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Development of an electronic device for real-time water quality monitoring using the Internet of Things (IoT).

Desarrollo de dispositivo electrónico para el monitoreo de la calidad del agua en tiempo real mediante uso del Internet de las Cosas (IoT).

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ABSTRACT

The present study will highlight the importance of maintaining water quality amid the pressure on water resources, as it affects health and various productive activities. The objective was to develop a device utilizing electrometry principles for real-time monitoring of critical parameters in underground wells, thereby facilitating decision-making. Additionally, a study was conducted involving design and experiments with a data-collecting prototype, performing simulations under conditions as close as possible to a real well. To achieve this, sensors were integrated to measure pH, conductivity, dissolved solids, temperature, and turbidity. These sensors were calibrated, and their readings were compared with those obtained using laboratory equipment. This information was transmitted to a cloud database using a data-collecting microcontroller and a wireless module, which sent the collected data. The data was then analyzed in Excel spreadsheets. The results demonstrated stable measurements and accuracy, confirming the system's reliability. In conclusion, the device proved to be a valuable tool for continuous water quality monitoring, with recommendations for field validation and parameter expansion.

KEY WORDS: Water Quality, Real-Time Monitoring, Electronic Sensors, Internet of Things, Aquifers.

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ABSTRACT

Este estudio destacará la importancia de mantener la calidad del agua ante la presión sobre los recursos hídricos, esto, debido a que afecta a la salud y varias actividades productivas. El objetivo fue el desarrollar un dispositivo, usando los principios de electrometría para el monitoreo en tiempo real de los parámetros cruciales en pozos subterráneos, facilitando la toma de decisiones. Además, se realizó un estudio que consistió en diseñar y experimentar con un prototipo recopilador de datos, realizando simulaciones en las condiciones más cercanas a un pozo real. Para ello, se integraron sensores para medir pH, conductividad, sólidos disueltos, temperatura y turbidez. Estos fueron calibrados, y sus lecturas se compararon con equipo de laboratorio, esta información se transmitió a una base de datos en la nube mediante el uso de un microcontrolador recopilador de datos y un módulo inalámbrico que envía la información recopilada, el cual fue ajustado en hojas de cálculo de Excel para su análisis. Los resultados demostraron mediciones estables y precisión, de manera que afirma la confiabilidad del sistema. En conclusión, el dispositivo demostró ser una herramienta para el monitoreo continuo de la calidad del agua, recomendándose su validación en campo y la ampliación de parámetros.

KEY WORDS: Calidad del agua, Monitoreo en tiempo real, Sensores electrónicos, Internet de las Cosas, Acuíferos.

Introduction

The development of our society has exerted an increasing demand on natural resources to me*et al*l needs, with water being a fundamental and priority element for all human activities. This condition has led to an unprecedented level of water stress on the ecosystems that sustain water supply, not only in terms of quantity but also considering the deterioration of its quality.

The quantity and use of water differ among countries. Agriculture, except for Europe, is the sector with the highest global water consumption, ranging from 70 % to 90 % of the total, while public use accounts for 7 % to 18 %; and the industrial sector consumes between 1 % and 11 % (SEMARNAT, 2019).

According to the World Health Organization (WHO) guidelines, drinking water is defined as water that can be consumed throughout life without causing adverse effects on survival (Blanco, 2015). This implies that not only a sufficient quantity of water is sought, but also the quality necessary for its safe use.

Aquifers are natural structures with the capacity to store water by retaining suspended contaminants through natural filtration. The deposits that form aquifers within geohydrological structures are exploited through advanced extraction systems, which are of vital importance in northern Mexico as they represent the primary source of surface water supply capable of meeting demand. However, water quality may be affected by well-related parameters, such as the presence of metal and metalloid deposits, which, at significant dissolved concentrations, can be harmful. Similarly, wells and waterwheels located near coastal areas are affected by seawater intrusion, which alters the water's composition by salinizing it, thereby limiting its use for certain activities.

The diverse uses of groundwater further increase its complexity, as it is commonly employed not only in agriculture but also in industrial processes. These processes require specific water characteristics, which vary depending on the type of product being manufactured (Aragón *et al.,* 2022).

In recent years, the exploitation of aquifers in arid and semi-arid regions has intensified. Worldwide, one of the most emblematic examples of this situation is the case of water supply in Iran, where 60 % of the consumed water originates from underground sources (Mirzaei *et al.*, 2019).

In the case of México, Ciudad Victoria, Tamaulipas state, has two major aquifers officially recognized by CONAGUA identified as: "VICTORIA-CASAS" and "VICTORIA-GUÉMEZ." Together, they cover nearly 100 % of the municipality's territory. According to the base method described in NOM-011-CNA-2015, these aquifers show a negative annual average availability (DMA) of groundwater, with -0.91155 hm^3/year (hm^3 = 1 million cubic meters) and -28.768 hm^3/year, respectively (CONAGUA, 2020).

This indicates that there is no available volume to grant new concessions, with annual deficits of 1,200,593 m^3 (Gerencia de Aguas Subterráneas, 2023a) and 30,128,354 m^3 (Gerencia de Aguas Subterráneas, 2023b), respectively. As a result, there has been an exponential increase in water stress due to various internal and external factors, leading to changes in the chemical composition of water in key groundwater collection points. This directly impacts the ecosystems surrounding wells, causing water to lose its suitability for assigned uses, including human consumption, agriculture, and industry, among others.

According to Blanco (2015), as the population increases and water consumption rises, its impact on water quality will become more significant. Additionally, the fact that water has become contaminated with multiple types of suspended solid elements, including physical, chemical, and microbiological pollutants.

Furthermore, the lack of up-to-date and continuous records on water quality parameters increases the risk to public health and the manufacture of defective products, such as contaminated crops in agriculture, as well as losses of products, machinery, and sensitive equipment.

O'Grady *et al.* (2021) reported that, given the increasing risks associated with ecosystem changes, recent advances in strategies for developing water quality monitoring systems can be leveraged to implement reliable monitoring approaches that enhance understanding of the processes affecting aquifer water quality. In recent years, the development of field-deployed sensors has significantly improved data collection.

In recent years, several authors have utilized low-cost platforms based on open-source technologies, such as Arduino and ESP32, for water quality monitoring (Fonseca *et al.*, 2022; Kelechi *et al.*, 2021; Kumar *et al.*, 2024). These devices are capable of measuring key physicochemical parameters, including pH, turbidity, temperature, total dissolved solids, and conductivity. However, most of these applications have been tested under controlled environments, without considering the complexity of groundwater well conditions. In addition, only a few studies have adapted these technologies to Mexican water quality standards, which limits their applicability in local contexts. This technological gap, coupled with the needs of communities that rely entirely on groundwater for agricultural, industrial, or domestic activities, motivated the present study. The aim is to design, implement, and validate a real-time electronic water quality monitoring system that integrates low-cost sensors with wireless transmission capability. The prototype is based on an Internet of Things (IoT) architecture and validated through a certified laboratory of instruments, in compliance with applicable Mexican official standards.

Material and Methods

Study area

The research was conducted in the aquifers of Ciudad Victoria, the capital of Tamaulipas state, Mexico. This city is located in a semi-desert region with a warm, temperate and sub-humid climate. Average annual temperatures range between 23 and 28 °C (Instituto Nacional de Estadística y Geografía [INEGI], 2024), with an annual precipitation of approximately 1,100 mm (Figure 1). The groundwater aquifers in this region serve as the primary source of water supply for the population, industry, and agriculture, as surface water availability is limited.

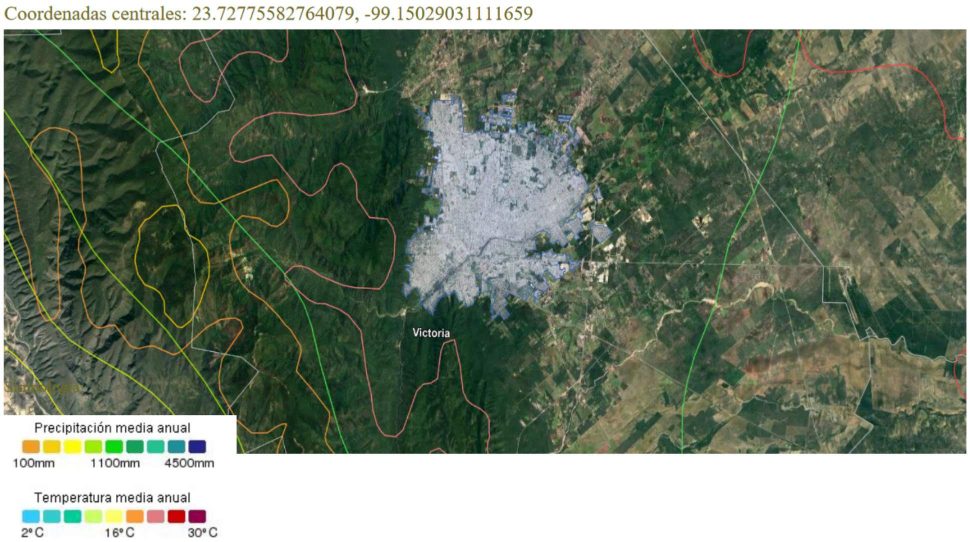

Figure 1. Average annual precipitation and average annual temperature in Ciudad Victoria, Tamaulipas.

Source: INEGI, 2024.

Geographical location of the aquifers

The Victoria-Guémez aquifer, identified with code 2807, is located in the west-central region of Tamaulipas (Figure 2), covering a surface area of 1,947 km^2. The boundaries are defined as follows: to the east, by the Vicente Guerrero Dam; to the north, by the impermeable claystone barrier of the Méndez Formation, which runs almost parallel to the Guayabas and Corona streams, approximately 3 km apart. To the west lies the Sierra Madre Oriental. At the same time, the southern boundary is marked by the claystone outcrops of the Méndez Formation, roughly aligned in parallel from the Vicente Guerrero Dam to the San Marcos River (Gerencia de Aguas Subterráneas, 2023b).

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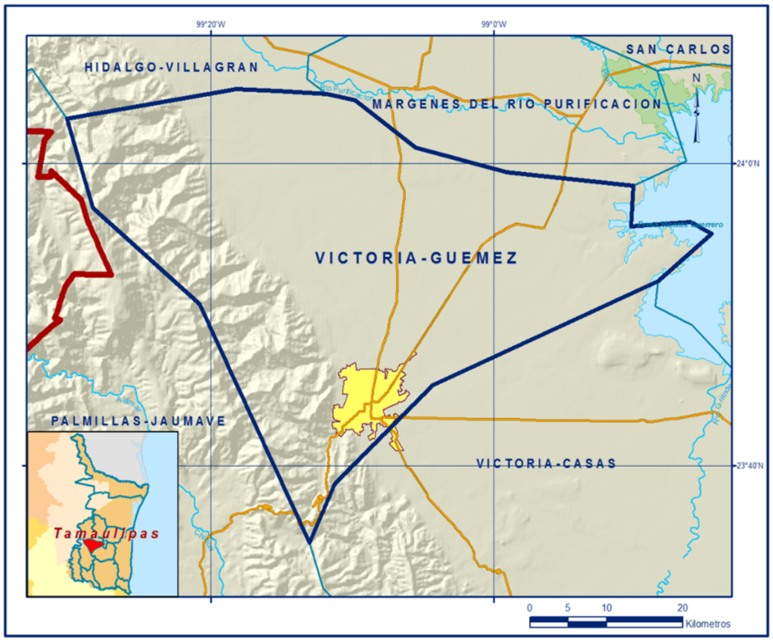

Figure 2. Victoria-Guémez Aquifer.

Source: CONAGUA, 2023.

The Victoria-Guémez aquifer extends across part of Ciudad Victoria, the municipality of Güémez, and a portion of Hidalgo. The most significant economic activities occur in Santa Engracia, Güémez, and Ciudad Victoria, where rapid growth in agriculture, services, and population has intensified competition for groundwater use, resulting in excessive extraction of this resource (Gerencia de Aguas Subterráneas, 2023b).

The Victoria-Casas aquifer, identified by code 2808, is located in the south-central region of Tamaulipas (Figure 3), between latitudes 23°19′ and 23°40′ N and longitudes 98°19′ and 99°14′ W. It covers a surface area of 1,907 km^2. It is bordered by the Jiménez-Abasolo aquifer, the Palmillas-Jaumave aquifer to the southwest, the Llera-Xicoténcatl aquifer to the south, the Aldama-Soto La Marina aquifer to the east, and the Victoria-Guémez aquifer to the northeast (Gerencia de Aguas Subterráneas, 2023a).

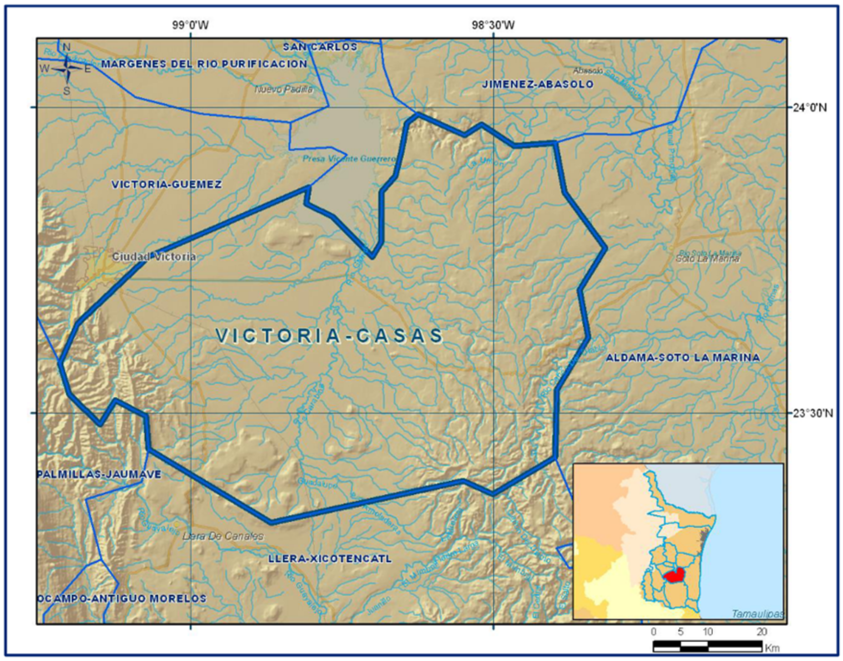

Figure 3. Victoria-Casas Aquifer.

Source: CONAGUA, 2023.

This aquifer extends across four municipalities, partially covering Victoria, Güémez, and Llera, but the most considerable portion lies within the municipality of Casas. In addition, a small portion of the aquifer extends into the eastern area of Soto La Marina (Gerencia de Aguas Subterráneas, 2023a).

Hydrogeochemistry and water quality

In the Victoria-Guémez aquifer, the most recent monitoring was performed in 54 groundwater wells on September 19, 1995. Measurements showed that total dissolved solids (TDS) ranged from 348 to 2,416 ppm (parts per million), with most values below 1,000 ppm (Gerencia de Aguas Subterráneas, 2023b).

For the Victoria-Casas aquifer, no hydrogeochemical information from physicochemical analyses of groundwater samples is currently available. Regarding water quality, this aquifer is characterized by its TDS concentration. In 2006, a survey was performed with on-site measurements of TDS. The results generally indicated that the total dissolved solids did not exceed the 1,000 ppm limit established by Mexican NOMs (standards) for human consumption.

However, locally, values above this threshold were recorded due to specific contamination hotspots (Gerencia de Aguas Subterráneas, 2023a).

Methodology

Methodological design

For the development of the real-time electronic water quality monitoring device, an experimental and structured methodological approach was adopted, divided into five main stages:

1. Design of the data acquisition system.
2. Construction and assembly of the prototype.
3. Sensor calibration and measurement validation.
4. Data transmission and cloud storage.
5. Data analysis.

This approach was applied under controlled laboratory conditions, simulating the environment of a groundwater well using a 500 mL beaker, thereby ensuring experimental repeatability.

System architecture diagram

The system architecture was designed with a modular structure. Each module fulfills a specific function: data acquisition, signal processing, data transfer, wireless communication, and remote data storage. Figure 4 presents the overall diagram.

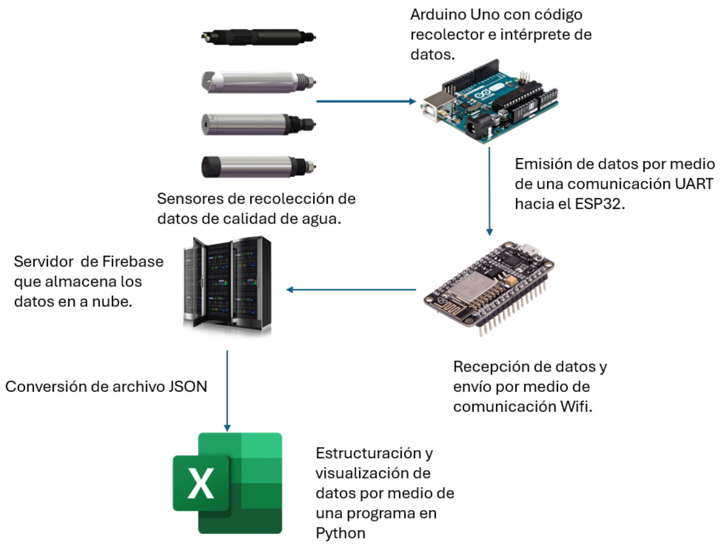

Figure 4. System architecture diagram.

Source: Authors' elaboration with PowerPoint software by Microsoft.

This design enables real-time operation with potential for integration into large-scale remote monitoring systems.

Experimental conditions

The tests were conducted under controlled conditions. Table 1 summarizes the parameters of the experiments. Readings were recorded at 5-minute intervals over a continuous 1-hour period, allowing for the evaluation of measurement stability.

Table 1. Experimental conditions.

Controlled variable	Value
Ambient temperature	18 - 23 ºC
Relative humidity	50 – 60 %
Test solution	Standard pH 7 solution
Sample volume	500 mL
Location	Industrial Engineering Master's Laboratory

Source: Authors' elaboration.

Methods for water quality determination

To take readings and assess water quality, various aspects were considered depending on the region, specific area, and environment, since the parameters will be weighted differently depending on whether the water source is used for agriculture, industry, or human consumption. With this in mind, it can be concluded that water quality is defined by the specific purpose for which it is intended.

Some analytical parameters will be more relevant than others depending on the water's purpose. The most common include (Sánchez *et al.,* 2016):

- pH
- Electrical conductivity
- Turbidity
- Temperature
- Total dissolved solids

A detailed explanation of the methods used to determine these parameters, as well as the criteria of the intended use of the resource (agricultural, industrial, or domestic), is provided in Appendix A.

Applicable Mexican NOMs (Standards)

These NOMs employ standardized and reliable procedures to ensure accurate results in water quality analyses. The NOMs provide guidelines for various types of water to ensure precision and comparability in both laboratory and field tests. In addition, NOMs have objectives and scope, as well as principles for measurement methods, equipment specifications, calibration procedures, measurement protocols, reporting requirements, and necessary precautions for parameter readings.

In the development of the present prototype, these NOMs were adopted to ensure reliable and comparable measurements. The selection and calibration of electronic sensors, as well as the analytical methodology, followed the guidelines established by these regulations, ensuring that the designed system complied with recognized quality and accuracy standards.

To further guarantee measurement reliability, technical guidelines established by various official Mexican NOMs were used as a basis. These are described in Appendix B.

Beyond these parameters, additional laboratory analyses can be performed to detect specific dissolved chemical substances suspected of contaminating water sources, depending on local environmental conditions. Examples include nitrates, hydrocarbons, ammonium, chloroethylene, sodium chloride, chloride ions, and sulfate ions, among others, which vary according to the surrounding human activities (Mancilla-Villa *et al.,* 2021).

Equipment and materials

It is essential to consider all relevant materials, as exhaustive laboratory testing was conducted over extended periods. Specialized equipment was required to ensure precise and accurate sampling each time data were collected.

Equipment description

Arduino Uno: A microcontroller board based on the Atmega328P chip, widely used in electronic projects due to its ease of use and versatility (Mabrouki *et al.*, 2021).

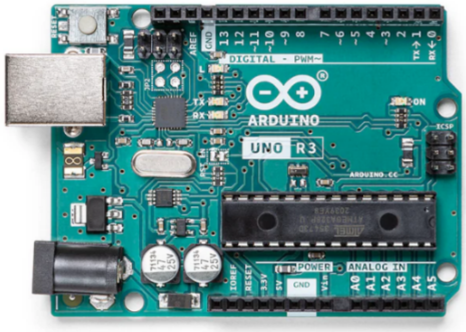

Figure 5. Arduino Uno.

Source: Arduino (n.d.). Arduino Uno [Image].

Retrieved from https://store.arduino.cc/products/arduino-uno-rev3?queryID=undefined

pH Sensor: A sensor designed to measure the pH of liquid solutions accurately. It features a specialized housing that allows for continuous readings over extended periods, enabling its use in both industrial and laboratory conditions, with the added adaptability for integration with Arduino platforms (Mohd *et al.*, 2024).

Figure 6. SEN0169-V2 pH sensor by DFRobot.

Source: DFRobot (n.d.). SEN0169-V2 [Image].
Retrieved from https://www.dfrobot.com/product-2069.html

Temperature Sensor: A module designed to measure water temperature, known for its accuracy, ease of use, and resistance to environments with high humidity levels.

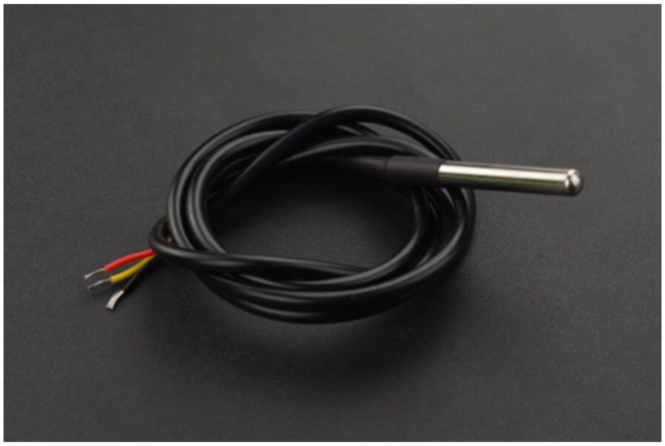

Figure 7. DS18B20 temperature sensor by DFRobot.

Source: DFRobot (n.d.). DS18B20 [Image].
Retrieved from https://www.dfrobot.com/product-689.html

Total Dissolved Solids (TDS) Sensor: A sensor designed to measure the amount of total dissolved solids in water, which provides an estimate of the concentration of dissolved substances. These may include minerals, salts, and/or organic matter (Silva & Coello, 2020).

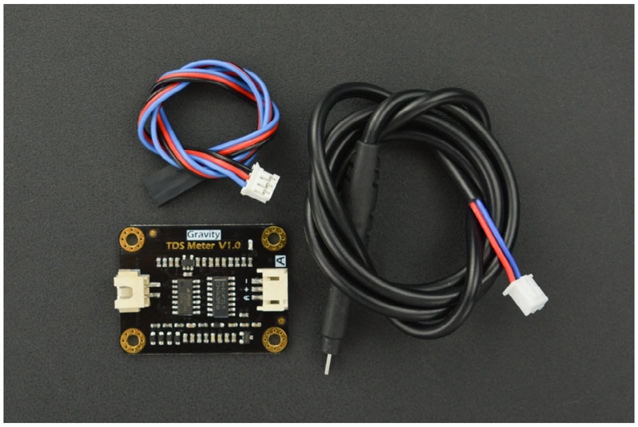

Figure 8. SEN0244 TDS sensor by DFRobot.

Source: DFRobot (n.d.). SEN0244 [Image].
Retrieved from https://www.dfrobot.com/product-1662.html

Turbidity Sensor: A water clarity sensor that measures the degree of transparency or opacity. Its operation is based on detecting suspended particles in the water by measuring light passing through the sample and how it is scattered (Kumar *et al.*, 2024).

Figure 9. SEN0189 Turbidity Sensor by DFRobot.

Source: DFRobot (n.d.). SEN0189 [Image].
Retrieved from https://www.dfrobot.com/product-1394.html

MakerBot Replicator Z18 3D Printer: This large-format printer features a build volume of 30 x 30.5 x 45.7 cm and utilizes PLA (polylactic acid) as its primary printing material.

Figure 10. MakerBot Replicator Z18 3D Printer.

Source: MakerBot (n.d.). Replicator Z18 [Image].
Retrieved from https://www.makerbot.mx/3d-printers/replicator-z18/

PLA (Polylactic Acid): A biopolymer commonly used in 3D printing due to its ease of handling, low warping, and high-quality surface finish. It is particularly suitable for prototypes that are constantly exposed to humidity, as it is derived from renewable resources such as cornstarch.

Figure 11. PLA printing material by manufacturer XTZL3d.

Source: XTZL3d (n.d.). PLA [Image].
Retrieved from https://xtzl3d.com/products/xtzl-pla-3d-printing-filament-1

ESP32: Developed by Espressif, is a versatile microcontroller widely used in Internet of Things (IoT) projects, as it integrates wireless connectivity and multiple functionalities that makes it suitable.

Figure 12. ESP32 development board module.

Source: DigiKey (n.d.). ESP32 [Image]. Retrieved from https://www.digikey.com.mx/es/products/detail/espressif-systems/ESP32-DEVKITC-VIE/12091811

Technical table of sensors and associated standards

For the use of electronic sensors compatible with the Arduino platform, a comparative table was considered to calibrate each sensor according to the manufacturer's guidelines and in comparison with the reference standards. This information is presented in Table 2.

Table 2. Technical specifications of the sensors used.

Parameter	Sensor (Model)	Associated NOMs (Standard)	Operating Range	Accuracy	Manufacturer	Sensor Type
pH	SEN0169-V2	NMX-AA-008-SCFI-2016	0 - pH	±0.1 pH	DFRobot	Electrometric
Conductivity/ Total Dissolved Solids	SEN0244	NMX-AA-034-SCFI-2015/ NMX-AA-093-SCFI-2018	0 - 1000 ppm	±10 %	DFRobot	Conductivity meter
Temperature	DS18B20	NMX-AA-007-SCFI-2013	-10 - 85 ºC	±0.5 ºC	DFRobot	Nephelometric
Turbidity	SEN0189	NMX-AA-038-SCFI-2021	0 - 1000 NTU	± 5 %	DFRobot	Digital thermistor

Source: Authors' elaboration based on data retrieved from the manufacturer (DFRobot).

Electronic circuit assembly

In the present study, a circuit was developed to integrate sensors for pH, temperature, total dissolved solids/electrical conductivity, and turbidity. An Arduino Uno microprocessor was used to convert voltage signals from each sensor into numerical values through its analog ports, storing them in the serial monitor. These data were then transmitted to another microcontroller, which was responsible for uploading the information to a cloud-based database (Figure 13).

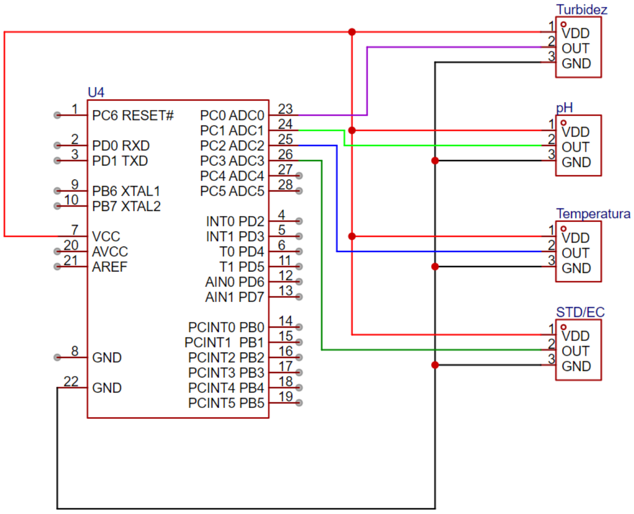

Figure 13. Diagram of the Arduino Uno with water quality sensors.

Source: Authors' elaboration based on EasyEDA Pro.

For data transmission through the Internet of Things (IoT), the ESP32 module was used. A voltage divider circuit was implemented to reduce the signal value and prevent damage to the ESP32 when operating alongside the Arduino Uno, since the latter outputs 5-volt signals (Figure 14).

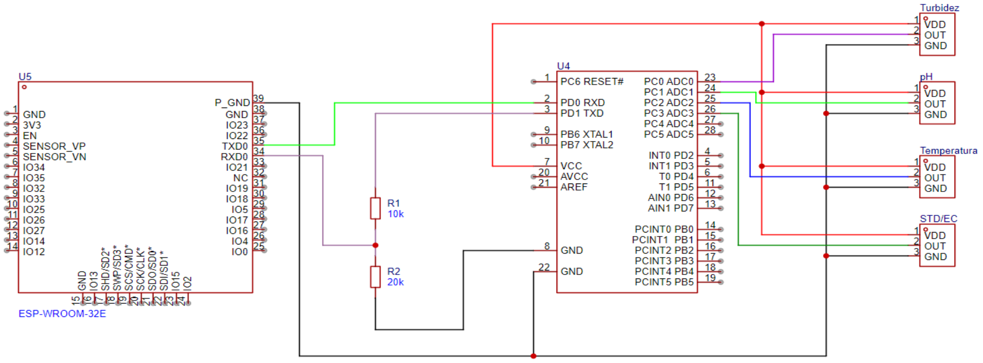

Figure 14. Schematic of the ESP32-Arduino Uno serial communication interface.

Source: Authors' elaboration based on EasyEDA Pro.

Programming logic flow

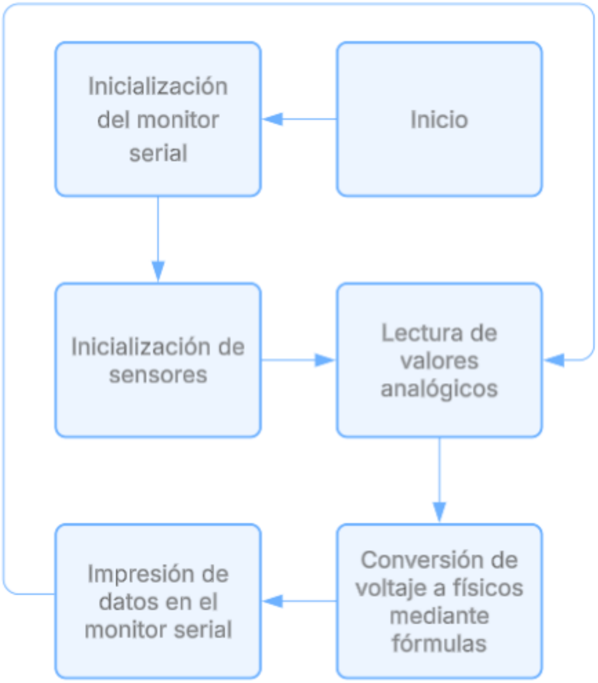

Figure 15. Flowchart of the Atmega328P microcontroller code.

Source: Authors' elaboration based on Lucidchart.

Atmega328P microcontroller programming

The code was developed using the Arduino IDE and is responsible for reading and processing data from water quality sensors (Kelechi *et al*., 2021): pH, temperature, and total dissolved solids. It initializes the TDS and pH sensors, configuring their ranges and voltage references. In the main loop, pH is measured by reading the voltage and applying formulas to obtain the corresponding values (Fonseca *et al*., 2022). Temperature is measured using the DS18B20 sensor, and readings are displayed on the serial monitor along with pH and TDS value after compensation applied. Since TDS and electrical conductivity (EC) are related, EC is calculated from the TDS value using standard formulas. Finally, the measured values of pH, EC, TDS, and temperature are printed to the serial monitor for real-time monitoring.

ESP32 microcontroller programming

The second code enables the ESP32 module to receive data from the Arduino Uno via serial communication and upload this information to Firebase for storage and monitoring (Khan *et al*., 2024). Wi-Fi communication is configured using network credentials and specific authentication to access the database (Sunardi *et al*., 2023). Additionally, the time is synchronized with an NTP server, which records the exact date and time for each measurement. The main loop continuously reads serial data, separates each sensor value (pH, TDS, EC, and temperature), stores the data in specific variables, and uploads it to Firebase at one-minute intervals. Data is organized by date and time in a JSON file, enabling structured and chronological storage in the cloud, which facilitates remote monitoring and analysis.

Python programming

The implementation of this code was designed to facilitate the structuring and visualization of the database in Firebase. Obtaining the JSON file is complicated because the data is displayed linearly, making it difficult to find information easily. Therefore, a code was developed to convert the JSON extracted from the database into an Excel file. This conversion organizes the water quality parameter information along with the time and date when the data was measured, with each date represented as a separate sheet in Excel and each sheet containing hourly records. This structure makes it easier to analyze and visualize data in office programs.

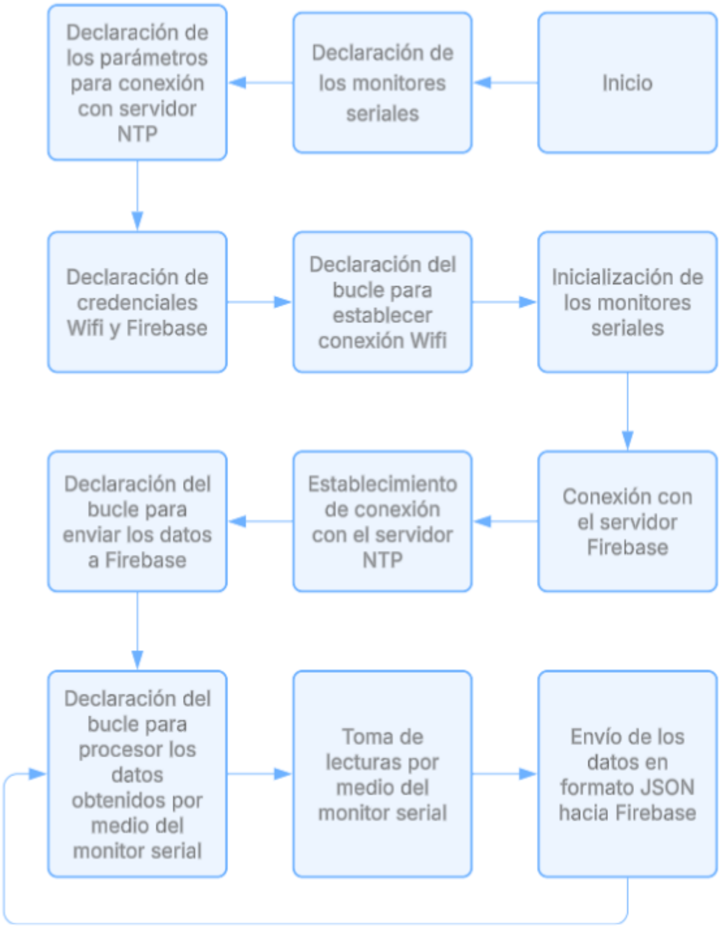

Figure 16. Flowchart of the ESP32 microcontroller code.

Source: Authors' elaboration based on Lucidchart.

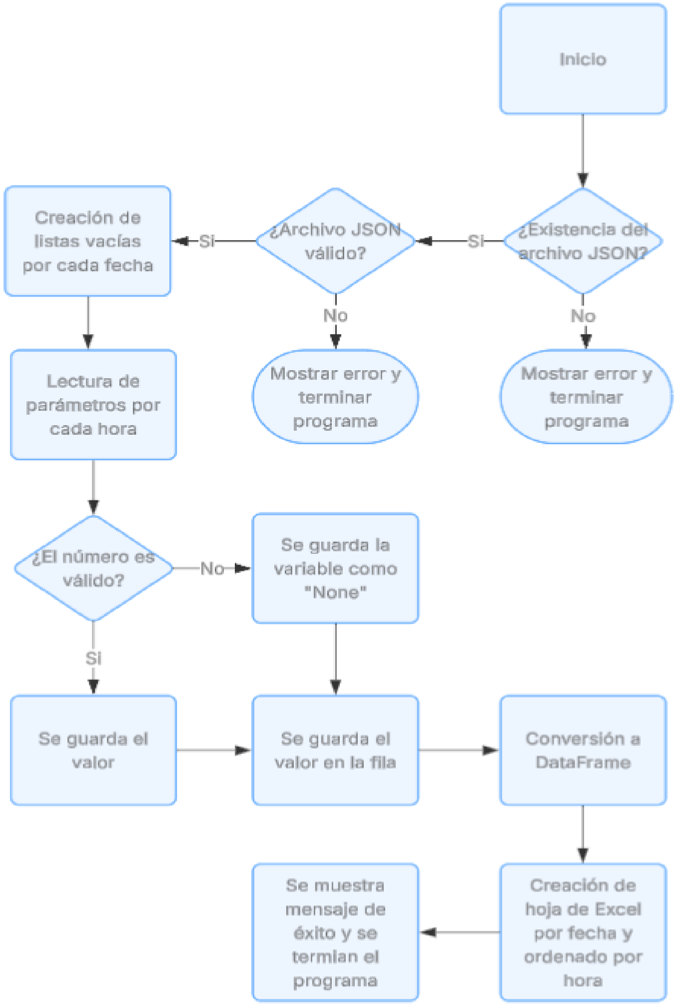

Figure 17. Flowchart of the Python code.

Source: Authors' elaboration based on Lucidchart.

Data processing and analysis

Once the data are stored and transformed into Excel worksheets, a statistical analysis is performed using the following indicators:

- Mean absolute error
- Relative error (%)

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- Standard deviation

For comparative purposes, sensors from HANNA Instruments were used. Table 3 summarizes the technical specifications of these instruments according to the manufacturer:

Table 3. Technical specifications of the HI98127 pH and temperature meter.

pH range	-2 a 16 pH
pH resolution	0.1 pH
pH accuracy	±0.1 pH
Temperature range	-5.0 a 60.0ºC / 23.0 a 140.0ºF
Temperature resolution	0.1ºC/±1ºF
Temperature accuracy	±0.5ºC/±1ºF

Source: Retrieved from https://hannainst.com.mx/medidor-de-bolsillo-phep-4-de-ph-3-temperatura-con-hi98127

Design and fabrication of the sensor holder

The measurements of the sensors were taken into account when creating the 3D design of the sensor support. In addition, the circumference of the hydraulic column was taken into account for the size of the base circumference to facilitate the immersion and extraction of the device. The following figures are the plans that were obtained as a result of the design creation.

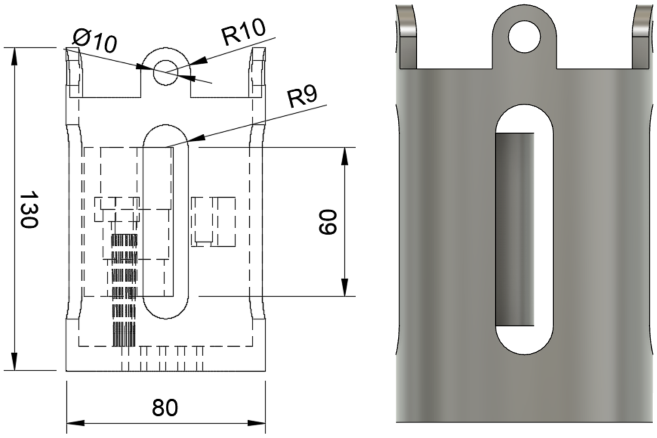


Figure 18. Dimensions and front orientation of the design.

Source: Authors' elaboration based on Autodesk Fusion.

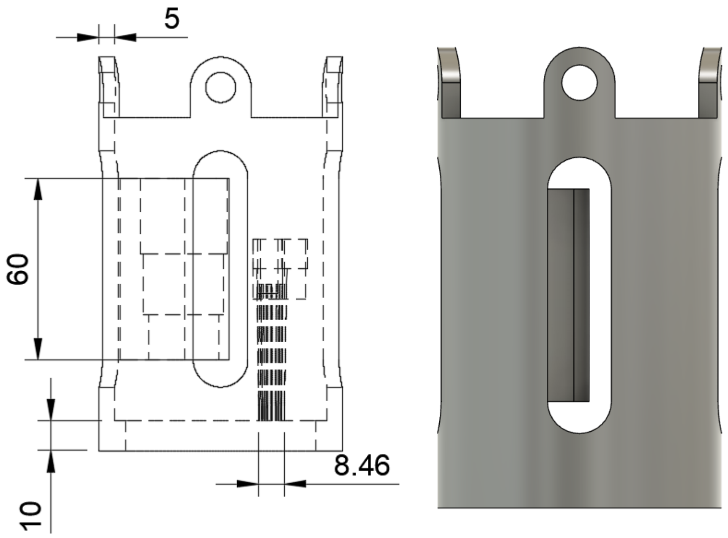


Figure 19. Dimensions and left-side orientation of the design.

Source: Authors' elaboration based on Autodesk Fusion.

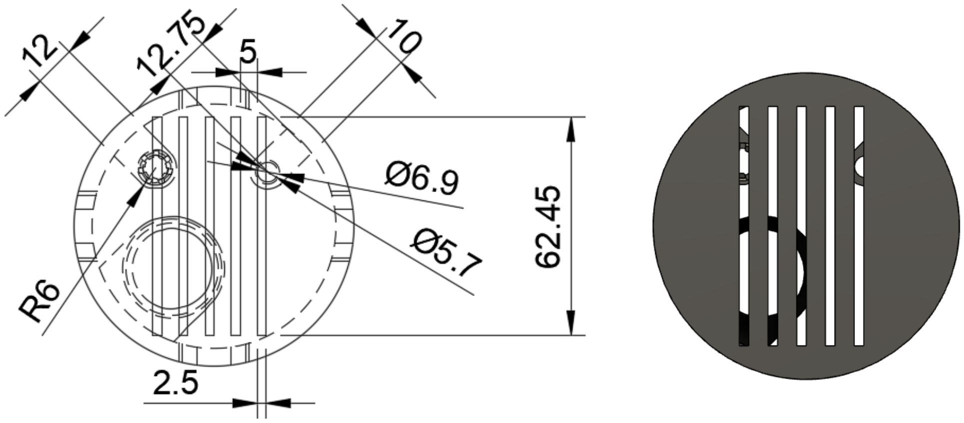


Figure 20. Dimensions and bottom orientation of the design.

Source: Authors' elaboration based on Autodesk Fusion.

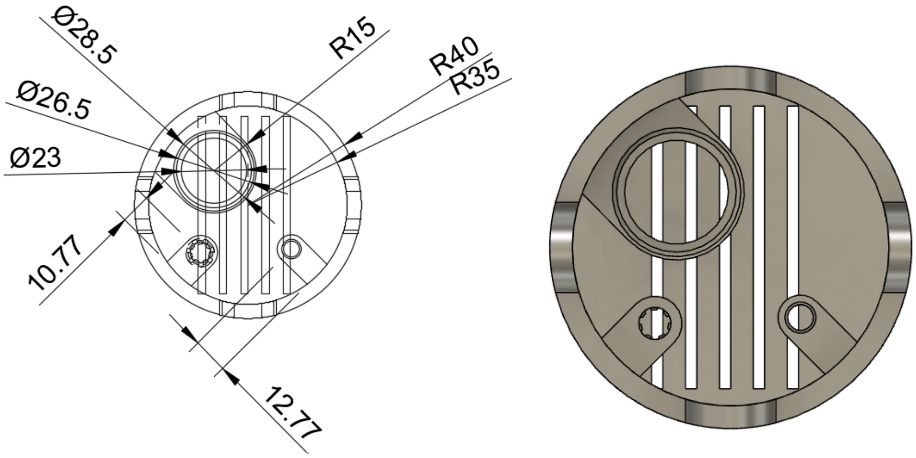


Figure 21. Dimensions and top orientation of the design.

Source: Authors' elaboration based on Autodesk Fusion.

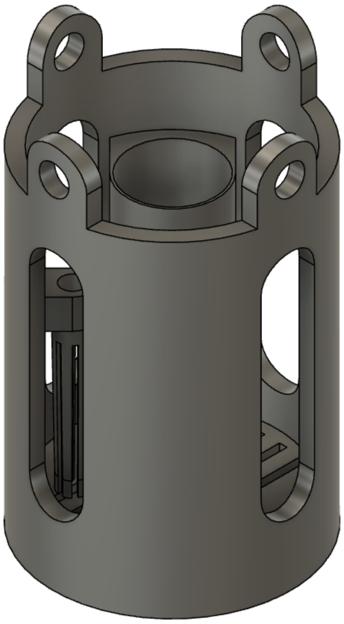


Figure 22. Final design in an isometric view.

Source: Authors' elaboration based on Autodesk Fusion.

Results and Discussion

The device designed for real-time monitoring of water quality in underground wells underwent experimental testing under controlled conditions, during which two critical parameters were evaluated: pH and temperature. Data collection was conducted in a 500 mL beaker, allowing us to compare measurements obtained with commercial sensors with those obtained with laboratory sensors. The recorded information was translated using Python code and organized into an Excel spreadsheet, facilitating comparative analysis.

Experimental results

During experimentation, several trials were conducted, and the data were structured into a test matrix focusing on pH and temperature. The preliminary results are shown below:

- pH measurement: The SEN0169-V2 sensor demonstrated a stable response within the expected range for groundwater. Measurements remained close to an average value of pH 7, with variations ranging from 0.02 to 0.17 units. The mean absolute error was 0.114 pH units, with a relative error of 1.66 %, considered low given that commercial sensors typically have an accuracy of ±0.1 to ±0.2 pH. The calculated standard deviation was 0.056, indicating consistent measurements.

- Temperature measurement: During experimentation with the DS18B20 sensor, the temperature readings exhibited a standard deviation of 0.38, indicating that the measurements were consistent throughout the testing period. An average absolute error of 0.065 °C and a relative error of 0.28 % were obtained, which is lower than the typical precision of ±0.5 °C reported for commercial sensors. This outcome reflects low variability, supporting the sensor's suitability for real-world applications

Discussion

The central hypothesis of this device's development proposes that a water quality monitoring system based on Arduino and ESP32 technology can provide reliable and stable measurements, comparable to laboratory measurement devices, enabling its application in real-time monitoring of groundwater wells, provided that necessary adjustments are made to adapt to field conditions.

The obtained results under controlled conditions support the hypothesis, as the device readings show a strong correlation with laboratory data, indicating that the prototype meets the standards established by Mexican water quality regulations. The stability observed in pH and temperature readings demonstrates that the initial sensor calibration is reliable, and the system could be implemented in real field scenarios, such as monitoring groundwater wells. Furthermore, structuring the data in Excel spreadsheets facilitates analysis, allowing the detection of variations and trends that could alert to water quality issues in the aquifer through sampling of wells in key areas.

Table 4. pH experiments matrix.

October 8th, 2024 - 11:05	MII Laboratory - using pH 7 buffer solution	6.9	7	0.1
October 8th, 2024 - 11:10	MII Laboratory - using pH 7 buffer solution	6.9	6.92	0.02
October 8th, 2024 - 11:15	MII Laboratory - using pH 7 buffer solution	6.9	6.97	0.07
October 8th, 2024 - 11:20	MII Laboratory - using pH 7 buffer solution	6.9	7	0.1
October 8th, 2024 - 11:25	MII Laboratory - using pH 7 buffer solution	6.9	7	0.1
October 8th, 2024 - 11:30	MII Laboratory - using pH 7 buffer solution	6.9	6.97	0.07
October 8th, 2024 - 11:35	MII Laboratory - using pH 7 buffer solution	6.8	7	0.2
October 8th, 2024 - 11:40	MII Laboratory - using pH 7 buffer solution	6.8	6.97	0.17
October 8th, 2024 - 11:45	MII Laboratory - using pH 7 buffer solution	6.8	6.97	0.17
October 8th, 2024 - 11:50	MII Laboratory - using pH 7 buffer solution	6.8	6.97	0.17
October 8th, 2024 - 11:55	MII Laboratory - using pH 7 buffer solution	6.8	6.97	0.17
October 8th, 2024 - 12:00	MII Laboratory - using pH 7 buffer solution	6.8	6.87	0.07
October 8th, 2024 - 12:05	MII Laboratory - using pH 7 buffer solution	6.8	6.87	0.07

Source: Authors’ elaboration based on Excel.

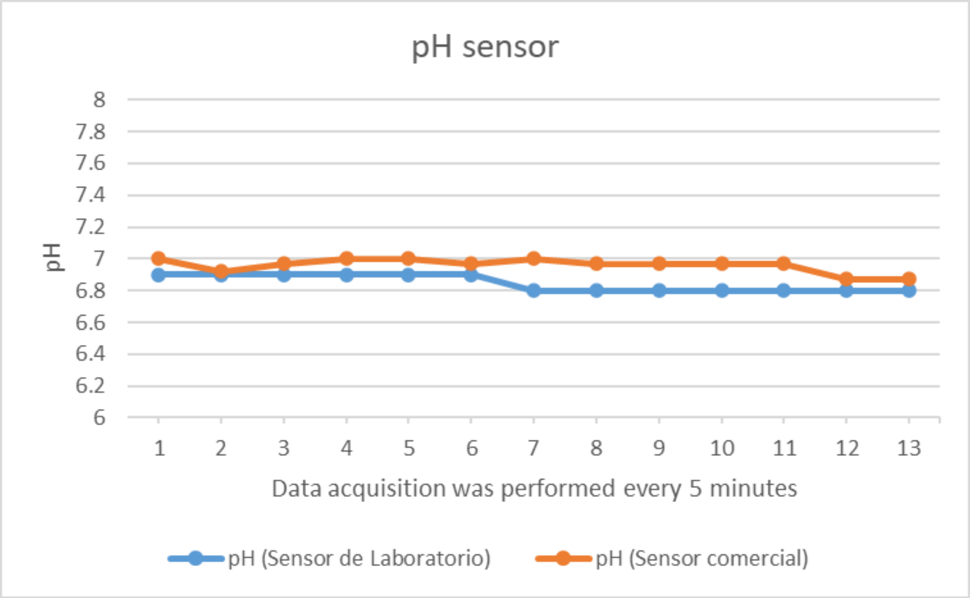


Figure 23. Comparative results graph.

Source: Authors' elaboration based on Excel.

However, the device has important limitations. Experiments were conducted in a controlled environment, which ensures replicability but does not reflect the complexity and variability of a real groundwater well. Factors such as aquifer heterogeneity, the presence of specific contaminants that vary by sampling zone, and variable environmental conditions can impact measurement accuracy. Additionally, due to budget constraints, it was not possible to acquire sensors for the other measurements developed for the prototype, resulting in no reliable verification beyond the supplier specifications for total dissolved solids (TDS) and turbidity sensors. For future applications, such as remote monitoring of wells in rural or hard-to-access areas, hydrological studies, or support for governmental water management programs, technical adjustments are needed for field deployment. Such adjustments include encapsulation and environmental resistance, since constant exposure to humidity, temperature changes, well pressure, and contaminants that represent a risk of damaging the electronic components; autonomous power supply through battery and solar energy systems; and the deployment of more robust communication modules, such as LoRa, as an alternative to traditional Wi-Fi, offering long-range radio frequency communication for real-time data transfer. Therefore, pilot field tests are recommended to validate and refine the system in real-world conditions.

Table 5. Temperature experiments matrix.

Oct 8th, 2024 - 11:05	Biomedical Laboratory - using a pH 7 buffer solution	23.5	23.56	0.06
Oct 8th, 2024 - 11:10	Biomedical Laboratory - using a pH 7 buffer solution	23.6	23.5	0.1
Oct 8th, 2024 - 11:15	Biomedical Laboratory - using a pH 7 buffer solution	23.5	23.44	0.06
Oct 8th, 2024 - 11:20	Biomedical Laboratory - using a pH 7 buffer solution	23.5	23.37	0.13
Oct 8th, 2024 - 11:25	Biomedical Laboratory - using a pH 7 buffer solution	23.4	23.31	0.09
Oct 8th, 2024 - 11:30	Biomedical Laboratory - using a pH 7 buffer solution	23.4	23.31	0.09
Oct 8th, 2024 - 11:35	Biomedical Laboratory - using a pH 7 buffer solution	23.4	23.31	0.09
Oct 8th, 2024 - 11:40	Biomedical Laboratory - using a pH 7 buffer solution	23.2	23.25	0.05
Oct 8th, 2024 - 11:45	Biomedical Laboratory - using a pH 7 buffer solution	23.3	23.25	0.05
Oct 8th, 2024 - 11:50	Biomedical Laboratory - using a pH 7 buffer solution	23.1	23.19	0.09
Oct 8th, 2024 - 11:55	Biomedical Laboratory - using a pH 7 buffer solution	23.2	23.19	0.01
Oct 8th, 2024 - 12:00	Biomedical Laboratory - using a pH 7 buffer solution	23.2	23.19	0.01
Oct 8th, 2024 - 12:05	Biomedical Laboratory - using a pH 7 buffer solution	23.2	23.19	0.01

Source: Authors' elaboration based on Excel.

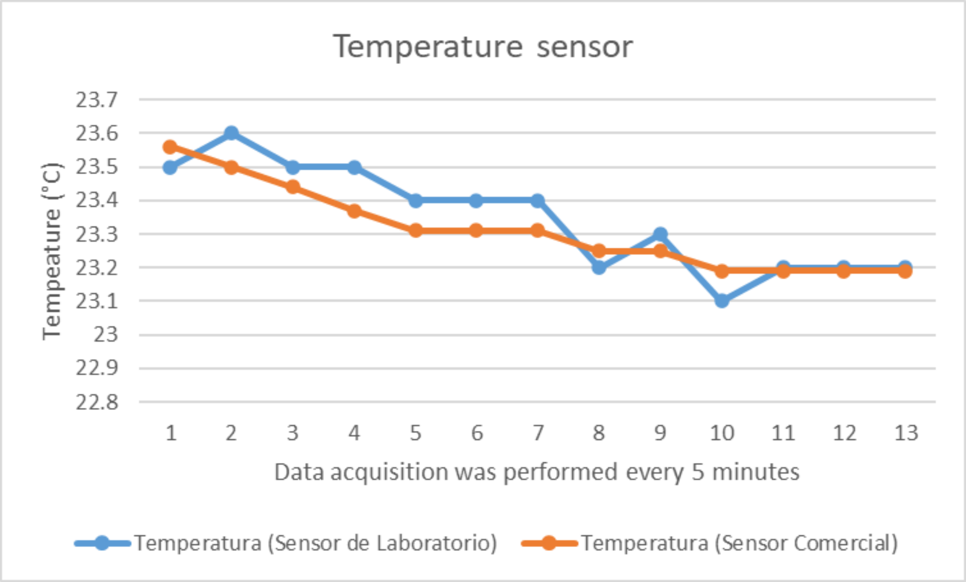
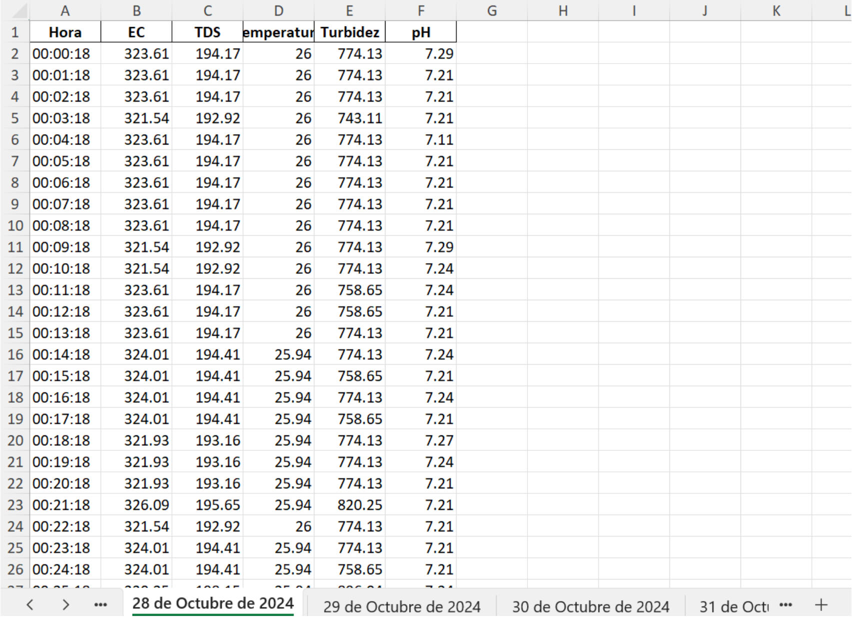


Figure 24. Comparison results graph.

Source: Authors' elaboration based on Excel.

When the data were processed through the Python script, extracting information from the database and organizing it into an Excel file, the output result was a chronologically structured dataset. Organizing the information by date and time confirmed the consistency of the measurements, allowing for the identification of trends and deviations in real-time for subsequent analysis.



Hora	EC	TDS	emperatur	Turbidez	pH
00:00:18	323.61	194.17	26	774.13	7.29
00:01:18	323.61	194.17	26	774.13	7.21
00:02:18	323.61	194.17	26	774.13	7.21
00:03:18	321.54	192.92	26	743.11	7.21
00:04:18	323.61	194.17	26	774.13	7.11
00:05:18	323.61	194.17	26	774.13	7.21
00:06:18	323.61	194.17	26	774.13	7.21
00:07:18	323.61	194.17	26	774.13	7.21
00:08:18	323.61	194.17	26	774.13	7.21
00:09:18	321.54	192.92	26	774.13	7.29
00:10:18	321.54	192.92	26	774.13	7.24
00:11:18	323.61	194.17	26	758.65	7.24
00:12:18	323.61	194.17	26	758.65	7.21
00:13:18	323.61	194.17	26	774.13	7.21
00:14:18	324.01	194.41	25.94	774.13	7.24
00:15:18	324.01	194.41	25.94	758.65	7.21
00:16:18	324.01	194.41	25.94	774.13	7.24
00:17:18	324.01	194.41	25.94	758.65	7.21
00:18:18	321.93	193.16	25.94	774.13	7.27
00:19:18	321.93	193.16	25.94	774.13	7.24
00:20:18	321.93	193.16	25.94	774.13	7.21
00:21:18	326.09	195.65	25.94	820.25	7.21
00:22:18	321.54	192.92	26	774.13	7.21
00:23:18	324.01	194.41	25.94	774.13	7.21
00:24:18	324.01	194.41	25.94	758.65	7.21

Figure 25. Results of converting a JSON file to an Excel file.

Source: Authors' elaboration based on Excel.

Conclusions

The device developed for measuring water quality in aquifers in Tamaulipas has obtained results whose precision and accuracy satisfactorily meet expectations for use in water supply works or groundwater wells, making it an affordable and functional tool for real-time monitoring of groundwater quality parameters in wells. The close relationship between the measurements of the device developed and commercial and certified laboratory sensors, together with the capacity for data transmission and the structuring of data in the cloud through an easily manipulated file, confirms the viability of its development in aquifers in Tamaulipas that are in a state of overexploitation of water resources, adding weight to the implementation of this technological tool for the management of this resource. As part of the continuity of this project, a telemetry network will be established to subject the developed prototype to real-world conditions and uncontrolled variables, similar to those in the laboratory. This may result in the expansion of both the range of monitored parameters and other electrometric measurements of water quality according to the capabilities of the sensors.

Author contributions

Identification of the field of application and conceptualization of the work (UGC, LAVO). Application to engineering and methodological development (UGC, LAVO). Software handling (UGC). Program development (UGC, IAATR). Circuit analysis (UGC, IAATR). Data management (UGC). Experimental basis in groundwater hydrology and experimental validation (UGC, LAVO). Data analysis (UGC, LAVO). Manuscript writing and preparation (UGC, LAVO). Writing, review, and editing (UGC, LAVO, HCR, DAPV). Funding acquisition (UGC, LAVO).

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Ethical declarations

The content of this document and the integral development of the project were entirely conducted within the academic framework of the Master's in Industrial Engineering at the Instituto Tecnológico de Ciudad Victoria. Intellectual property registration for the prototype and associated programs is in process.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Acknowledgments

The authors thank the Secretariat of Hydraulic Resources for Social Development of the State of Tamaulipas, Tecnológico Nacional de México Campus Cd. Victoria, and the coordination of the Master's program in Industrial Engineering at this campus for their support in the development of this project.

Conflict of Interest

The authors declare no conflict of interest.

Appendices

Appendix A. Methods for Determining Water Quality

NMX-AA-008-SCFI-2016

This method uses an electrometric approach, measuring the potential difference generated by a hydrogen-ion-sensitive electrode in the solution. It is mandatory for environmental monitoring and compliance with standards, including NOM-001-SEMARNAT-2021, which establishes maximum allowable limits for contaminants in wastewater discharges into national waters and assets for regulated industries.

NMX-AA-093-SCFI-2018

Conductivity is measured based on the water's ability to conduct electric current, directly related to the concentration of dissolved ions. This is essential for hydrogeological studies, contamination assessment, and compliance with standards, including NOM-011-CONAGUA-2015, which establishes the method to determine the mean annual availability of national surface and groundwater for exploitation, use, or groundwater management. This complements TDS measurement using conversion factors.

NMX-AA-038-SCFI-2021

Based on the nephelometric principle, a light beam passes through the sample, and total scattering is measured, yielding a value proportional to suspended particles, expressed in NTU. This standard is crucial for monitoring potable water and ensuring compliance with NOM-127-SSA1-2021.

NMX-AA-007-SCFI-2013

Temperature is measured using calibrated thermal sensors that employ thermal transduction, ensuring the values represent the actual sample conditions. Critical for environmental studies, water quality assessment, and industrial processes. Calibration must use certified standards.

NMX-AA-034-SCFI-2015

The gravimetric method measures TDS by filtration, evaporation, and weighing of residue. Essential for determining concentrations of salts, minerals, anions, or cations from sources such as marine intrusion, fertilizers, or industrial activity.

Appendix B. Applicable Mexican Standards

NMX-AA-007-SCFI-2013

This standard establishes guidelines for measuring water temperature in various types of water bodies, ensuring accuracy and comparability in both laboratory and field settings. The measurement principle is based on the use of thermal sensors, which record temperature variations through changes in electrical resistance or digital signals.

For this prototype, the DS18B20 sensor was used, a high-precision digital thermistor that allows water temperature measurement with adjustable resolution via programming. Its calibration and use were based on the standard's guidelines, ensuring that measurements are reliable for evaluating groundwater quality in wells.

NMX-AA-008-SCFI-2016

This standard establishes guidelines for measuring pH in different types of water, ensuring accuracy and stability. The measurement principle for pH devices is based on the use of potentiometric electrodes, which determine the activity of hydrogen ions in the sample.

For this prototype, the SEN0169-V2 sensor from DFRobot was used, a high-precision pH electrode suitable for field applications. Its calibration and use were based on both the standard's and the manufacturer's specifications, ensuring reliable measurements.

NMX-AA-034-SCFI-2015

This standard establishes guidelines for measuring total dissolved solids (TDS) in water, ensuring accuracy and stability. Its measurement principle is based on the relationship between electrical conductivity and the concentration of dissolved solids.

For this prototype, the SEN0244 sensor from DFRobot was used, which estimates TDS from electrical conductivity. Its calibration and use were based on the standard's guidelines, ensuring reliable data.

NMX-AA-093-SCFI-2018

This standard establishes guidelines for measuring electrical conductivity in water, ensuring accuracy and stability. Its measurement principle is based on the water's ability to conduct electrical current, which is determined by the concentration of dissolved ions.

For this prototype, the SEN0244 sensor from DFRobot was used, applying a formula to convert TDS values to electrical conductivity. Its calibration and use were based on the standard, ensuring reliable measurements.

NMX-AA-038-SCFI-2001

This standard establishes guidelines for measuring turbidity in water to ensure accuracy and stability. Its measurement principle is based on light scattering, where the intensity of light scattered by suspended particles is compared to a standardized reference.

For this prototype, the SEN0189 sensor from DFRobot was used, which employs a photodetector and an infrared light source to quantify turbidity. Its calibration and use were based on the standard to ensure reliable data.

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