite	-2.90	1.60	5.00	10.50	12.20
S2 Antaccocha	-1.30	3.00	5.20	9.70	14.40
S3 Pampachacra	-1.90	1.10	3.80	9.00	13.50
S4 Huaylacucho	0.60	4.10	7.00	10.20	13.00
S5 San Gerónimo	0.50	1.90	4.50	10.50	13.70
(WHO, 2011)	< 20	< 20	< 20	< 20	< 20
b) Hydrogen potential (pH)					
S1 Sachapite	6.76	7.13	7.52	7.60	7.80
S2 Antaccocha	6.86	7.35	7.50	7.68	7.98
S3 Pampachacra	6.60	6.99	7.14	7.35	7.87
S4 Huaylacucho	6.88	7.14	7.32	7.44	7.89
S5 San Gerónimo	6.80	7.19	7.67	7.76	8.24
(DIGESA, 2010) (WHO, 1971)	6.5 - 8.5	6.5 - 8.5	6.5 - 8.5	6.5 - 8.5	6.5 - 8.5
c) Turbidity (NTU)					
S1 Sachapite	0.50	1.43	2.20	2.90	4.94

S2 Antaccocha	0.34	2.09	2.85	3.45	4.51
S3 Pampachacra	1.00	1.42	2.10	3.20	4.98
S4 Huaylacucho	0.50	1.23	2.07	2.70	4.90
S5 San Gerónimo	0.80	1.57	2.20	3.47	4.91
(DIGESA, 2010) (WHO, 1971)	< 5	< 5	< 5	< 5	< 5

Source: Authors, (2025).

Figure 10 illustrates through a box plot the distribution of the data collected from the ten days of remote monitoring experimentation.

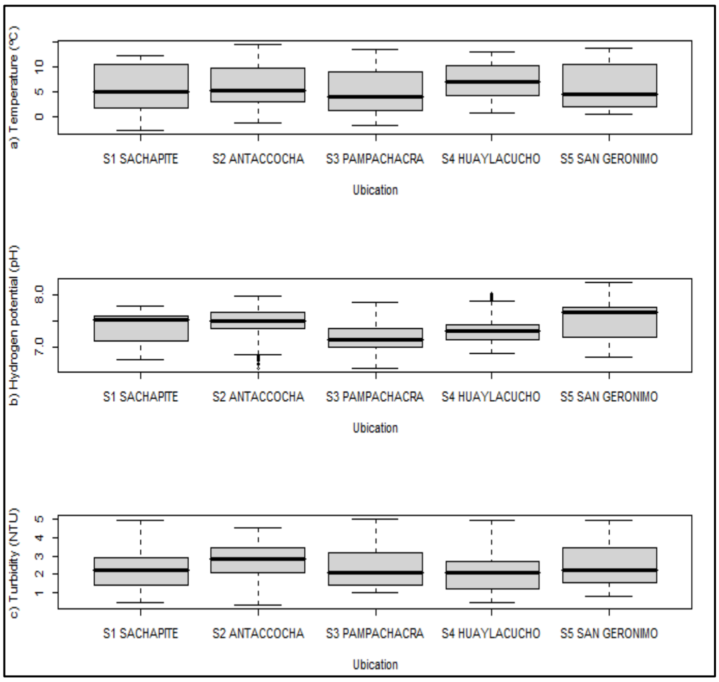

Figure 10. Remote monitoring of water quality in the reservoirs. a) Temperature, b) pH and c) Turbidity
Source: Authors, (2025).

The results for temperature, pH and turbidity reveal significant variations in water quality among the five rural communities. Temperature measurements ranged from a minimum of -2.90 ºC in S1 Sachapite to a maximum of 14.40 ºC in S2 Antaccocha between night and day respectively, with intermediate values ranging between 3.8 ºC and 7. 0 ºC, which highlights the cold climate of the region with which naturally ensures low water temperature (< 20 ºC), fulfilling the recommendation of the WHO [22] so that the various microorganisms such as V. Cholerae, Legionella spp among others do not have high growth rates and propagation.

The pH levels were within the acceptable range of 6.5 to 8.5 of the Peruvian standard [42] and WHO [23] with a minimum value of 6.60 recorded in S3 Pampachacra and a maximum value of 8.24 in S5 San Gerónimo, which indicates the adequate neutrality of the monitored waters, evidencing a natural pH balance and the safety it represents for consumption within the monitored communities.

As for turbidity levels, all were found to be below the WHO threshold of 5 NTU with a variation ranging from a minimum of 0.34 NTU identified in S2 Antaccocha to a maximum value of 4.98 NTU in S3 Pampachacra, results that suggest good water clarity and quality with respect to suspended particles or sediments from soil erosion of the rural springs from which the water is obtained.

Therefore, the results indicate that the remotely monitored water sources have favorable physicochemical characteristics (ºC, pH, NTU) and meet the drinking water quality guidelines of Peruvian and WHO regulations. Likewise, they temporarily reflect the adequate preservation of water quality conditions in relation to previous physicochemical evaluations [43]; preservation that is probably due to the rural geographic location of the waters where anthropogenic intervention is minimal and moderate hydrological cycles that however are susceptible to alteration due to climate change effects which should be taken into consideration [44-46].

Finally, it highlights the importance of monitoring water in order to ensure its quality [32],[47], which, remote monitoring with wireless sensors is a feasible tool that facilitates continuous water monitoring minimizing the geographical gaps and limitations of the rural environment.

IV. CONCLUSIONS

In the research, wireless sensors have been implemented that allowed remote and real-time monitoring of water quality in complex rural geographic spaces with an accuracy of 98.98%, 96.81%, and 89.82% for temperature, pH, and turbidity respectively. A high effectiveness of around 98.7% has been achieved in the transmission and reception of data covering distances of up to 8.73 km in mountainous rural geography with altitudes between 4072 m and 4196 m, demonstrating the feasibility of using LoRa wireless technology in minimizing geographic distances during remote monitoring of water quality. Similarly, it has been verified that the received signal strength RSSI and signal to noise ratio SNR in long distance comunications have a tolerance margin of up to 9% for the RSSI with respect to the limit value of -135 dBm indicated by the manufacturer of the Wifi LoRa 32(V2) and that the SNR is in the range of 9 dB to 13 dB, showing that the transmitted signals are of good quality with a minimum packet loss error rate.

Remote monitoring of water quality in the five rural communities involved confirmed that the temperature, pH, and turbidity meet Peruvian and World Health Organization standards, with temperatures below 20 ºC (minimum -2. 90 ºC in S1 Sachapite and maximum 14.40 ºC in S2 Antaccocha); pH within the range of 6.5 and 8.5 (minimum 6.60 pH in S3 Pampachacra and maximum 8.24 pH in S5 San Gerónimo) and turbidity below 5 NTU (minimum 0.34 NTU in S2 Antaccocha and maximum 4.98 NTU in S3 Pampachacra).

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