IoT Watercare: Water Quality Control System in Unofficial Settlements of Peru Based in an IoT Architecture

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Abstract—**Many homes in the country of Peru, especially those located in unofficial settlements, are not connected to public service networks, and in the case of residential water, require tanker truck delivery. However, this water has often been contaminated from the upstream storage, conveyance and delivery systems that provide it, and thus will not comply with government water quality standards, ultimately compromising the health of the people who rely on it. While the topic of quality monitoring in traditional water networks has been studied, research has not focused on water quality control in under-developed and under-served unofficial settlements. This study introduces an IoT architecture and web-based system for real-time monitoring of the key water quality parameters to help municipalities and other government entities to act early when large volumes of low-quality water are detected. The system proposed was implemented across five layers: capture, communication, processing, storage and presentation. Two experiments were conducted in a residential home with real time measurement of temperature, turbidity, TDS y pH. When comparing the results of both experiments, the pH parameter had a better precision with a 2% error rate. In addition, the survey results showed that the experts agree with the proposal.**

I. Introduction

According to the World Health Organization (WHO) [1], following established health guidelines and access to good quality water are key for human health. Due to the COVID-19 pandemic, increased personal hygiene has been promoted in order to avoid an infection or spread of this virus. One of these measures is constant hand washing. According to Castro and Musuk [2], although the United Nations establishes that the access to clean drinking and sanitation water is a human right, many populations lack this access, which in turn makes the implementation of hygiene measures to prevent coronavirus infection and spread more difficult, reflecting the harsh reality that a large number of people in the world do not have access to this basic and essential element of healthy living.

Additionally, the WHO [1] also establishes that 844 million people do not have a basic potable water distribution service. This shows that large numbers of people must survive by obtaining water from other sources that could be contaminated. Likewise, this low-quality water facilitates the transmission of various diseases such as diarrhea, cholera, dysentery, typhoid fever. It is necessary to emphasize that this contamination in water is responsible for more than 502 000 deaths for diarrhea a year.

According to the National Institute of Statistics and Information (INEI) [3], in the period of May 2019 to April 2020, 9.2% of the Peruvian population did not have their water supplied through the municipal water system, where 1.2% were supplied instead by tanker trucks sent by the State. In the case of the capital city of Lima, according to Yrigoyen [4], only 77.7% of households are connected to the municipal water system, with 10.0%, predominantly in the unofficial settlements, receiving their water from tanker trucks and ultimately storing it in residential tanks, buckets, and other receptacles.

These numbers provide the scope of the vulnerable Peruvian population who lack access to safe water and are bolstered by the Center of Sustainable Development Goals for Latin America (CODS), that found that the water provided by the tank trucks is of poor quality [5]. CODS performed laboratory tests on water samples of two tanker trucks that carried water to the Nueva Esperanza neighborhood, in the Villa Maria del Triunfo district of Lima, showing the presence of fecal bacteria, lead, inadequate levels of chlorine and free life organisms across both samples. From the results, a biologist from Cayetano Heredia Peruvian University concluded that the water sampled had not been through any purification process, thus putting the health of the habitants of this specific unofficial settlement at risk [5]. Definitely, the evidence collected in this investigation is crucial for establishing the problem.

There have been efforts to correct these risks. In the unofficial settlements of San Genaro, in the Chorrillos district of Lima, Ray Pinedo [6] carried out a community initiative to improve their water quality. The author conducted a test of the water pre-treatment and confirmed the presence of coliform bacteria in high levels and water turbidity that exceeded permissible limits, as well as insufficient quantities of residual chlorine, all demonstrating the clear urgency to improve this water quality.

For this reason, this study seeks to find water quality monitoring solutions for the tanker delivered water in the unofficial settlements of Lima.

To counter the problem of water contamination detection, different proposals have been emerged. Chen y Han [7] developed a prototype composed of a sensor capable of measuring different parameters of the water as well as a camera for capturing images of the water. Miry et al. [8] and Pérez-Padillo [9] proposed systems that sent SMSs and emails that alerted recipients that the monitored parameters were out of the threshold ranges. The study by Alahi [10] stands out as he developed a monitoring system for nitrate levels, obtaining good results for precision and low energy consumption using the LoRaWAN technology. Although these and other studies have water quality monitoring as their main subject, none of those studies are focused on measuring the water quality in the environment of unofficial settlements.

This study seeks to address this gap by presenting an scalable and easy-to-use Internet of Things (IoT) solution installed in residential receptacles of unofficial settlements where the water is delivered by tanker trucks. The system monitors, in real time, the most relevant quality parameters of the water (pH, TDS, temperature, and turbidity) in order to prevent the consumption of contaminated water.

The paper is organized in this way. Section 2 presents related works. The details of the proposed system architecture are presented in Section 3. Section 4 presents the validation protocol and its execution. The results of the validation are presented in Section 5. Finally, the conclusions and future work are presented in Section 6.

II. LITERATURE REVIEW

The review of the literature relies on the work of Wong et al. [11], where the following phases were applied: (1) Planning of the review, (2) Development of the review and (3) Results and Analysis.

In the Review Planning phase, five research questions were generated in order to guide the literature review and analyze the resulting articles. The questions were: Q1: What software components are used in water quality monitoring systems? Q2: What devices are used in IoT systems for water quality monitoring? Q3: What parameters are considered for water quality monitoring? Q4: What communication methods are used for the transmission of data in water quality monitoring systems? Q5: In which sectors have water quality monitoring systems been applied?

The following key words have been defined to locate articles related to the research topic: Internet of the things, drinking water monitoring, cloud computing, water quality, IoT architecture, water quality monitoring, tanks and pipelines.

The following inclusion criteria for the articles found has been defined. First, the articles must be found in the 1st, 2nd or 3rd quartiles in the Scopus and Web of Science databases. Second, the selected articles should be published after 2018. Finally, articles categorized as “Engineering” and “Computer Science” were prioritized.

In the Review Development phase, the aforementioned criteria were applied in the search for relevant scientific articles. A preliminary review of the content of each article was performed and those articles and those articles most relevant to the criteria wereS selected.

Thirty articles passed the Review Development stage and were selected for the Results and Analysis phase. These articles were analyzed according to a proposed taxonomy, consisting of five categories, with each category related to the five questions established in the Planning phase (see Table I).

TABLE I. DISTRIBUTION OF SCIENTIFIC ARTICLES BY TAXONOMIC CATEGORY

Category	Reference
Software components (Q1)	[7-10], [12-30]
Devices (Q2)	[7-10], [12-37]
Water Quality Parameters (Q3)	[7-10], [12,15], [16-18], [20-27], [29-37]
Connection Methods (Q4)	[7-10], [12-37]
Sectors (Q5)	[7,10,12], [15-18], [20-27], [29,31], [32-37]

A. *Software components*

8 software components have been found that use monitoring systems for water quality control (Table II). Among them is the use of cloud platforms. In works such as from Pasika & Gandla [26] and Miry & Aramice [8], the ThingSpeak platform has been used for the analysis of data collected by sensors. In other research, platforms such as IBM Cloud [19] or Tencent Cloud [30] were also used for the same purpose, in addition to providing remote storage and access to that data. On the other hand, it has been found the use of databases such as MySQL [20], [30] and Mongo DB [14], [23] to persist the collected data. For the most part, these databases are accompanied by the use of REST APIs to add processing and business logic layer to the water monitoring systems [12], [13], [23].

Systems that use artificial intelligence algorithms to define the level of contamination have also been developed [14], [16] [27]. On the other hand, Chen & Han [7] use the Grafana tool to improve the visualization of collected data, while Mamun et al. [22], use GeoMedia Software to add geographic information to their system.

For data communication between IoT devices and the monitoring system, some works have used messaging brokers to send data in real time [12][14]. Finally, it has been possible to see the use of blockchain [21] to detect contamination points in irrigation canals, and chatbots used to facilitate access to monitoring data in aquaculture ponds [12].

TABLE II. SOFTWARE COMPONENTS IDENTIFIED IN THE LITERATURE

Components	Reference
Cloud service platforms	[8], [9], [10], [12], [14], [15], [17], [20], [19], [30], [23], [24], [26], [29]
REST API	[13], [12], [14], [19], [23], [30]
Artificial Intelligence Algorithms	[14], [16], [27], [32], [33]
Data base	[7], [12], [14], [18], [19], [20], [23], [28], [30]
Messaging Brokers	[12], [14], [23]
Data visualization software	[7], [22], [24], [25], [28]
Blockchain	[21]
Chatbots	[12]

B. Devices

Various devices have been found to be used in IoT systems for monitoring water quality (Table III). In general, these systems have sensors that measure certain parameters to determine the state of water quality. Among these, the most used are the pH [15], [29], [34], turbidity [7], [16], [24] and temperature sensors [15], [26], [29]. In the work of Noorjannah Ibrahim et al. [24], an LDR light sensor and an LED light have been used to detect the turbidity of the water.

Likewise, electrical conductivity sensors [22], [32] and total dissolved solids [16], [31] have been used in some articles. These parameters have proportional measurements, since both are based on the measurement of the conductivity of water. Also, dissolved oxygen [12], [18] and oxidation potential and reduction (ORP) [7], [22] sensors are quite used.

However, in almost all the works reviewed, in order to connect and process the data measured by the sensors, microcontrollers are used, being the most used the Arduino UNO [10], [31] and STM32 [16], [20] models.

Finally, there are other sensors such as nitrate sensor [10], [23] and ammoniacal nitrogen sensor [37], which are less used in the studies reviewed. Also, as an addition to these systems, GPS devices [16], [22] have been used to obtain geographic data.

TABLE III. DEVICES USED IN IOT SYSTEMS

Devices	Reference
Ammonia nitrogen sensor	[37]
Water flow sensor	[15],[36]
Oxidation reduction potential sensor	[7], [22], [33]
Temperature sensors	[20], [21], [22], [26], [17], [33], [15], [12], [25], [27], [18], [29], [31], [32], [35], [36], [37]
pH sensors	[12], [20], [30], [26], [25], [22], [29], [16], [15], [32], [27], [18], [21], [31], [33], [34], [35], [37]
Water level sensors	[12], [17], [21], [26], [32]
Electrical conductivity sensors	[7],[21], [22], [32], [33], [35]
Turbidity sensors	[7], [30], [26], [8], [16], [15], [29], [32], [27], [31], [35], [36]
Total dissolved solids sensors	[8], [16], [33], [27], [30], [31]
Dissolved oxygen sensors	[20], [33], [29], [12], [32], [18], [7], [37]
GPS	[15], [16], [22], [32], [27]
Nitrate sensors	[10], [23]
LDR light sensor	[24]
Microcontrollers	[8], [9], [10], [12], [13], [14], [15], [16], [17], [18], [19], [20], [22], [23], [24], [26], [27], [28], [29], [31], [32], [33], [34], [35], [36], [37]

C. Water Quality Parameters

In the reviewed studies, a total of nine parameters have been used for monitoring water quality applying IoT technologies (Table IV). These parameters are considered according to the nature of each problem.

The studied systems measure several parameters at the same time in order to correctly define the level of water quality. It has been found that the most used parameters are pH [15], [29], [34], which is used to measure the acidity or alkalinity of the water, turbidity [7], [16], [24], to know the level of opacity of the water, and temperature [15], [26], [29]. This is related to the most used sensors from the previous point. Likewise, some works have considered electrical conductivity [22], [32], [33] and total dissolved solids [8], [16], [31]. Both parameters are based on the conductivity of water but have different units of measurement. The use of oxygen-based parameters such as dissolved oxygen in water [18], [20], [37] and oxidation potential and ORP [7], [22], mostly used to measure water quality of not fit for human consumption sources, has also been considered. Finally, there were studies that considered the measurement of nitrate [10], [23] and ammoniacal nitrogen [37] to determine water contamination.

TABLE IV. PARAMETERS USED FOR WATER QUALITY MONITORING

Parameters	Reference
Ph	[12], [18], [20], [21], [26],[16], [15], [22], [25], [33], [29], [32], [27], [30], [31], [34, [35], [37]
Temperature	[20], [21], [22], [26], [17], [33], [15], [12], [32], [25], [27], [18], [29], [31], [35], [36], [37]
Turbidity	[30], [26], [8], [24], [16], [15], [7], [32], [27], [31], [35], [36]
Conductividad eléctrica (EC)	[21], [22], [33], [7], [32], [35]
Total dissolved solids (TDS)	[8], [16], [33], [27], [30], [31]
Nitrate	[23], [10]
Dissolved oxygen (DO)	[20], [33], [29], [12], [7], [32], [18], [37]
Ammonia nitrogen	[37]
Oxidation reduction potential (ORP)	[7], [22], [33]

D. Connection Methods

Various connection methods have been applied for data transmission in IoT water monitoring systems (Table V). The most used methods were Wi-Fi [15], [24], [25] and GPRS [16] [35] [36]. The latter has a greater range, since it uses cellular networks to send data. Likewise, in works such as those by Alahi et al. [10] and Jia [32] LoRa, another technology for long-range communication, has been used. Similarly, Sigfox [9] and NB-IoT [20]. On the other hand, there are technologies that have not been widely used in the works collected, as is the case of Demetillo et al. [18], who used another method of wireless communication called X-Bee. Also, there is the use of 3G [17] or 4G [30], which also work with cellular netwroks and are improved versions of the aforementioned GPRS. Finally, articles where communication is carried out through physical connections, such as Ethernet [7], [8], RS485 [7], [21] and USB [31], have been reviewed.

TABLE V. CONNECTION METHODS FOR DATA TRANSMISSION

Methods	Reference
Wi-Fi	[7], [12], [15], [16], [19], [24], [25], [26], [29], [35]
LoRa	[10], [13], [14], [28], [32]
GSM/GPRS	[16], [14], [18], [22], [23], [27], [29], [34] [35], [36], [37]
RS485	[7], [21]
X-Bee	[18]
NB-IoT	[20]
3G	[17]
4G	[30]
Ethernet	[7], [8]
Sigfox	[9]
USB	[31]

E. Sectors

13 sectors have been identified where studies have applied IoT systems to control water quality (Table VI). In the study by Alahi et al. [10], the appliance is focused on lakes, rivers, and streams, since he has tested water samples from these sites. Monitoring has also been carried out in aquaculture ponds, where different marine species are raised [12], [20], [25]. In the works [18] and [22], measurements of the quality of the sea water have been carried out as part of the tests of their system.

In the case of drinking water, monitoring systems have been developed for distribution network pipes [33], water tanks [24], [26], [35], and tap water [10], [22]. In addition, in [7] and [23], they have developed water monitoring systems in treatment plants to verify the quality of the water that will be distributed to households.

The sectors that have not had much relevance and where only one study has been found are irrigation canals [21], wetlands [32] and water supply sources in rural areas [37]. No studies related to water control in unofficial settlements have been found.

TABLE VI. SECTORS WHERE WATER QUALITY MONITORING SYSTEMS HAVE BEEN APPLIED

Sectores	**Reference**
Aquaculture ponds	[12], [20], [25]
Wells	[17]
Drinking water pipelines	[33], [34], [36]
Lakes	[10], [15], [16], [18]
Streams	[10], [22], [31]
Rivers	[10], [22], [27], [29]
Sea	[18], [22]
Rural water supply sources	[37]
Water from treatment plants	[7], [23]
Water tanks	[24], [26], [35]
Wetlands	[32]
Irrigation canals	[21]
Tap water	[10], [22]

III. PROPOSED SYSTEM: *IOT WATERCARE*

In this section, a quality monitoring system called *IoT WaterCare,* (Fig. 1) is proposed for the water delivered by tanker trucks to the residents in the unofficial settlements of Lima, Peru. This system will serve as a tool to support municipalities and other governmental entities to monitor the water quality of the different unofficial human settlements in Lima and take early emergency action when water quality is possibly compromised. In addition, the system will have a specific user interface that will allow technicians to connect IoT devices to their respective water containers and start water quality measurements. Also, technicians will be able to turn the devices off through this feature in case they need maintenance. The proposed architecture consists of five layers: capture, communication, processing, storage and presentation.

The first layer captures the water quality data collected through sensors from the residential storage receptacles, with a microcontroller processor sending the captured data to the next layer. The second layer communicates the captured data from the *IoT* devices to the next layer through a MQTT *service*. The third layer processes the captured data and provides access through a *RESTful API*. The fourth layer stores the processed data from the application in a relational database. Finally, in the fifth layer an application presents and manages the water quality monitoring information as well as administrative information, under two user roles: Administrator (system administrator) and Technician (*IoT* technical service).

Fig. 2 shows the context diagram and Fig. 3 the containers diagram and architecture of the system without going further in the code structure, and how the Domain-Driven Design approach was applied for the logic architecture of the project. For that, four Bounded Contexts were defined: i) Monitoring, (ii) Places Management, (iii) Scheduling, and (iv) Security Management. Each one belonging to one of the subdomains of the system. In the same way, although it is a monolithic architecture as such, the system logic has been separated according to these Bounded Contexts in the *RESTful API*.

1) The Monitoring Bounded Context: Manages the water quality parameters information captured from the residential storage receptacles in the unofficial settlements, as well as managing contaminated water receptacle alerts and the information about the individual residential receptacles and capturing devices.

2) The Places Management Bounded Context: Manages the identification information for each residence and each unofficial settlement, as well as their geographic location, the status and history of technical service activities and, most importantly, the status of the water quality for individual residences, and the necessity of providing treatment for unofficial settlements with multiple instances of individual residence contamination.

3) The Scheduling Bounded Context: Manages the technical service activities that will be carried out periodically in specific residences in an unofficial settlement. With this information, technicians and administrators will know what activities are required on a specific date, in a specific residence.

4) The Security Management Bounded Context: Manages the information related to the accounts, roles and profiles of the different users of the application (Administrators and Technicians).

A. Capture Layer

As it is shown in Fig. 1, the Capture layer encompasses the four sensors (temperature, turbidity, pH, TDS) for measuring the water quality parameters, the microprocessor (Arduino UNO) and the connection module. Additionally, the microcontroller will process data from the sensors that will be sent through a Wi-Fi communication device. The four water quality parameters most widely used in the review of the literature were chosen.

1) Microcontroller: The *Arduino UNO* [38] microcontroller was selected as it is compatible with the sensors and has enough connection points. Likewise, the operational and maintenance literature for this controller is extensive, which allows for a faster and more efficient development and maintenance of the system.

2) Sensors: According to Fig. 1, the considered sensors in the proposed architecture are temperature, turbidity, pH and TDS.

The temperature sensor DS18B20 allows a digital measurement of the liquid temperature due to its impermeable capabilities. It is able to make measurements in ranges from -55°C to +125 °C [39]. This sensor's mechanism allows the capture of voltage and, subsequently, its conversion into temperature values. This sensor has an alert mechanism in case the temperature is outside of pre-defined thresholds.

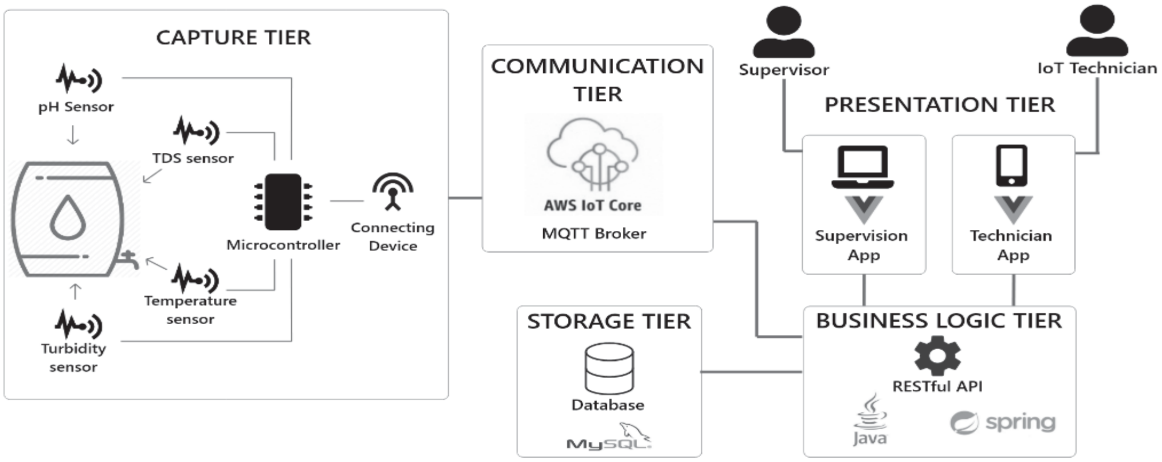


Fig. 1. Physical architecture diagram of the proposed system

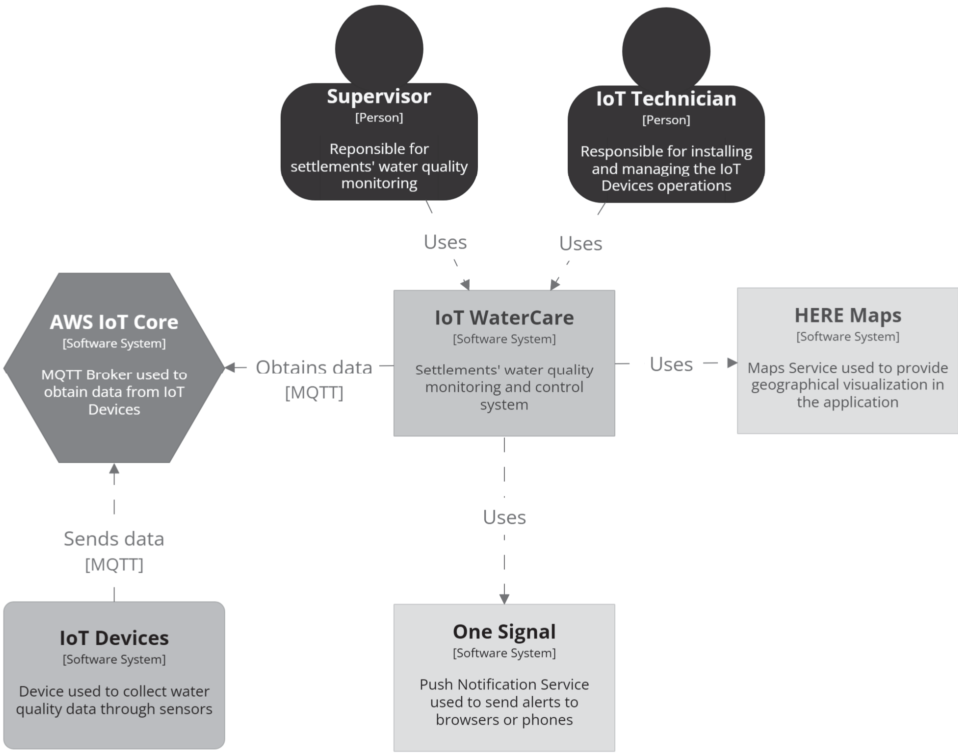


Fig. 2. System context diagram

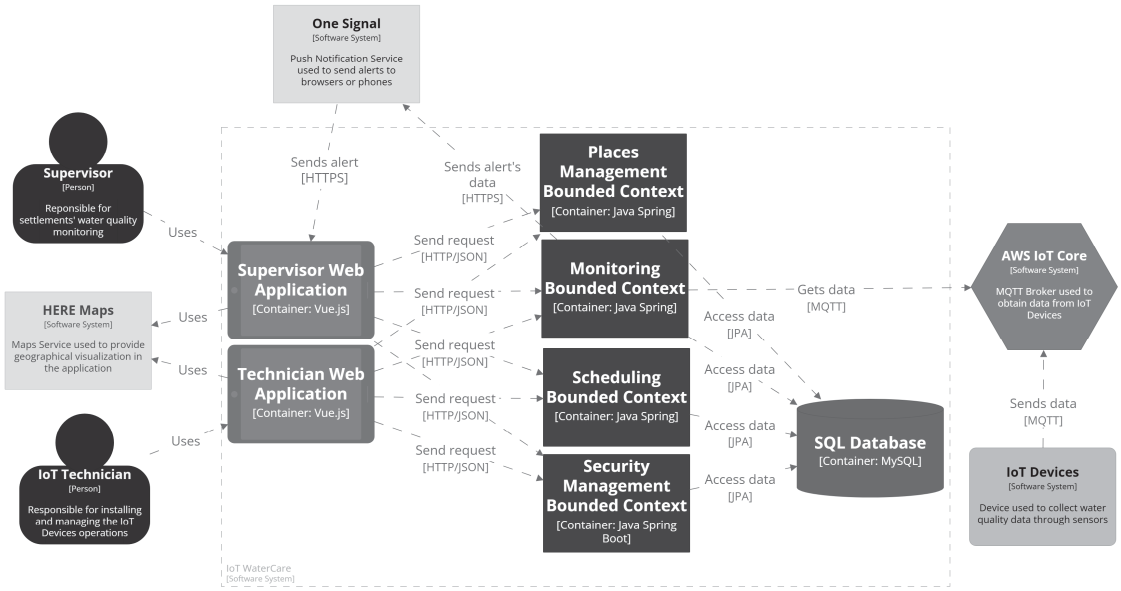


Fig. 3. System Container Diagram

The turbidity sensor SEN0189 measures the amount of scattered light to determine potential contaminants caused by suspended solids. The measurement unit is the Nephelometric Turbidity Units (NTUs), with the range of permitted values for safe water falling between 0.0 to 5.0 NTU, as set by the Ministry of Health regulation [40]. According to the manufacturer of this sensor DFRobot [41], the sensor emits an exit value of voltage between 0.0 and 4.5 V. However, to convert the measurement into NTUs with high precision, only exit values of voltages between 2.5 and 4.2 V are used.

The pH sensor SEN0161 measures the level of acidity or alkalinity of the water. According to the Ministry of Health of Peru (MINSA) [40], the adequate *pH* levels for water safe for consumption are between 6.5 to 8.5, given that *pH* is measured within a range from 0 to 14. The output limit values of this sensor go from -414.12 mV to 414.12 mV [42], which present the pH values of 0 and 14, respectively. A 0.0 mV value represents a *pH* value of 7 [42], or neutral.

Another important parameter to assess is the level of Total Dissolved Solids (TDS). This provides a reference value of how clean the water to be measured is. The *TDS* SEN0244 sensor, manufactured by *DFRobot*, measures how many milligrams of soluble solids are dissolved in a liter of water. This sensor is analogue and works with voltages in the range of 3.3 to 5.5V [43]. This sensor will be used in the project in order to assure that the total of dissolved solids do not exceed the maximum permissible level according to MINSA of 1,000 mg/l [40].

3) Wireless connection device: Of the many different communication methods for IoT projects, Wi-Fi was chosen for its ubiquity and confirmed functionality. The ESP32 microcontroller [44] was used, which has an integrated Wi-Fi module. A Wi-Fi connection is compatible with the MQTT service and current security protocols, such as the TLS v1.2.

B. *Communication layer*

The data collected by the sensors at the capture layer are sent to a service in the *Amazon* cloud, called *AWS IoT Core* [45], where all capture layer devices have been previously identified and registered. A *MQTT* protocol message broker sends the captured data in real time to the connected platforms or application components through the RESTful API component that resides in the business logic layer.

C. *Business logic layer*

This layer processes the captured data and saves the information in a database while defining the status of the water quality for each parameter. Through programming logic that defines the permissible limits of each parameter of the captured data, an assessment of whether each individual location's water quality is safe or not can be made. As well as monitoring the water quality, this component permits the presentation layer web application to manage the specific information of the unofficial settlements. This layer will also manage the technical service itineraries of device installations and maintenance, as well as water treatment. This RESTful API has been developed with the Spring framework, written in the Java language, and therefore follows all Open-Source conventions.

D. *Storage Layer*

For the storing layer, a MySQL relational database is used. Fig. 4 presents a part of the entity-relation diagram and shows the tables that are related to the Monitoring Bounded Context. Here the captured water quality parameters, water reeptacle information, and alert information from the devices are stored. Other tables are also contained for the other Bounded Contexts, such as persisting personal data from the users, information of the scheduled technical activities and their status, data about the unofficial settlements and their individual residences, among others.

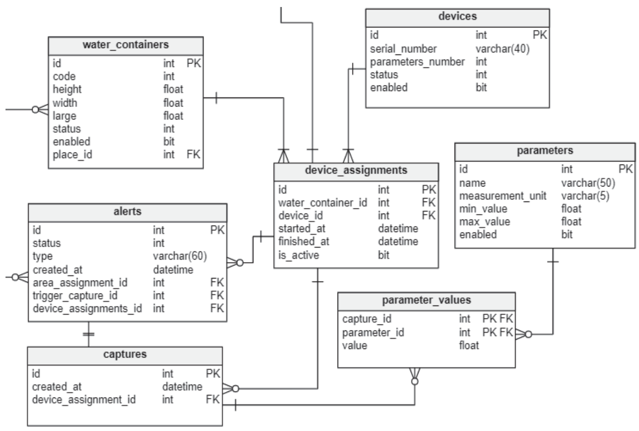


Fig. 4. Tables related to monitoring bounded context

E. *Presentation Layer*

The proposed *IoT WaterCare* solution was developed in Spanish and with the *JavaScript Vue.js* framework and libraries as *Vuetify* for the layout and the interfaces style, *Chart.js* for the graphics render, *HERE Maps* for the display of the unofficial settlements and the individual residences, and *OneSignal* for transmitting the various alerts.

The solution is composed of two modules: (i) the water quality monitoring module and (ii) the technical service module. The main functionalities of the GUI solution are a (1) *Dashboard* that presents the situation in the unofficial settlements and the water quality of the individual residences, (2) monitoring of the unofficial settlements and their individual residences, (3) Display of the locations of each unofficial settlement, (4) monitoring screen presenting the parameters of the water receptacles of an individual residence, (5) technical visit schedules for device installation and/or maintenance and water treatment, a (6) module of alerts about the water quality parameters, and a (7) module to connect IoT devices to water containers and turn them off if they require maintenance. With this functionality, a supervisor can find, from a PC or a mobile device, the status of the water quality at any individual residence, whether "Contaminated" or "At risk" when the values of the parameters exceed the permissible limits, or "Safe" when they are within the permissible limits according to those established by MINSA [40]. Fig. 5 shows some interfaces of the proposed system.

IV. Validation

The validation of the current system was carried out in a residence of the unofficial settlement called "Vista Alegre del Carmen", located in the district of Comas, Lima Province, in Peru. In addition, a survey was conducted with 4 experts in environmental issues and water quality monitoring.

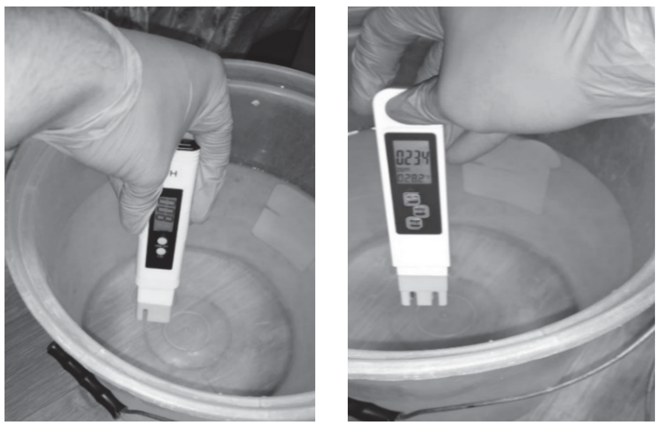
To validate the *IoT WaterCare* proposed system, two experiments were carried out, with Experiment 1 the control and Experiment 2 the testing of the *IoT WaterCare* system on tanker truck water under two Scenarios: water delivered three days previous to testing (Container 1) and water delivered roughly four hours previous to testing (Container 2). Experiment 1 measured the *pH* and *TDS* with standard digital sensors, while Experiment 2 used the proposed system to measure *pH* and *TDS* as well as *temperature* and *turbidity*, with both experiments conducted on both receptacles (Table VII).

Table VII. Measurement device validation scenarios

Experiments	**Parameters**	**Container (5 liters)**	**Scenario**
With digital sensors	pH, TDS	1	Water collected 3 days previous
		2	Water collected the same day
With IoT WaterCare	pH, TDS, temperature, turbidity	1	Water collected 3 days previous
		2	Water collected the same day

A. *Experiment 1: Use of digital sensors*

The standard pH measuring device was immersed in the corresponding receptacles to make the measurement, waiting until the sensor registered a stable value and a photo could be taken. Figures 5(a) and 5(b), show the Experiment 1 pH and TDS results, respectively for Scenario 1. The experiment was executed in the same way for Scenario 2. It should be mentioned that the pH digital sensor has a measurement range of 0 to 14, while the TDS digital sensor has a measurement range of 0 to 9.999 ppm (parts per million). Also, the ppm measurement unit is equivalent to the mg/L unit.



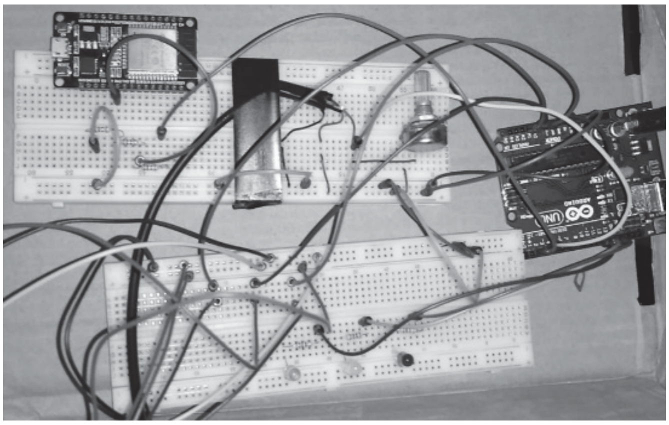
(a) (b)

Fig. 5. Measurement with digital sensors in scenario 1

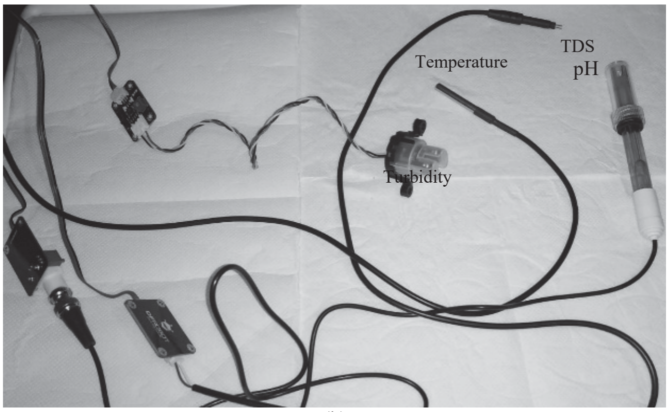
B. *Experiment 2: Use of IoTwaterCare*

1) Hardware Setup: The validation of the proposed system was carried out by implementing a prototype with the water quality sensors and the microcontrollers *Arduino UNO* y

ESP32, that were mentioned in Table VII. The microcontroller *ESP32* has an integrated *Wi-Fi* module that can transmit sensor captured information and it is connected to the *Arduino UNO*. Fig. 6(a) shows the cable connections between these two microcontrollers and the four sensors. Fig. 6(b) shows the four sensors used in the experiment to capture *pH, TDS, temperature y turbidity*. To assure a correct result, the prototype sensors were previously calibrated with special solutions to *buffer or standard,* as per the sensors instructions [42] [43].



(a)



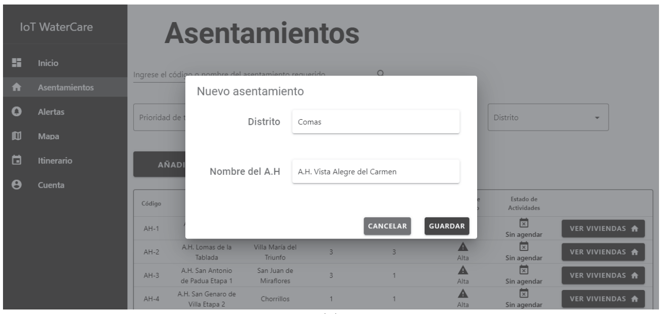
(b)

Fig. 6. IoT Devices used in the experiment 2

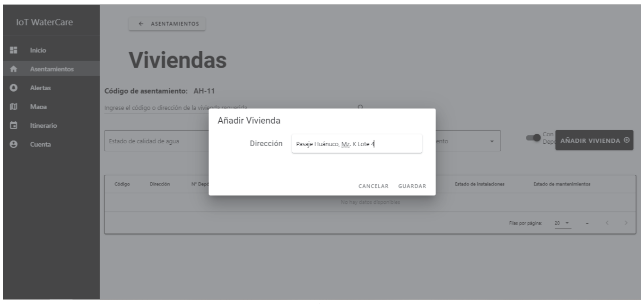
2) *Software setup:* To setup the *IoT WaterCare* system, the data about the unofficial settlement chosen in the study (Fig.7(a)) and the data of the individual residence (Fig.7(b)) were registered. Next, a visit from technical service to the residence was scheduled in order to install the sensors in its water receptacles, registering the visit hour and the technician.

To register the dimensions of each water receptacle, the following data was considered: height, width and length (Fig. 8 (a)). The sensor's serial numbers were also registered (Fig. 8(b)).

The information was stored and the first water quality parameters were displayed (Fig. 10). At the end of installation, the sensors required roughly ten minutes to register stable measurements, specifically the pH sensor.



(a)



(b)

Fig. 7. *IoT WaterCare* user interfaces for settlement and house registration

(a) (b)

Fig. 8. IoT device installation process with *IoT WaterCare*

Fig. 9 shows the four installed sensors: T*emperature (1), turbidity (2), pH (3), and TDS (4*), immersed in the water container (DP-23) under Scenario 1.

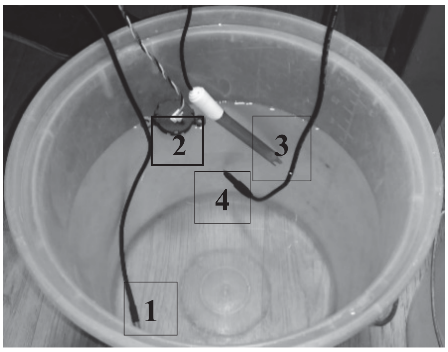
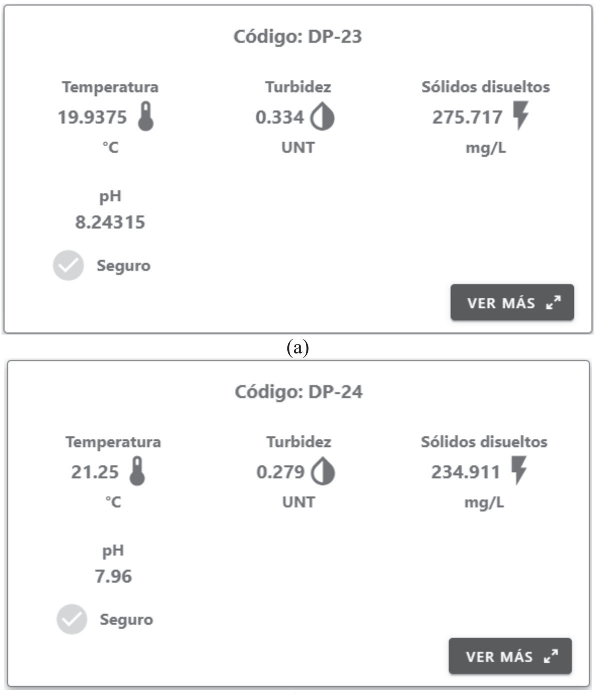


Fig. 9. Water quality measurement for the scenario 1

Fig. 10(a) shows the captured measurements of the four parameters of the water container DP-23 under Scenario 1. All are in the "Safe" range, so the system did not send any alerts and just stored the information. The above steps were then repeated for Scenario 2 (Fig. 10(b)).



(a)

(b)

Fig. 10. Measurement of the water quality parameters with *IoT WaterCare*

C. Expert judge validation

In addition, a validation of the study was carried out with expert judgment in order for them to use the system and give their appreciation in this regard. For this, 4 experts in environmental issues and water quality monitoring (environmental and sanitary engineers) were contacted.

The validation consisted of 3 steps: (i) Explanation of the System with the Zoom platform, (ii), use of the System by the experts, and (iii) development of a survey. The experiment was performed separately with a duration of approximately 1 hour each.

The following steps were performed for the simulation of the system:

- The experts were asked to log into the system and navigate through all the functionalities.
- A simulation of a contaminated tank alert was performed so that they could be redirected to the respective tank screen and consult the information in real time.
- They were asked to schedule a visit from a technician for a house that required treatment of its tanks.

Finally, an online survey [46] made up of 7 closed questions and one open question (Table VIII) was prepared applying the Likert scale for the closed questions (1 = totally disagree, 2 = disagree, 3 = Neither agree nor disagree, 4 = agree and 5 = totally agree). The open question is posed with the purpose of looking for opportunities for improvement.

TABLE VIII. SURVEY QUESTIONS

	Question	Type
Q1	Do you think it was easy to navigate through the application?	Close-Ended
Q2	Do the graphs displayed on the Home screen meet the objective of showing a summary of the containers' water quality in unofficial settlements?	Close-Ended
Q3	Do you consider that the way in which the containers' water quality parameters are detailed is appropriate for efficient monitoring?	Close-Ended
Q4	Does the sending of alerts allow early action to be taken when a water container is contaminated?	Close-Ended
Q5	Do you consider that the map of registered settlements and dwellings allows monitoring to be more interactive and faster?	Close-Ended
Q6	Do you consider that the process carried out to schedule a visit to a home was simple?	Close-Ended
Q7	Do you consider that the functionalities of the application allow efficient monitoring and control of drinking water?	Close-Ended
Q8	According to your experience, what aspects should be improved or added to the application to fulfill its objective in a better way?	Open

V. RESULTS AND DISCUSSION

In Table IX, the results of Experiment 1 are shown, where standard digital sensors for *pH* and *TDS* were used for Scenario 1 and Scenario 2. The results show that the pH was slightly higher in Scenario 1 (8.00) when compared to Scenario 2 (7.82), most probably because the water from Scenario 1 had been stored for roughly 72 hours in the receptacle since it was delivered from the tanker truck. The TDS value is higher in Scenario 2, which could be caused by some solid waste that has been transported by the tank truck.

Table X show the results of Experiment 2, where the *IoT WaterCare* system was used for both Scenario 1 and Scenario 2. The results show that the values for turbidity, *TDS* and *pH* parameters were higher for scenario 1. This is again probably because the water of Scenario 1 had more storage time than Scenario 2, where generally the *turbidity, TDS* and *pH* tend to increase. Temperature, however, was higher in Scenario 2, possibly because the water of Scenario 2 had been received recently from the tank truck and the water of Scenario 1 was stored in the shadows.

In order to effectively compare the results of Experiment 1 (control) and Experiment 2, Eq. (1) was used to determine the difference (*d*) between the values measured, and Eq. (2) determining the error rate (*er*). The variables used are *miotd* (measurement with IoT device) and *mds* (measurement with digital sensor) and are used only for the variables tested across both experiments, *pH* and *TDS*.

$$d = |miotd - mds| \qquad (1)$$

$$er = (|miotd - mds|/mds)*100 \qquad (2)$$

Table XI shows a summary of the outcomes obtained when applying Eq. (1) and (2) on both experiment's results for each scenario.

In Scenario 1 (water stored for approximately 72 hours), the *pH* and *TDS* values and their corresponding *d* (difference) and *er* (error rate) for both experiments are shown. The *er* of the *pH* (3%) is much lower than the *TDS (17.95%)*, showing that the *pH* measurement with the *IoT WaterCare* system was sufficiently precise. The *TDS* measurement had a higher error rate and could be attributed to the TDS sensor requiring more calibration time.

Additionally, for Scenario 2 (water stored in an approximate time of 5 hours), the results show that the *pH* and *TDS* values obtained with *IoT WaterCare* have little difference from the control values obtained with the digital sensors, getting a error rate much lower than Scenario 1 (1.79% and 2.49%, respectively). It should be mentioned that Scenario 2 had a longer calibration time for the *TDS* sensor than in Scenario 1, which might explain the large error rate of Experiment 1's *TDS* result.

These results show us that we can compare the effectiveness of the proposal by making use of digital sensors, similar to the work of Truong [29], where he compared the measurements of his water quality sensors against a system with more sophisticated sensors by calculating the error rate. Furthermore, in [10], the authors measure the nitrate concentration in the water of a specific location with their proposed system. Then, they calculate the error rate between their measurements and the results obtained by a laboratory machine.

TABLE IX. WATER MEASUREMENT RESULTS FOR EXPERIMENT 1

Measured parameter	Scenario 1	Scenario 2
pH	8.00	7.82
TDS, mg/L	234	241

TABLE X. WATER MEASUREMENT RESULTS FOR EXPERIMENT 2

Parameter	Scenario 1	Scenario 2
Temperature, °C	19.94	21.25
Turbidity, UNT	0.33	0.28
TDS, mg/L	275.72	234.91
pH	8.24	7.96

TABLE XI. COMPARISON OF THE MEASUREMENT TYPES APPLIED TO SCENARIO 1 AND 2

Scenario	Parameter	Experiment 1	Experiment 2	*d*	*er* (%)
1	pH	8	8.24	0.24	3
	TDS, mg/L	234	276	42	17.95
2	pH	7.82	7.96	0.14	1.79
	TDS mg/L	241	235	6	2.49

Fig. 11 shows the results obtained from the survey carried out on the 4 experts, where we can see that 100% of the experts answered the questions with a score of 5 (tottaly agree) regarding the usability of the system (Q1), the importance of sending alerts about contaminated containers (Q4) and the ease in the process of scheduling a visit to a house in the unofficial settlement (Q6). And, regarding the other questions (Q2, Q3, Q5), 75% of the experts have given a rating of 5 (completely agree) and 25% a rating of 4 (agree).

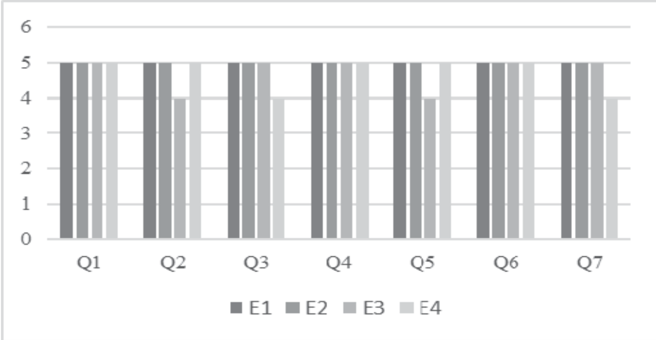


Fig. 11. Summary of responses to the expert survey

Regarding the answers to question Q8, two experts made recommendations to improve the graphical interface of the system. Likewise, one of them recommended adding the conductivity parameter of the water and another mentioned that the route made by the tank trucks should be taken as a contaminating factor of the water. Finally, one of the experts did not have any suggestions, since he considered that the needs raised were covered with the functionalities.

VI. CONCLUSION AND FUTURE WORK

Different works were found in the literature for monitoring drinking water, such as: monitoring systems for distribution network pipes [33], water tanks [24][26][35], and tap water [10][22], however, none of them focused on drinking water consumption in human settlements.

In the current study, an IoT architecture was proposed for real time monitoring of quality parameters (*temperature, pH, turbidity and TDS*) for water delivered by tanker truck to unofficial settlements in Peru. This was done through an implementation of a web system (*IoT WaterCare*) and the setup of its corresponding IoT devices. The proposed architecture was implemented in five layers: capture, communication, processing, storing and presentation.

Two experiments were made in a residence of an unofficial settlement located in the district of Comas in the capital city of Lima, Peru. Experiment 1 (control) consisted of measuring two water parameters (*pH* and *TDS*) with digital sensors. The second experiment consisted of measuring the same water parameters (*pH* and *TDS*), as well as temperature and turbidity, with the proposed *IoT WaterCare* system, under two different scenarios.

The outcomes of Experiment 1 showed that *pH* and *TDS* measurements with the digital sensors had differences for both Scenarios, probably due to the extended storage time.

In Experiment 2, real time monitoring with the *IoT WaterCare* system was carried out under the same conditions. The results showed that the majority of values for the parameters were higher in Scenario 1, again due to the extended storage time, except for “temperature”, which was a little bit higher in Scenario 2.

The *IoT WaterCare* results showed good precision relative to the control, as their error rates, on average, were low (2% for *pH* and 10% for *TDS*). The *TDS* error rate was higher in comparison to the *pH* error rate because of the short time of calibration that was done for Scenario 1.

Regarding the validation carried out on the functionality of the system with expert judgment, it was obtained that 100% of the respondents gave an average rating of 4.86, a value very close to the maximum rating (5 = Totally agree). And the open question (Q8) allowed to obtain 3 important appreciations for the improvement of the proposal.

Future works could improve results by adding an ultrasonic sensor to measure water levels of the receptacles, and to use the GPRS SIM 7600E device instead of the Wi-Fi module, and to use more time in the calibration of the *TDS* sensor. Also, sampling could be increased to include more residences and deliveries from the same trucks, as well as across different unofficial settlements.

Acknowledgment

We would like to thank the house family of the unofficial settlement "Vista Alegre del Carmen", for their time and collaboration for the execution of the experiment. Also, we thank the experts who participated in the demonstration of the system functionalities and placed their appreciations in the survey.

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