Residential Water Consumption Monitoring System Using IoT and MQTT Communication

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Abstract. Water shortage across the globe causes changes in the life of the human being, not to mention that water is a resource that must be preserved for future generations. The companies that distribute and charge fees for residential water services have problems performing the periodical manual readings. Thus, showcasing inaccuracy in the costumer statements at the end of every month. The following paper describes the development process of a low-cost intelligent control and monitoring system of residential water consumption. The system design uses a flow sensor that measures the influx of liquid as it passes through the pipes. Based on the value that the conventional meter marks at the beginning of the day, it is possible to determine the daily consumption. The processing of acquired data is performed with a low-cost controller (SBC). Also, the respective control actions were transmitted towards a solenoid valve, which controls the passage of water to the house. Next, an access and communication point is established applying bidirectional MQTT (Message Queue Telemetry Transport) protocol to send and receive data wirelessly through Internet of Things (IoT). Data was stored and managed on a local server. The prototype displays information through an LCD screen and in a web page. To achieve this, the server sends information such as date-time, username, meter number, etc. The results showcase that the measurements were performed as expected. Thus, validating the possibility of using it in a larger sample.

Keywords: Flow sensor · IoT · MQTT · Water measurement

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1 Introduction

Water as a resource represents a crucial role in sustaining and enabling life on planet earth (above oxygen or other nutrients) [1]. Water can be found in its natural state, or it might have undergone a modification process [2]. Despite, the attempts to raise awareness in the population about its decrease due to climate change and incorrect use that ultimately led to excessive waste, these objective to this date has not been possible to meet. According to the reports presented by the United Nations Organization (UN) in the last decade, approximately one fifth of the world's inhabitants experience water shortages [3]. Predictions state that by the year 2030 hundreds of millions of people will be displaced in search of water resources due to its widespread shortage [4].

Even though, Latin America has approximately 31% of the global water sources, this region could be heavily affected in a possible future crisis [5]. The country with the highest consumption of drinking water (237 L per inhabitant/day) is Ecuador, surpassing the average for the region by 40% (169 L inhabitant/day) [6]. A large part of the population ignores this problem and does not consume water consciously. Contributing to the current environmental deterioration. Leaks produced from defective water pipes, leaving open faucets produces excessive water consumption [7]. The monthly consumption bills issued by the residential water management institutions showcase these problems. These companies collect data readings from residential water meters manually, a difficult task to perform due to urban and rural demographic growth. Based on the mentioned problems, the need to implement interconnected technological tools to facilitate the management of residential water consumption, both for the user and for the private company is generated [8].

In each residence there is an analog meter that is installed by the local water service provider, on a mandatory basis. The process consists of the mobilization of personnel to the user's home, the identification of the meter and the reading of the current value of consumption. This is repeated periodically with an interval of 30 days, on exceptional or improbable cases this would not be performed. According to the data collected from the manual readings, the accounting department performs the manual calculation, and issue the customer invoice afterwards. This invoice is uploaded to the company's web portal and in this way the client can download it and decide to pay it. However, poor readings and human errors cause a mismatch of the real consumption values, causing inconveniences for the client and the supplier. Therefore, this scenario shows the need to automate this process since human errors are difficult to eliminate and can only be reduced [9].

The continuous progress of society requires the optimization of daily processes [10]. In order to, mitigate the effects of climate change. Based on a bibliographic review, several research works related to residential water monitoring systems have been found. Despite, efforts to standardize these devices, as mentioned in [4] the various components used, and the constantly evolving technologies do not allow this. In [8] a prototype that goes in series with a conventional meter that is part of a complex SCADA system was presented. The study by Li et al. [11] implements a self-powered meter that works based on a turbine design and Bluetooth. While Fuentes and Mauricio [12] make a smart residential water meter using IoT, showing good results in reading water consumption and detecting water leaks. Wang [13] implements ultrasound sensors to make a water

consumption meter. However, the research paper lacks the results data that validates the designed equipment. The study presented in [14] allows the monitoring of water consumption through M2M-LoRa of rural villages in India, with this waste can be avoided. However, there is no evidence of the operation of this system either. Finally, Kumar Jha et al. [15] developed a smart meter using Arduino, Raspberry Pi and an interface for data presentation. This system evaluates the quality of the water by measuring the levels of pH, temperature, turbidity, dissolved oxygen, and conductivity.

The waste of water represents a greater expenditure for the user, while leaks and other failures in the system represent a problem for the residential water distribution service company. Current meters and the actual manual consumption measurement methods require a process of innovation. Furthermore, the proposed research work describes a device that performs the numerical estimation of residential water consumption in an urban residential unit using bidirectional communication under the MQTT protocol. The primary objective is to provide accurate data on a daily, weekly, or monthly basis and to send notifications to the user when excessive consumption occurs. Researchers and the open-source software, hardware development communities will benefit indirectly. Furthermore, the application of secure protocols in this prototype enables the replication and improvement in future research studies. All electronic components and integrated circuits (ICs) were adapted to the Latin American regional standards of availability and application, for easy acquisition. Thus, the content of this research paper will show the feasibility of the proposed implementation, from a technological and economic standpoint.

This document has four sections, including the introduction in Sect. 1. The materials and methods used in the development of the prototype are described in Sect. 2. The results are presented in Sect. 3 and the conclusions in Sect. 4.

2 Materials and Methods

Documented bibliographical research was performed, to collect information about the theoretical concepts involved in the design of the data acquisition and monitoring stages of the system [16]. This academic paper focuses on the domain of applied research type, since its purpose is the generation of knowledge with direct application to the problems of society and various industries. In addition, a systematic study was carried out during field research activities to determine the characteristics of the system to be designed. Data acquisition and validation of proper operation was executed in a university laboratory. Several performance tests were required to validate each of the design stages, and the final prototype. The results were documented in this experimental research proposal. Figure 1 shows the block diagram of the system which is divided into three stages. In the first stage, data acquisition and preprocessing were performed at regular intervals. This was achieved using a water flow sensor that sends electrical signals to the controller system. In the second stage, calculations quantify the amount of residential water consumption and display the values on the system LCD screen. Through wireless communication the system connects to the local server applying MQTT protocol that uses minimal bandwidth to avoid the loss of data. Enabling the operation of the database that acquires information in real time. In addition, it has alarms (notifications) that notify the user when a pre-defined limit of residential water consumption in the residential unit is exceeded.

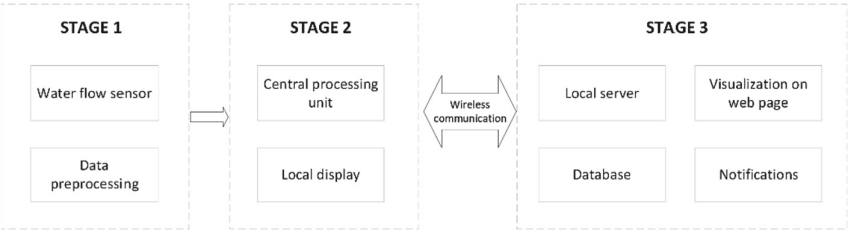

Fig. 1. General diagram of the proposed system.

2.1 Hardware

The elements that are part of the wireless system have been selected according to the design provided in Fig. 2. A technical analysis of each of the components and/or devices involved in each of the design phases was performed. The overall system is composed of six modules that are power supply, sensing, control and data processing, communication, visualization and monitoring.

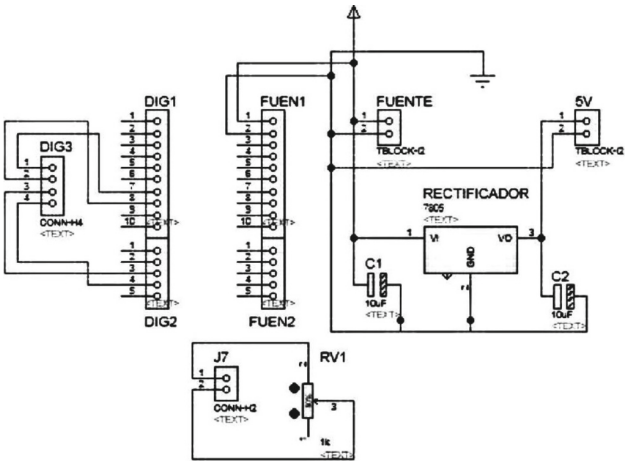

Fig. 2. Electrical design of the prototype.

Power Supply. The system requires a Direct Current (DC) voltage of 5 V for all electronic components. The prototype will be placed in a residential unit that provides direct access to an Alternate Current (120 VAC) power outlet that is close to residential water meter equipment, therefore the power supply must be regulated. A L7805 voltage regulator and two electrolytic capacitors were used to generate a stable DC 5 V power supply output.

Sensing. The use of a water flow sensor makes it possible to quantify the amount of water that passes through the pipe in domestic residential units. According to the Ecuadorian

standard NHE NEC-2011, it is stablished that the diameter of the pipe will be half an inch and the pressure less than 4.9032 Bar. The usual flow rate for this pipe diameter will be between 6 and 12 L/m (liters per minute), for this proposal the flow rate was at 12 L/min. The YF201 sensor was selected. Internally it's made up of pinwheel sensor to measure how much liquid has moved through it. Externally, the camera has a Hall Effect sensor that detects the magnetic field of the magnet of the blades from the internal pinwheel sensor and the movement of the rotor. The sensor has two inputs and one output that sends a square wave whose frequency is proportional to the flow rate. Both its conversion factor from frequency (Hz) to flow rate (L/min) and the diameter of its liquid inlet are suitable for this study. In addition, a half-inch solenoid valve was used to control the flow of water to the sensors by switching between open and closed states. The activation of this solenoid valve will be triggered when the user has unpaid values. A water solenoid was selected because it has an operating voltage of 12 V and was designed specifically for residential water flow.

Control and Data Processing. The controller of this system is the Node Micro Controller Unit (MCU) ESP8266 card, due to its features and low cost. Sensor readings and measurements were analyzed. For this proposed design the flow that circulates is directly proportional to the frequency of the output wave. The MCU board has built-in Wi-Fi wireless communication, without requiring the use of external modules. After this stage, the processed data will be sent to a local server for storage and subsequent monitoring.

Communication. The system data transmission requires wireless communication, in order to minimize the use of wiring. This minimizes errors due to disconnection and facilitates its installation at home. IEEE 802.11 (Wi-Fi) technology is chosen after analyzing parameters such as range, transmission speed, bandwidth, frequency, and modulation. The information was transmitted to a local server that enables the user to observe the data in real time. The server was installed on a single board computer, for this design a Raspberry Pi B4+ will be applied. It has a RAM memory that can be expanded to 2 GB or 4 GB depending on the requirements and has 2 micro-HDMI ports. For the wireless connection, a two antennas Cisco Wireless Router was used. The device works under the IEEE 802.11 b/g/n protocol at a frequency of 2.4 GHz in a single band and a transmission speed of 300 Mbps.

Visualization. The selected component is a 16 × 2 liquid crystal LCD screen that is connected to the Node MCU card through an I2C serial communication adapter.

2.2 Software

Data acquisition begins with the initialization of variables and parameters for the quantification of the value of water consumption. Figure 3 shows the aforementioned.

The flow sensor provides information in the form of a square wave, which corresponds to a Hall effect pulse output whose frequency in Hz is proportional to the flow rate Q (l/min) as shown in Eq. (2), starting from (1). The K factor depends on the build-in parameters of the sensor and in the case of the YFS201 flow sensor it is 7.5 with a precision margin of 10% and the Q variable corresponds to the flow value obtained. To

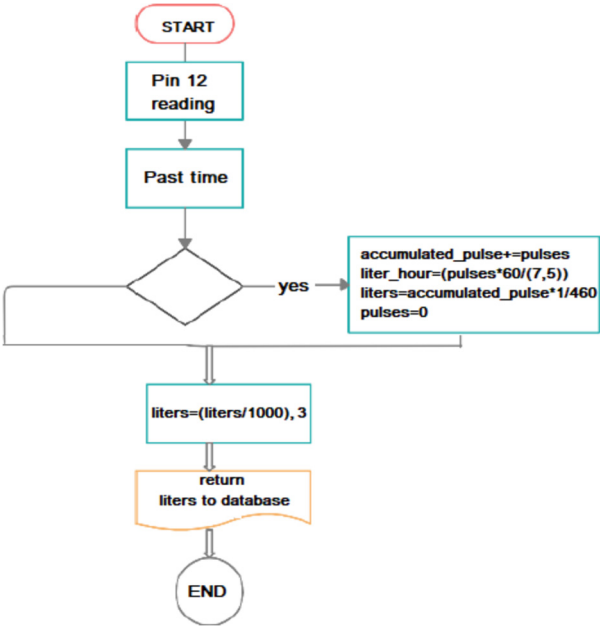

Fig. 3. Process flowchart for sensor data acquisition.

configure and program the board, the frequency of the square wave from the sensor is required. The measurement was calculated by implementing a periodic check that counts pulses in certain time intervals and then divide this value by the length of this interval in seconds. The source code for the board is found in Appendix 4 in the Arduino IDE interface.

$$f\,(Hz) = K * Q \tag{1}$$

$$Q = \frac{f\,(Hz)}{K} \tag{2}$$

Communication Protocol. IoT protocols are sets of M2M (machine to machine) communication standards established so that the devices that are part of the network can communicate efficiently, are scalable, and have interoperability. The MQTT protocol is ideal for IoT as it represents a lightweight method for messaging via a publish/subscribe model with low power devices, uses low bandwidth and requires minimal system requirements. MQTT provides three specific levels of quality of service (QoS). Based on the level of difficulty, the broket guarantees the reception of a message from the client side. Therefore, as the QoS level increases the necessary bandwidth increases too. Security is a key factor to consider in any communication system. The MQTT protocol has different security measures that can be applied to shield these communication link. This includes SSL/TLS transport, authentication by username and password, or by certificate. However, the design must consider that many of the IoT devices have limited memory space, so SLL/TLS can be a significant process to load.

Local Server. The Mosquitto server was developed with the MQTT protocol. The server works from level 0 of quality of service and can be developed with C programming language. Broker installation instructions were programmed in the Raspberry board. For this, Raspbian operating system must be previously installed. The operation of the local server is centered on a LAMP server, these acronyms represent the acronym for a system that uses the following free software tools: Linux, Apache, and MySQL/MariaDB. Therefore, after the installation of Raspbian each software packages were installed from the console, since it is an operating system based on Debian of GNU/Linux.

Database. In PhpMyAdmin, a database called AQUA was created, and it contains different tables such as: "meters", "history" and "owners", which contain all the variables necessary to identify the user, the water flow measurement, the date, and the current system state, as shown in Fig. 4. In addition, the information was displayed on the developed website in a clear and organized user interface.

Result Grid | Filter Rows: | Edit: | Export/Import: | Wrap Cell Content:

id	cedula	nombre	apellido	direccion	telefono	celular	email	estado	created
1	1804388286	Daniela	Cunalata	Ambato	032548976	0998755638	danielacunalata@gmail.com	1	2020-04-28 07:41:15
2	1804493565	Juan	Morales	Pelileo	038867649	0984403580	juank_jc@gmail.com	1	2020-05-15 21:48:27
NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL

Result Grid | Filter Rows: | Edit: | Export/Import: | Wrap Cell Content:

id	numero	medicion	fecha	medidore_id	estado	created
60	333444	0.00000	2020-05-11	1	1	2020-05-11 04:38:11
61	333444	1.47200	2020-05-13	1	1	2020-05-13 04:38:28
62	333444	2.95500	2020-05-15	1	1	2020-05-15 04:36:56
65	333444	4.18500	2020-05-17	1	1	2020-05-17 04:38:45
66	333444	6.73600	2020-05-19	1	1	2020-05-19 04:39:00
67	333444	8.40100	2020-05-21	1	1	2020-05-21 04:39:12
68	333444	9.82000	2020-05-23	1	1	2020-05-23 04:39:25
69	333444	12.41100	2020-05-25	1	1	2020-05-25 04:39:41
70	333444	13.67200	2020-05-27	1	1	2020-05-27 04:39:57

Fig. 4. Database table

Monitoring. The last stage is related to the display of information through an HMI interface on a web page. Both PHP and HTML programming languages were used to display the information contained in the database in a friendly user interface experience. The web page implements security levels for access. The available roles are user and administrator, to access into the web page the user need to enter with a registered email account. The administrator interface contains a home tab that allows you to view the data of all system users with the following information: identity card, names, surnames and address. The administrator role can manage the information and edit it if necessary. The list of owners can be completely managed as shown in Fig. 5. Also, as system security configuration the access passwords for the administrator and each of the users can be modified at any time.

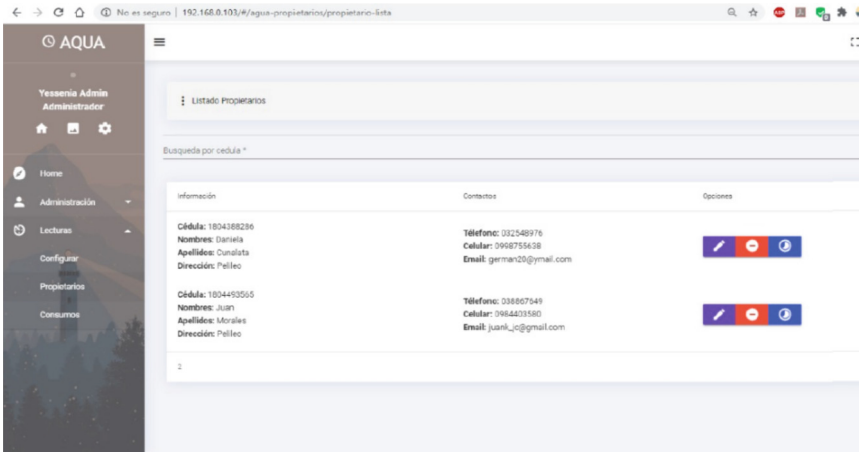

Fig. 5. Owners list.

Email Notification. Consumption control is extremely important, so the administrator can set a maximum value previously agreed with the user. As soon as, the flow rate measurement present data closer to the maximum value, an alarm gets triggered, and the user receives email notifications. Similarly, under prior agreement with the user, the system emits a signal to close the solenoid valve and stop the normal flow of residential water into the residential unit. To carry out the email notification system, the Google SMTP server was used, the same one that is used for the transfer of emails between various devices and has become more relevant with the growth of IoT platforms. The creation of an exclusive Gmail account for the system was require. This account serves as a source that sends email notifications to the users. It is essential to enable access to less secure applications, Gmail identifies an account as a vulnerable due to the static address configuration. If consumption is classified as above the stablished high threshold, the discussed countermeasures can be applied.

2.3 Implementation

Figure 6 shows the design of the electronic circuit boards of the system. A circuit case was designed, so that all the elements have protection and the display of water consumption on the LCD screen is as clear and legible as possible.

The prototype got installed in a user's residential unit with the build in characteristics that were specified specially for the solenoid valve and the flow sensor in the initial pipe and agreed by the user and the design team. Additional pipes and pipeline connectors were require to complete the installation and to have the system operating properly, as shown in Fig. 7.

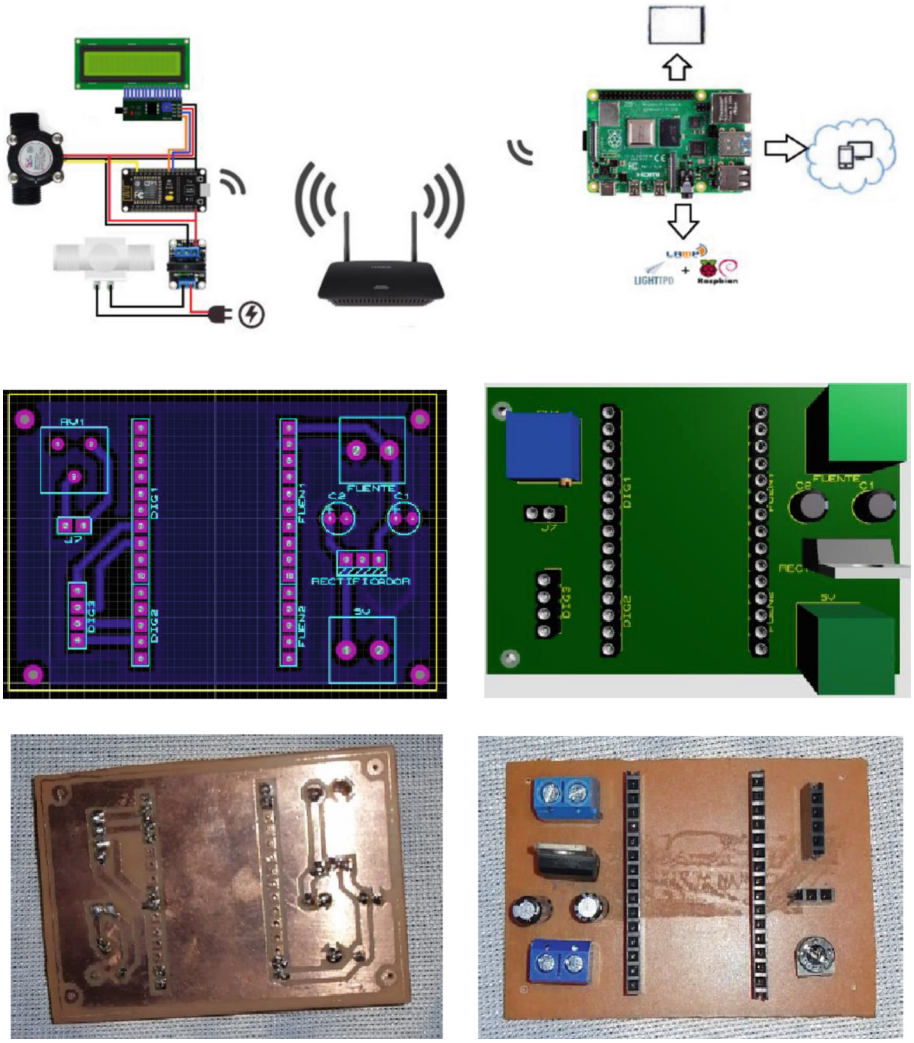

Fig. 6. Design of electronic boards



Fig. 7. Prototype installation in the user's residential unit.

3 Results

The system was successfully implemented, and the prototype performance was demonstrated by applying it in a residential unit. The system monitors water consumption, possible leaks, and enables the service company to cut off the residential water supply for cases of non-payment. In addition, performance was evaluated in conjunction with the conventional meter provided by the residential water service provider.

Figure 8 shows the user interface, with the administrator access that provides ease of learning and use. The main window is shown in Fig. 9, in this visual dashboard the water consumption readings are measured in cubic meters and are updated in real time including the user's data. Thus, enabling a quick and efficient response to any fortuitous event, since the user's location is known exactly.

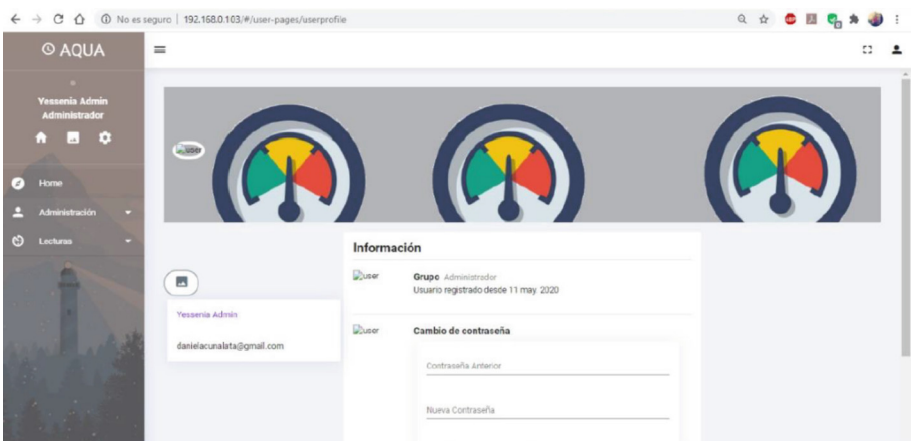

Fig. 8. User interface presented on the web.

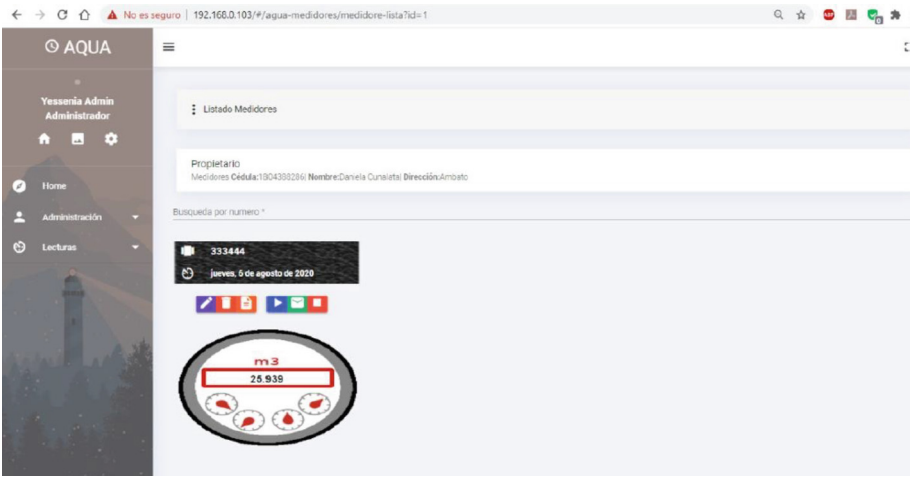

Fig. 9. Monitoring of residential water consumption in real time.

Table 1 shows the residential water consumption in the residential unit used for this proposal in a 30-day period. Measurements were taken with the conventional meter and with the prototype system. The range of error obtained between the measured values by both devices fluctuates in a 0,5% range as evidenced in Fig. 10. Moreover, it was observed that with the used the proposal prototype, exact and precise values of residential water consumption were obtained. Therefore, increasing the reliability of the system collecting the required data. In addition, the users will benefit from these insights by paying fair and precise measured values for their monthly consumption bills. On the other hand, the residential water service provider can analyze the collected data to optimize the management of the residential water supply network and reduce leaks.

For the purposes of this investigation, the needs of the user and the provider were satisfied. Table 2 shows a detailed budget for the electronic residential water monitoring system including design and implementation costs of the entire system. For this design, accessible components in the national markets and qualified labor were used.

3.1 Discussion

The designed equipment demonstrated a satisfactory performance. However, it cannot be compared with all the available proposals. Manoharan in [14] used more robust sensors and Lora technology, said technology amplifies the scope of implementation for a residential water monitoring system in a village. The previously mentioned research proposal does not provide results that can be compared and analyzed against our results. On the other hand, the economic aspect of this academic paper was preserved due to the similarity of this proposal aimed to be used in places with scarce resources. Likewise, the study by Alvisi [8] presents a SCADA system with a higher complexity and difficulty that makes it unfeasible to be developed under a limited budget. Li et al. [11] shows an interesting approach that includes a self-powered turbine. Although, this design has a remarkable limitation because it uses Bluetooth and limits the device to operate in

Table 1. Summary of measurements made with a conventional meter and the prototype.

Day	Daily consumption	Accumulated consumption	Reading number	Accumulated reading
1	0,000	0,000	2969	0
2	1,472	1,472	2970	1
3	1,483	2,955	2972	1
4	1,230	4,185	2973	1
5	2,551	6,736	2976	3
6	1,665	8,401	2977	1
7	1,419	9,829	2979	2
8	2,591	12,411	2981	2
9	1,261	13,672	2983	2
10	1,652	15,324	2984	1
11	1,284	16,608	2986	2
12	2,545	19,153	2988	2
13	1,487	20,640	2990	2
14	1,365	22,005	2991	1
15	2,546	24,552	2994	3
16	1,387	25,939	2995	2

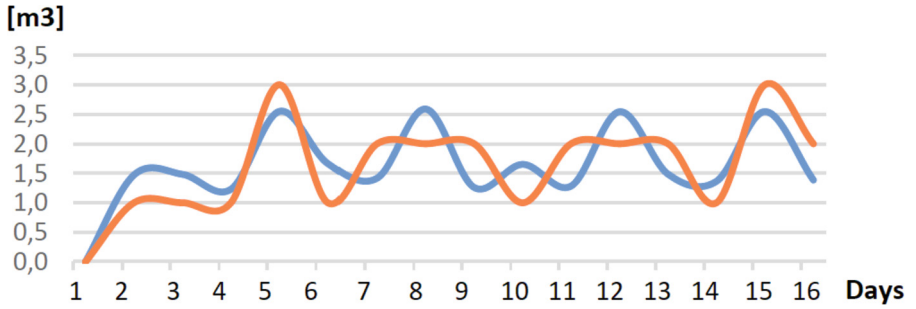

Fig. 10. Graphic representation of the variations between a commercial device and the prototype.

shorter ranges. Moreover, the designed equipment described in this research work was developed for a higher scale infrastructure. As a result, it is not able to detect water flows lower than 200 L/h. Over and above that, the Bluetooth module has a short range of operation. The presented proposal discussed in this academic paper showcases a higher accuracy and a wider range due to the communication through MQTT protocols.

On the other hand, Wang [13] uses ultrasonic sensors. However, tests were not performed to validate their use in practical scenarios. Whereas, in this research proposal

Table 2. Prototype cost summary.

Item	Description	Amount	Unir value	Total value
1	Raspberry Pi 4+	1	89,00	89,00
2	LCD displayCs	1	10,00	10,00
3	Case	1	18,00	18,00
4	Buzzer module	1	1,00	1,00
5	ESP8266 NodeMCU	1	9,00	9,00
6	Solenoid valve	1	12.0	12,0
7	L7805CV	1	0,80	0,80
8	Terminal board	5	0,50	2,50
9	Resistors	12	0,03	0,36
10	Printing	1	12,00	12,00
11	YF201 sensor	1	12,00	12,00
12	USB cable	1	1,50	1,50
13	Tin	1	0,50	0,50
14	Female sprats	2	0,50	1,00
Total				170,66

flow rate sensors have shown positive results. Fuentes and Mauricio [12] likewise use flow sensors. However, a valve that can shut off or enable the residential water supply was not implemented. Although, it is important to monitor consumption in real time, complementary solutions such as the implementation of a solenoid valve are also an important offering. As a result, residential water companies can mitigate the displacement of workers, and the user will avoid economic losses. Likewise, the importance of having quality water should not be overlooked as stated in the work provided by Kumar Jha et al. [15]. Although, the proposal design does not contemplate this aspect based on the objectives defined on the research work scope. Still the presented variant in [15] proposes an interesting application that should be considered for future research papers.

4 Conclusions

Currently, residential water metering is performed manually, and it is infrastructure relies on the use of residential water flow meters. Consumption bills of a home or property are traditionally calculated using the difference in volume in m^3 of a previous value and a current value over a 30-day period. Therefore, the customer does not know his daily or weekly consumption or the presence of faults or breaks in their pipeline infrastructure that would let them apply the necessary corrective measures. The development of IoT technologies focused on water flow measurement and wireless communication represent an ideal alternative to solve this problematic. Wi-Fi technology provides a wide range of operation, as well as a good operating frequency, cost, and availability of equipment.

It uses communication protocols for IoT devices that enables the implemented network to have scalability, security, efficiency, and interoperability between devices connected to the same network. Thus, offering greater functionality.

A thorough analysis was required upfront to understand the size of the network. This previous analysis led to the proper selection of the best IoT communication protocol, so that the advantages offered by each one were maximized. In such manner, traditional methods of measurement and billing of residential water consumption could be replaced with lower-cost proposals that provide clear and reliable measurements. Remote access for both users and administrators enable the streamlining of procedures. Thereby, reducing work time, expenditure of resources, and reducing human or systematic errors in the metering process. The proposal prototype was developed following the same guidelines as the proposals developed in the works of [3–7]. Being low cost one of the key aspects as well as the use of IoT. Therefore, it is demonstrated that efficient devices can be developed in the Latin American context.

To have a stable input voltage in the electronic circuit design a parallel circuit between two electrolytic capacitors is recommended as well as placing a voltage rectifier at the beginning of the circuit design. Device components such as the flow sensor, the solenoid valve, and the Node MCU board will not produce variations to the measured signal. All the outputs of the circuit must be connected to ground to avoid current fluctuations that alter the proper functioning of the electronic components. An aspect that stands out for this system is that it must be implemented in a place where it does not represent an obstacle for the inhabitants of the house and is protected from rain, wind, dust, or other environmental factors that may alter the performance of the internal circuits.

One of the limitations that were faced in this research work relates to the accuracy of the chosen sensor, in referenced bibliography the application of ultrasound sensors will be consider as an optimization upgrade that can be applied in the future research work. Despite this, the implemented sensors have an acceptable performance, and lie in the low-cost thresholds applicable for the system design budget. In addition, it should be noted that this process does not require such a high accuracy standard, so these sensors could be considered acceptable.

This proposal is aligned with the initiatives of smart cities management that aims to provide technology and efficiency to households. Although, the economic factor is a limiting factor in many countries. The availability of research projects like this aims for the improvement of the quality of life of the inhabitants. Reducing the environmental impact of wasted water resources and promoting a more efficient and conscious use of natural resources. As for future work, it is proposed to carry out tests in more residential units and perform analysis of the gathered data. As a result, the provision of continuous flow of information can be achieved. Resulting in increased agility and efficiency coupled with the benefits of cloud technologies. Similarly, a data analytics platform could be implemented with the use of Big Data. Further expanding the analysis and to adhere to other approaches found in the researched literature. Some extra implementations and optimizations could be considered such as the use of other sensors, communication protocols and the analysis of the quality of the residential water consumed on a daily basis by the users.

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