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Development of a Low-Cost Automated Hydrological Information System for Remote Areas in Morelia, Mexico

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Abstract: Measurement of meteorological variables is essential to assess and analyze extreme events, such as droughts and floods, and even more so when the purpose is to generate early warnings of such natural phenomena. Nowadays, several mechanisms can estimate climatic variables like precipitation and temperature. However, no device measures precipitation values in real-time and at a low-cost, much less are these installed in remote areas of difficult access. Therefore, an Automated Hydrological Information System was developed based on low-cost meteorological stations with two communication protocols, Wi-Fi and GSM. The devices are equipped with a self-sustainable power supply, including a solar panel and energy storage that can last for up to three cloudy days. The precipitation, temperature, and relative humidity values are sent to a database, where they are then processed and displayed on a web page, accessible for download. Users can easily access the data from an official application that redirects them to the website without the need for a computer or a mobile browser. Warning systems are feasible due to the use of IoT services such as ThingSpeak and Ubidots. Ultimately, they allow the analysis of information and immediately send alerts if it exceeds the tolerance ranges.

Keywords: Automated Hydrological Information System; IoT; low-cost sensors; real-time; remote areas

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Citation: Sánchez-Quispe, S.T.; Madrigal, J.; Rodríguez-Licea, D.; Domínguez-Mota, F.J.; Domínguez-Sánchez, C.; Lara-Ledesma, B. Development of a Low-Cost Automated Hydrological Information System for Remote Areas in Morelia, Mexico. *Water* **2023**, *15*, 3888. https://doi.org/10.3390/w15223888

Academic Editor: Daniel Dunea

Received: 5 September 2023
Revised: 3 November 2023
Accepted: 6 November 2023
Published: 8 November 2023

1. Introduction

Climate directly affects the human environment since it intervenes in biological, social, and economic aspects [1–3]. Hence the importance of its study to consider representative information that can aid in the development of various activities such as urban planning, agriculture, livestock, transportation, health, recreation, disaster prevention, weather forecasting, and evaluation of global warming and climate change, among others [4,5]. Climate helps determine the long-term average values of the elements of atmospheric weather, while these define the short-term atmospheric behavior (of one or several days). Having records of climatic variables allows estimation of what could happen in the following hours or days and, therefore, forecast any extreme event that may occur [6]. Nevertheless, the weather is affected by many factors and can suddenly change, making it difficult to form an accurate forecast [7]. On the other hand, records of climatic variables are also indispensable for the assessment of water resources since they allow the study of different components of the water cycle through the use of hydrological models, determining which model or set of models is best suited to the physical and meteorological conditions of each study area [8,9].

Some paradoxes of current economic systems concerning environmental problems and social inequality are the growing need to cope with market requirements and the pressure this generates on the environment, in addition to creating social and technological gaps [10]. Thus, it is crucial to explore innovative solutions to make the interests of social, economic, and environmental spheres compatible [11]. Technological innovation processes have historically shown discriminatory behavior and have been selectively located in certain regions, countries, or productive sectors. Nonetheless, these benefits need to extend to less privileged countries and sectors of the population to guarantee greater social equality, a healthy environment, access to education, and overall well-being. In recent decades, many advances have been made in meteorology, with sophisticated equipment that collects precise data from a given site and accurately determines the weather's behavior [12–14]. However, this equipment is usually expensive and located in fixed meteorological stations of public or private institutions dedicated to climate study.

One of the fundamental questions in meteorology is associated with how technological change can affect data records and the comparison between traditional and current systems [15]. In this sense, automatic stations allow access to meteorological information in real-time from remote and difficult-to-access places [16,17]. This procedure is impossible to carry out using conventional stations unless they are permanently manned by an observer and the observer has the technology to transmit the information to a data collection center. In this case, it would be an automatic geographic information system (AGIS) [18].

An Automated Hydrological Information System (AHIS) is based on an AGIS, designed to display, edit, store, manage, and analyze spatial data to generate results in real-time. The difference between an AHIS and an AGIS is in their field of study, in which the AHIS directly focuses on water resources.

The development of IoT-based devices for measuring meteorological variables is under constant research. Imtiaz et al. [19] designed an Arduino-based portable station with low-cost sensors for temperature, humidity, atmospheric pressure, and wind velocity. The data was sent to a MySQL database through HTTP protocol. With the station information, a public website was created to display and download the data. Srivastava et al. [9] developed a real-time air quality monitor system based on IoT with Arduino. This system measures temperature, humidity, atmospheric pressure, dust, noise, and gases, such as CO, NOx, CO_2, and CH_4. The data was transmitted to an IoT cloud with a Wi-Fi module. The information can be acquired through a ThinkSpeak channel, which allows temporary display and downloads to a smartphone or a PC using an internet network. Muñoz et al. [20] designed an Arduino-based weather data acquisition device to measure precipitation, relative humidity, and temperature in real-time for small geographical coverage in the Philippines. This device sends information to a database through General Packet Radio Service (GPRS 2G). Tomaschewski and Arigony-Neto [21] implemented an automatic Arduino-based weather station to measure temperature, wind, ATM pressure, and humidity and assess the impacts of climate change on glaciers. In this case, the data is stored in an SD card. Strigaro et al. [22] developed an Arduino MEGA-based weather station that measures air temperature, pressure, humidity, and precipitation. The precipitation sensor was the most expensive, so the authors designed a 3D-printed rain gauge (which was under testing). The collected data is transmitted through GPRS to a web service of the Open Geospatial Consortium. Haque et al. [23] designed a weather monitoring system controlled by Arduino MEGA. The parameters of this system are temperature, humidity, carbon monoxide, smoke, and raindrops, among others.

Despite the exponentially increasing use of Arduino-based sensors in recent years and IoT for data transmission [24,25], no station measures the amount of precipitation using low-cost sensors and transmits the information to a database in real-time. Some previously mentioned papers estimate precipitation, but only as a dichotomous variable (existence or absence). Meanwhile, other stations measure the amount of rainfall without applying low-cost sensors.

The problems identified in the current meteorological information systems result from a lack of required essential characteristics. Firstly, the fact that they are not automated real-time systems and take so long to update indicates that they cannot function as early warning systems. In addition, they have data visualization issues because they do not apply geographic information systems (GIS). Since they do not generate historical databases, current meteorological systems can not publish the information online. One of the most relevant concerns is the price of these systems, which complicates their implementation in developing countries or very remote areas. The approach to this problem is based on the development of an automatic hydrological information system capable of capturing, managing, analyzing, and visualizing temporal and spatial information in real-time, thus allowing it to function as an early warning system and evaluation of Integrated Water Resources Management. Its application should allow monitoring of any given study through low-cost technologies that send information to cloud databases on IoT. Additionally, it should link spatial-temporal data with websites or mobile applications, incorporating early warnings through various media such as emails and social networks to prevent environmental risks.

The remainder of this paper is structured as follows. Section 2 describes the materials and methods. Section 3 defines the case study, and Section 4 focuses on the discussion and analysis of the results. Finally, Section 5 states the conclusions.

2. Materials and Methods

To construct an effective Automated Hydrological Information System for remote areas where a large budget is unattainable, Low-Cost Automatic Weather Stations (LCAWS) that transmit to a database in real-time should be applied. Once the system for measuring climatic variables is in place, the database is created, and communication between it and the weather stations is established. A Wi-Fi system is needed to transmit remote information to the database. This system requires internet access at all times. If the signal is lost or unavailable, the weather station will be incapable of sending the information. When internet access is unavailable, a GSM communication system can be implemented, which works with radio waves and can operate in remote areas. If possible, a Wi-Fi system should be chosen over GSM, as the latter is 30% more expensive. Finally, an information processing and visualization system is developed to generate real-time warnings of abnormal weather events and download the stored historical data. This methodology is described in Figure 1.

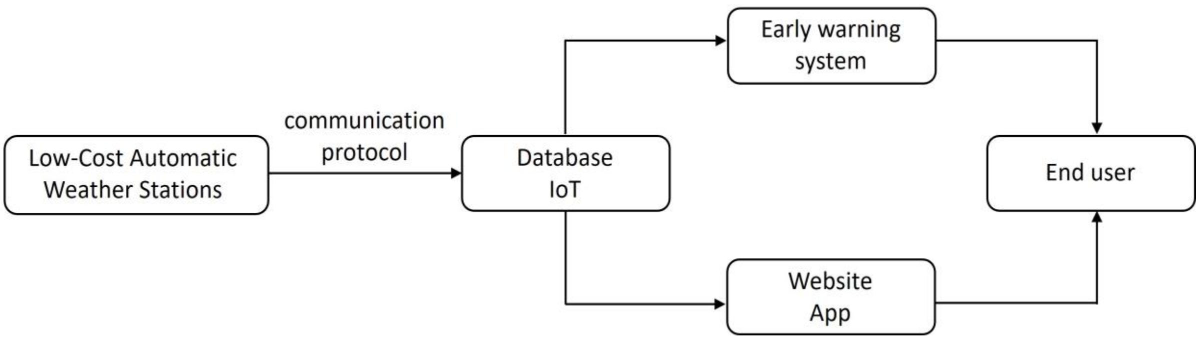

Figure 1. Methodology for developing the Automated Hydrological Information System.

The materials have been classified into three groups. The first group integrates the microcontrollers, sensors, and systems required to build the LCAWS. The second group includes the database and linkage services with platforms to display and publish early warnings. The third group contains tools to develop the platforms to visualize information and issue early warnings.

2.1. Instrumentation

A 3D-printed tipping bucket rain gauge sensor was used to produce a precipitation data acquisition device. It utilizes a reservoir with twin plastic compartments to measure incoming water, dividing it by the same weight. When one is filled, the center of mass is displaced from the axis, and a tilting motion occurs, emptying the collected water. The second compartment is placed in the catchment position [26]. The tilt movement activates a magnetic switch, turning on the circuit and sending a digital signal equivalent to a tilt of one of the cuvettes. The volume of each cuvette is 0.2 mm, equal to the sensor's resolution.

Arduino is based on the ATMEGA168, ATMEGA328, and ATMEGA1280 microcontrollers, and Arduino UNO is on the ATMEGA328 microcontroller (developed by Microchip Technology Inc. located in Chandler, AZ, USA.). It has several pins that can be configured as input or output. Any device capable of transmitting or receiving digital signals from 0 to 5 V can be connected to them. It also has analog inputs and outputs to obtain sensor data or send PWM control signals to other devices [27,28]. Meanwhile, Arduino IDE is an integrated development environment with a General Public License (GNU) and works as an executable code [29,30].

NodeMCU is an open-source development board with an integrated ESP8266 module and a Wi-Fi component that connects the system to the internet. It has digital and analog pins to connect various modules and sensors, an SoC processor, and 16 GPIO lines, and is powered by 5 V. A SIM900 GSM module was also employed, which is a data input and output module for Arduino UNO. It is based on a global system for mobile communications (GSM) and connects to the Arduino UNO board [31,32].

The DHT22 is an advanced sensor unit that provides a calibrated digital signal output consisting of two parts: a temperature sensor with a thermistor and a capacitive humidity sensor. It is equipped with an 8-bit microcontroller and has a short response time. It has a $\pm$0.5 °C relative error in temperature and $\pm$2% in humidity. Temperature values range from $-$40 °C to 80 °C, humidity values from 0 to 100%, and operating voltage values from 3.5 to 5.5 V. The operating current is 60 µA, and the resolution is 0.1 °C and 1% for temperature and humidity, respectively [33].

2.2. Data Storage and Linkage

Ubidots is an IoT hosting service which specializes in hardware and software development that allows the platform to integrate device production, cloud computing, and deployment [34]. Ubidots is applied for storing and interpreting sensor information in real-time, as well as creating IoT applications [27].

ThingSpeak is utilized to store data and display the information. ThingSpeak is an IoT cloud-based platform that shows data remotely collected by various sensors and sent over the internet [9]. It provides instant visualizations of the information published by multiple devices. ThingSpeak is often used for IoT prototyping and proof-of-concept systems [35].

IFTTT ("If This, Then That") is a free web service for creating strings of simple conditional statements, also called applets. IFTTT can link various popular internet services, such as Gmail, Instagram, Facebook, and SmartThings [36].

2.3. Visualization

Wix.com is a cloud-based web development platform that allows users to create HTML5 websites by simply dragging and pasting. Users can add features such as social media links, e-commerce, contact forms, email marketing, and community forums to their sites using a variety of applications [37].

2.4. Prototyping

Prototyping begins with the design of a preliminary model of a major subsystem or a scaled version of the entire system. Iterative processes are used to create this preliminary model [38]. During each iteration, requirements and alternative solutions to the problem are identified and analyzed, new solutions are developed, and a portion of the system is implemented. The prototype is then tested and evaluated.

Muñoz et al. [20] mention that before installing the experimental weather stations in the field, the sensors must be calibrated using a controlled climate or environment to obtain quality data. Climate-controlled calibration consists of simulating a climate of known magnitude to which the experimental sensor will be subjected, along with a comparison sensor or device (laboratory equipment or accurate commercial devices). The sensors should be tested for five days at 1-h intervals under the following: minimum, medium, and maximum conditions for temperature; low, medium, high, and slight for humidity;

moderate and heavy for precipitation. Subsequently, the data should be analyzed, and the accuracy of the experimental sensors should be determined. If the accuracy of the sensor does not meet the desired requirements, it should be adjusted in programming through a correction factor.

Strigaro et al. [22] explain that the purpose of sensor validation is to compare the quality of data from an experimental weather station with a commercial weather station. The method consists of installing the experimental weather station at the same site as the commercial one and collecting data over time for subsequent statistical analysis of the series. The sensor information is valid when it is within the pressure tolerance range corresponding to the type of sensor as indicated in the Guide to Instruments and Methods of Observation of the World Meteorological Organization [26].

3. Case Study

The methodology described above was implemented in Morelia, located in central Mexico. This city was selected because it suffers from recurrent flooding events, and the study aims to apply a hydrological monitoring system with sufficient tools to generate early warnings. Currently, Morelia has an infrastructure for monitoring meteorological variables through three different systems: nine stations of the National Meteorological System (SMN), ten stations of the city's water agency (OOAPAS), and three automatic stations of the National Water Commission (EMAS), as shown in Figure 2.

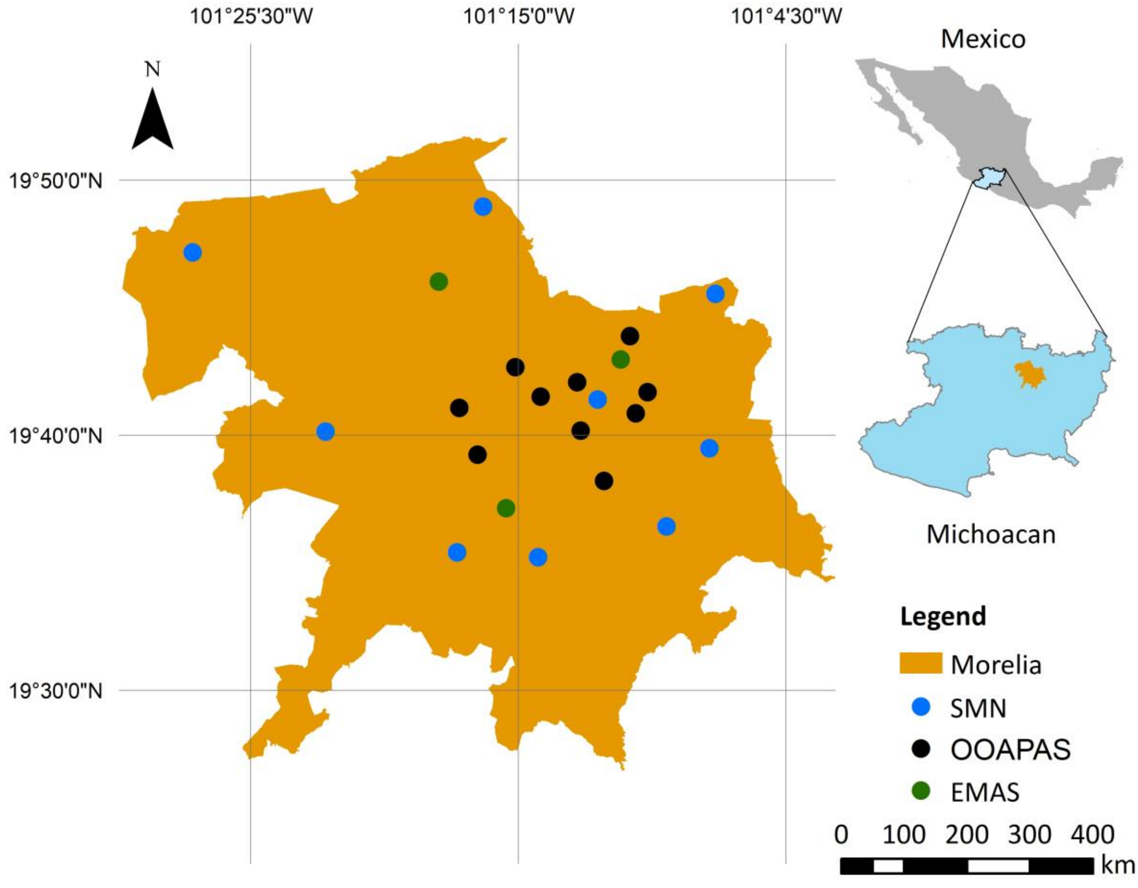

Figure 2. Case study.

The three information systems were analyzed considering essential characteristics in early warning systems, in addition to considering the implementation of low-cost technologies and the use of geographic information systems (GIS), as shown in Table 1.

Table 1. Analysis of existing weather stations.

Attributes	Weather Stations SMN	OOAPAS	EMAS
Public information	X	X	X
Historical database generation	X		X
Use of GIS	X	X	
Real-time monitoring		X	X
Low-cost			
Warning generation system			

Considering the limitations of the existing stations, it is necessary to develop a low-cost data acquisition device that sends the information in real-time so that it can be implemented in a database.

4. Results and Discussion

4.1. Wi-Fi Low-Cost Automatic Weather Stations (Wi-Fi LCAWS)

A Wi-Fi LCAWS needs to meet the following requirements: measurement of precipitation, temperature, and relative humidity of the air in real-time, self-sustainability in terms of energy, and transmission to the database through the Wi-Fi communication protocol. The design of the Wi-Fi LCAWS required four iterations to reach the final product. After analyzing these alternatives, it was decided to employ a NodeMCU ESP8266 microcontroller, a DHT22 sensor for air temperature and humidity values, and a tipping bucket rain gauge sensor for precipitation measurement. Figure 3 shows the device connection diagram.

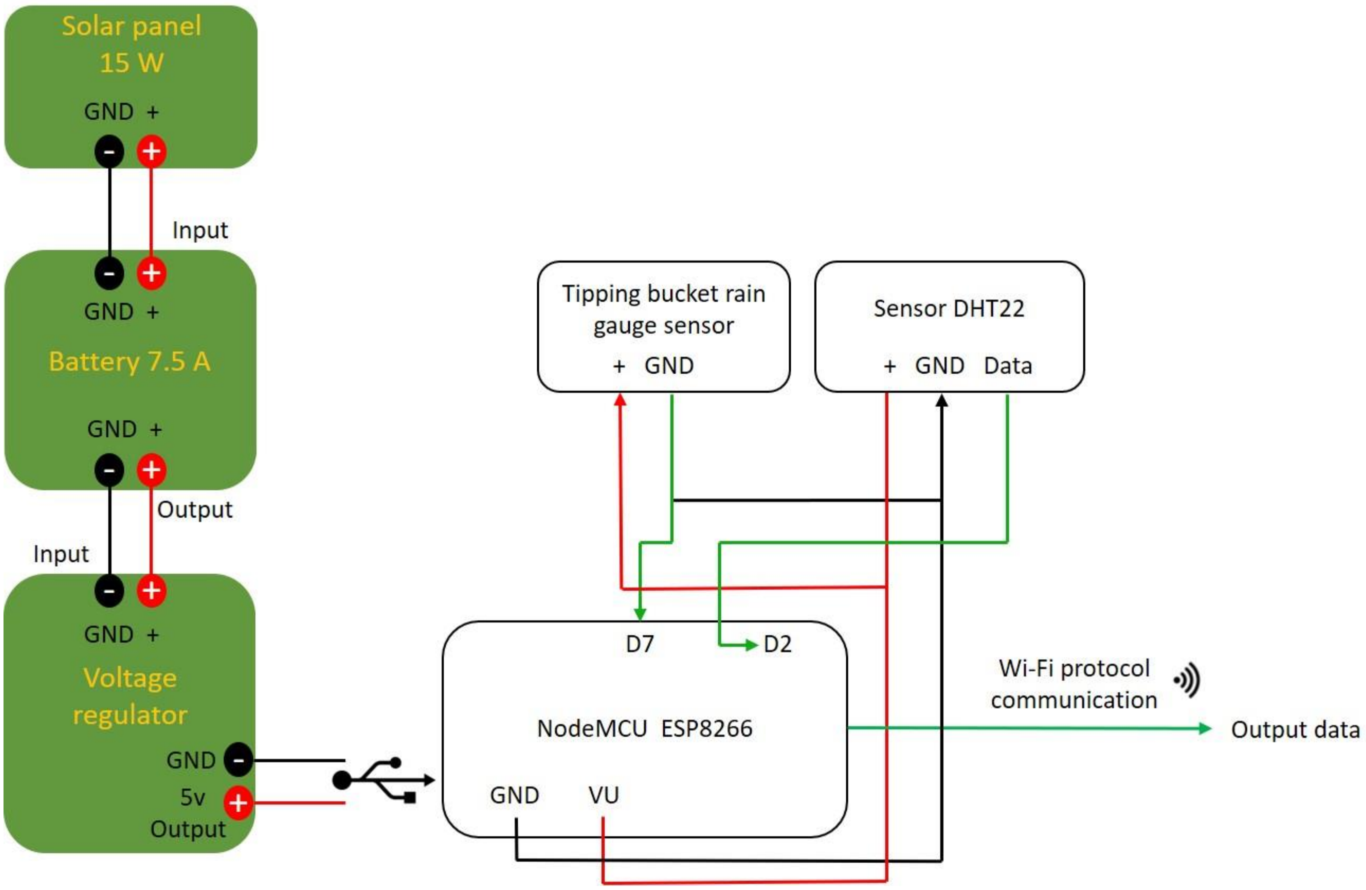

Figure 3. Wi-Fi LCAWS connection diagram.

Once the device was in operation, a review was carried out to observe its performance. The Wi-Fi connection was stable, and the communication of precipitation, temperature, and air humidity information was continuous and in real-time. The sensors responded correctly at various sensitivity points (low, medium, and high).

4.2. GSM Low-Cost Automatic Weather Stations (GSM LCAWS)

The GSM AWS design required only one iteration to reach the final product. An Arduino UNO board was used as the main microcontroller, a GSM SIM900 module for communication, a tipping bucket rain gauge sensor for precipitation measurement, and a DHT22 sensor for air temperature and humidity values. Figure 4 shows the GSM LCAWS connection diagram.

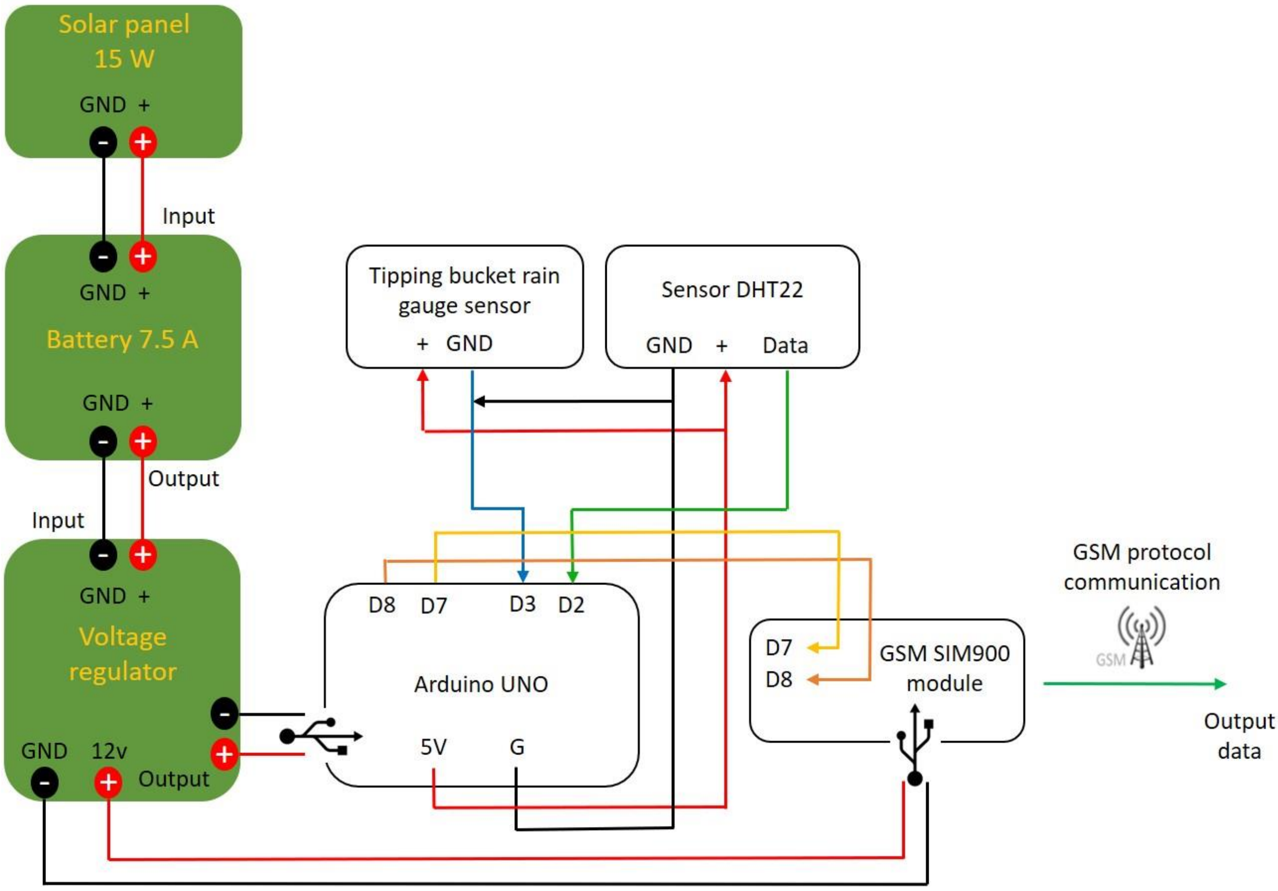

Figure 4. GSM LCAWS connection diagram.

The employed device maintains a connection to the database, as well as continuous real-time measurements via GSM communication. The self-sustaining power supply is sufficient for the system, as with the Wi-Fi LCAWS, with the capacity to power the device for two days in case of cloudy weather. Table 2 shows the characteristics of the power supply system, considering a 7.5 A battery and a solar panel with a 15 W capacity. In Figure 5, an example of an automated station is shown in operation.

Table 2. Self-sustainable electrical system.

Device	Current (mA)	Power (W)	Time of Use (h)
Modules and sensors	200	1	24

Figure 5. Example of the construction of an Automatic Weather Station.

In both cases, Wi-Fi LCAWS and GSM LCAWS, the total cost of a station is approximately $150 (US dollars), as indicated by the general breakdown shown in Table 3. The DHT22 sensor costs $10 while the 3D printed precipitation gauge is priced at $25. The estimated LCAWS maintenance fee per year is $75. A commercial station with wireless communication system, such as the Davis Vantage Pro2 Wireless station, costs around $1000.

Table 3. Breakdown of cost of LCAWS components.

Material	Cost
Modules, sensors, and communication system	$70.00
Phenolic plate	$25.00
Power supply	$30.00
Mounting frame	$25.00

4.3. Calibration and Validation of the LCAWS Elements

4.3.1. Accuracy and Calibration Test of the DHT22 Sensor

The accuracy test of the DHT22 sensor was performed by comparing the observations obtained concerning the data from a commercial NETATMO station placed next to the evaluated sensor. The comparison was conducted from 10 to 21 November 2022, capturing information every hour. The data was downloaded and plotted by the end of the collection period. Figure 6 shows the temperature and relative humidity results.

The average error obtained is 0.19% in the temperature series and 0.87% in the relative humidity series, with correlation coefficients of 0.95 and 0.93, respectively. In Mexico, the accuracy of an automatic weather station for temperature and relative humidity measurement is established by the Mexican Standard NMX-AA-166/1-SCFI-2013 [39], and its values are ±0.2 °C and ±2%, respectively. Taking into account the errors acquired in the comparison of the sensor for the NETATMO station and what is established in the Mexican Standard, it is concluded that the sensor is valid to operate as part of the LCAWS.

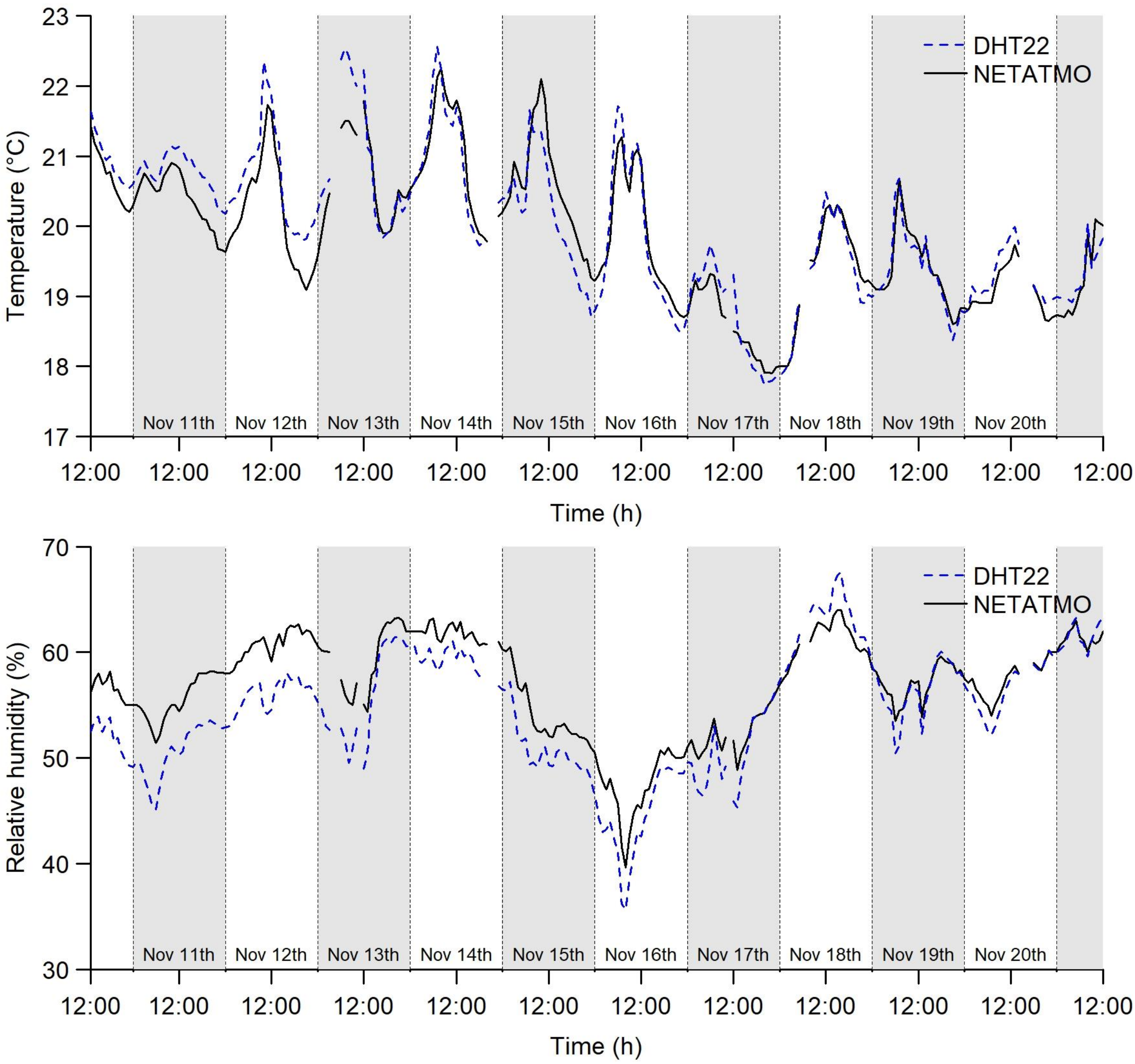

Figure 6. Temperature and relative humidity from DHT22 sensor and NETATMO station.

4.3.2. Accuracy and Calibration Test of the Tipping Bucket Rain Gauge Sensor

Calibration by controlled climates and validation by comparison of observations with a nearby station were jointly used to achieve the accuracy of the tipping bucket rain gauge sensor. The tipping bucket rain gauge sensor and the Davis Ventage Pro2 station (commercial station) were subjected to a controlled precipitation climate simulating two events with intensities of 12 mm/h and 36 mm/h and obtaining measurements every minute. These two intensities were selected to consider both a moderate precipitation intensity and a strong one that have caused flooding in the study area. The measurements for the controlled climate of 12 mm/h were taken for four hours (Figure 7). Once these were acquired, the results were compared, consisting of a 0.03 mm variation in the precipitation volume of both devices. For precipitation with an intensity of 36 mm/h, the measurement was obtained over 12 h, resulting in a variation of 0.00 mm in the precipitation volume (Figure 7).

According to the Mexican Standard NMX-AA-166/1-SCFI-2013 [39], the accuracy in the precipitation measurement should be ±0.1 mm, and based on the values obtained, it is determined that the measurement device for this variable complies with the established standards, given that correlation coefficients of 0.98 and 0.99 were obtained for intensities of 12 mm/h and 36 mm/h, respectively, and mean errors of 0.03 mm and 0.01 mm.

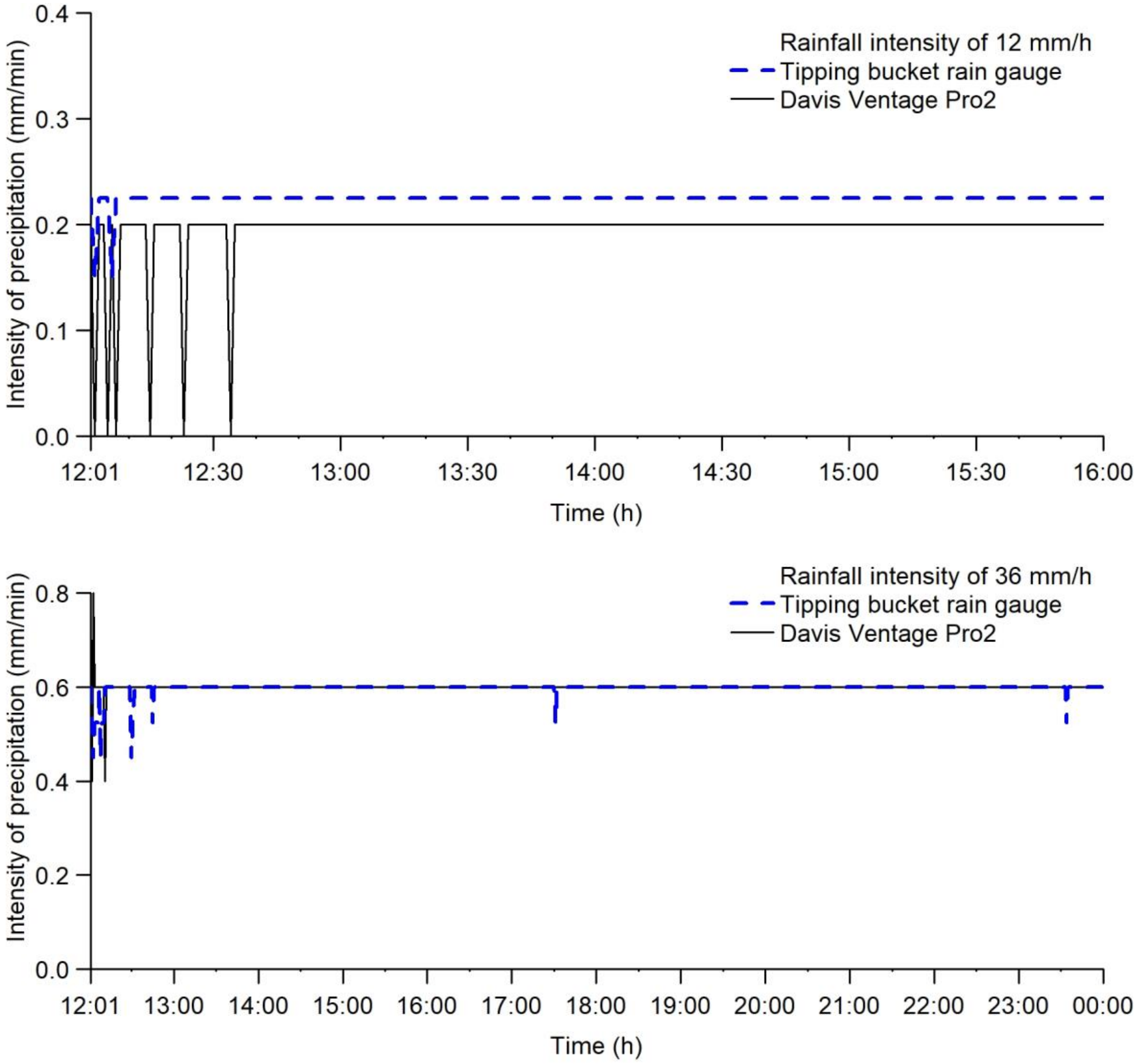

Figure 7. Precipitation measurements.

Once the LCAWS was calibrated in a controlled climate, it was replicated, reaching four devices which were installed in strategic locations in the study area and formed a network in the city of Morelia to validate the devices. Nowadays, eight additional stations are being implemented in the monitoring network. Figure 8 shows the locations of the four validated stations, which were placed together with commercial stations.

To validate the tipping bucket rain gauge sensor, 24-h accumulated rainfall was measured for one month (January 2023). The results of this validation are shown in Figure 9, omitting the days without precipitation.

For the validation of the DHT22 sensor, the temperature was measured for 24 h, taking measurements every minute from 20 to 21 January 2023. The validation of temperatures is shown in Figure 10.

4.4. IoT Database Service Implementation

The LCAWS have a preloaded code that allows connection with the database to send information. A channel was created with four fields for writing precipitation intensity and volume, temperature, and air humidity. Subsequently, a channel ID and an API KEY were generated and included in the LCAWS code. The minute-by-minute information report can be visualized on ThingSpeak.com through graphs that are later shared on the user interface platforms. As in ThingSpeak, the LCAWS sends precipitation information via Ubidots every minute to the IoT database, which is featured in widgets.

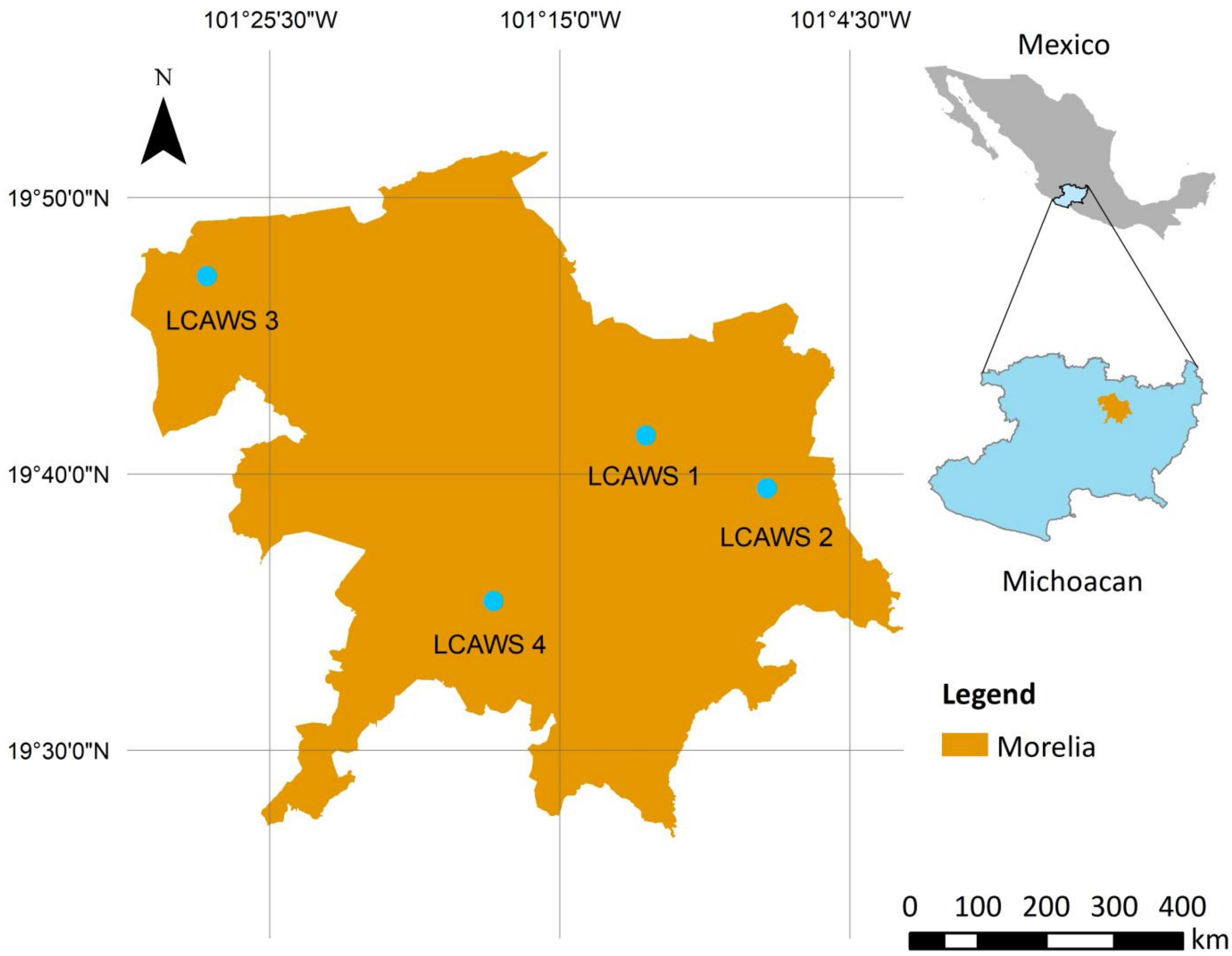

Figure 8. Location of the four validated stations.

4.5. Automated Hydrological Information System (AHIS)

Figure 11 shows an AHIS capable of collecting real-time precipitation, temperature, and air humidity information through the LCAWS, which sends it to ThingSpeak or Ubidots every minute and allows data acquisition and analysis. Early warnings are sent via Webhooks when there are measurements outside the precipitation intensity tolerance range, and they are posted to Facebook and Twitter. Warnings are issued when the LCAWS registers a precipitation intensity over 30 mm/h (heavy rainfall) [40].

Interface design is the most crucial step in information systems development since it is the layout with which the user interacts. Therefore, the interface's functionality and applicability are a priority. For the purpose of achieving these requirements, a low-fidelity prototype was tested on paper with real users. Once it was optimized, the high-fidelity prototype was generated on wix.com using its design tools.

The AHIS is developed under a systematic methodology which implies that its activity is continuously monitored so that it can be analyzed if any failure occurs. For constant functionality, it must undergo frequent maintenance regarding the revision of its devices and supervision of the IoT databases, hosting of the website, and Google Play developer account that supports the app.

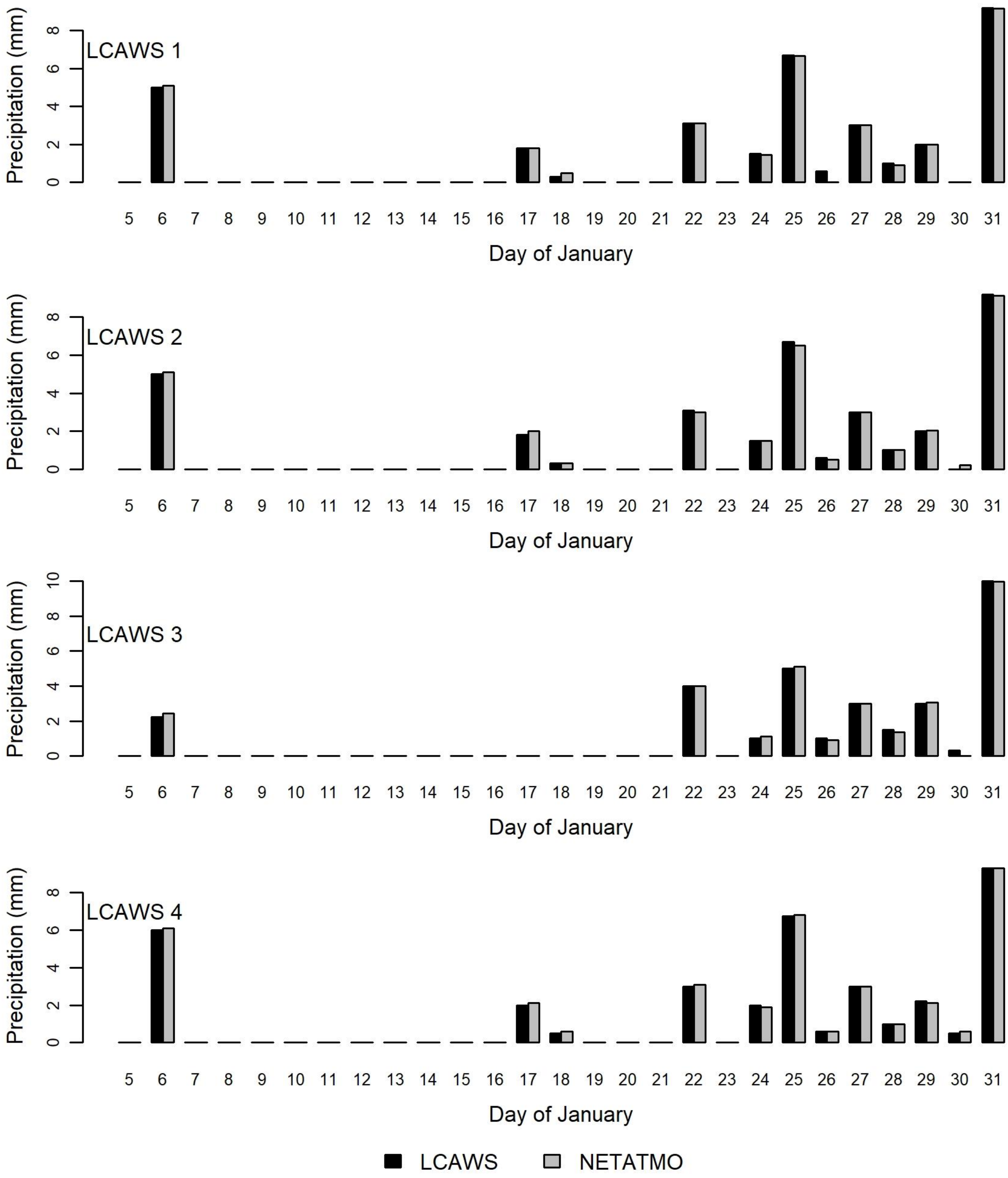

Figure 9. Validation of the tipping bucket rain gauge sensor.

Activity monitoring will be done through the database under a time review protocol so that it can be analyzed if the devices are active and sending information. This applies to the AHIS model that is based on ThingSpeak. In the case of AHIS, which is based on Ubidots, one of its SMS services is responsible for notifying the administrator of the devices being inactive.

To manage water resources and urban flood risk effectively, it is essential to have a robust meteorological monitoring network that contains sufficient historical information and spatially covers the area of interest. The lack of an automatic station network is a common issue in many cities of underdeveloped countries. In the case of Morelia, there is only one automatic station, and its data is accessible with a 24-h delay. The proposed network in this study allows access to real-time information with an adequate number of stations distributed throughout the urban area. Nevertheless, there is a delay in data access, which may extend up to 3 min.

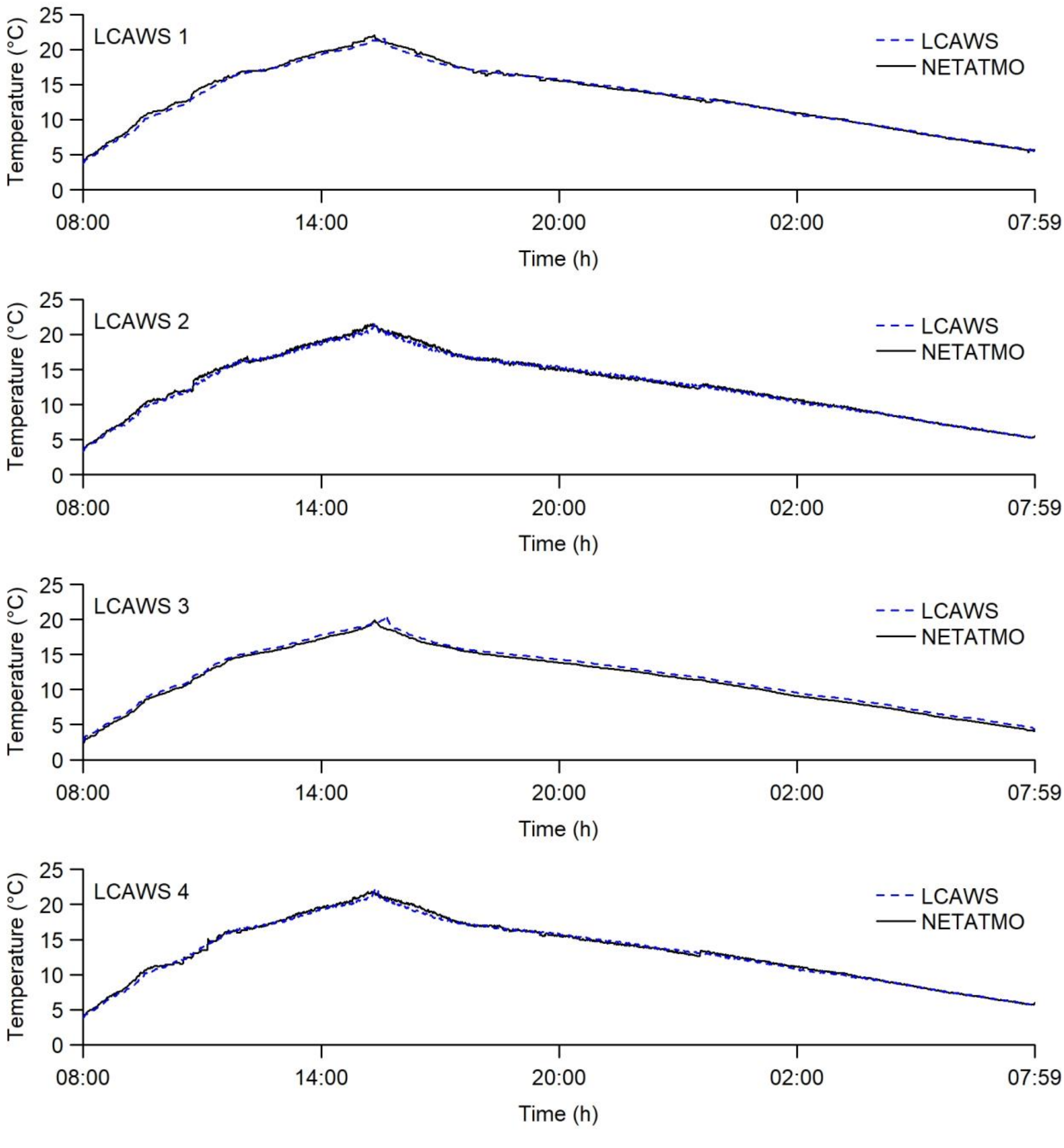

Figure 10. Validation of the DHT22 sensor.

This system offers the potential, in the short-term, to mitigate the effects of floods by facilitating early alerts and real-time monitoring of precipitation in different areas of the city. Furthermore, in the long-term, one minute interval historical precipitation data series will be available at each station, despite the current daily-scale data.

One current limitation of the system is the need to validate the station performance. However, accomplishing this necessitates the operation of the system over an extended period to account for diverse precipitation and temperature patterns, including extreme events.

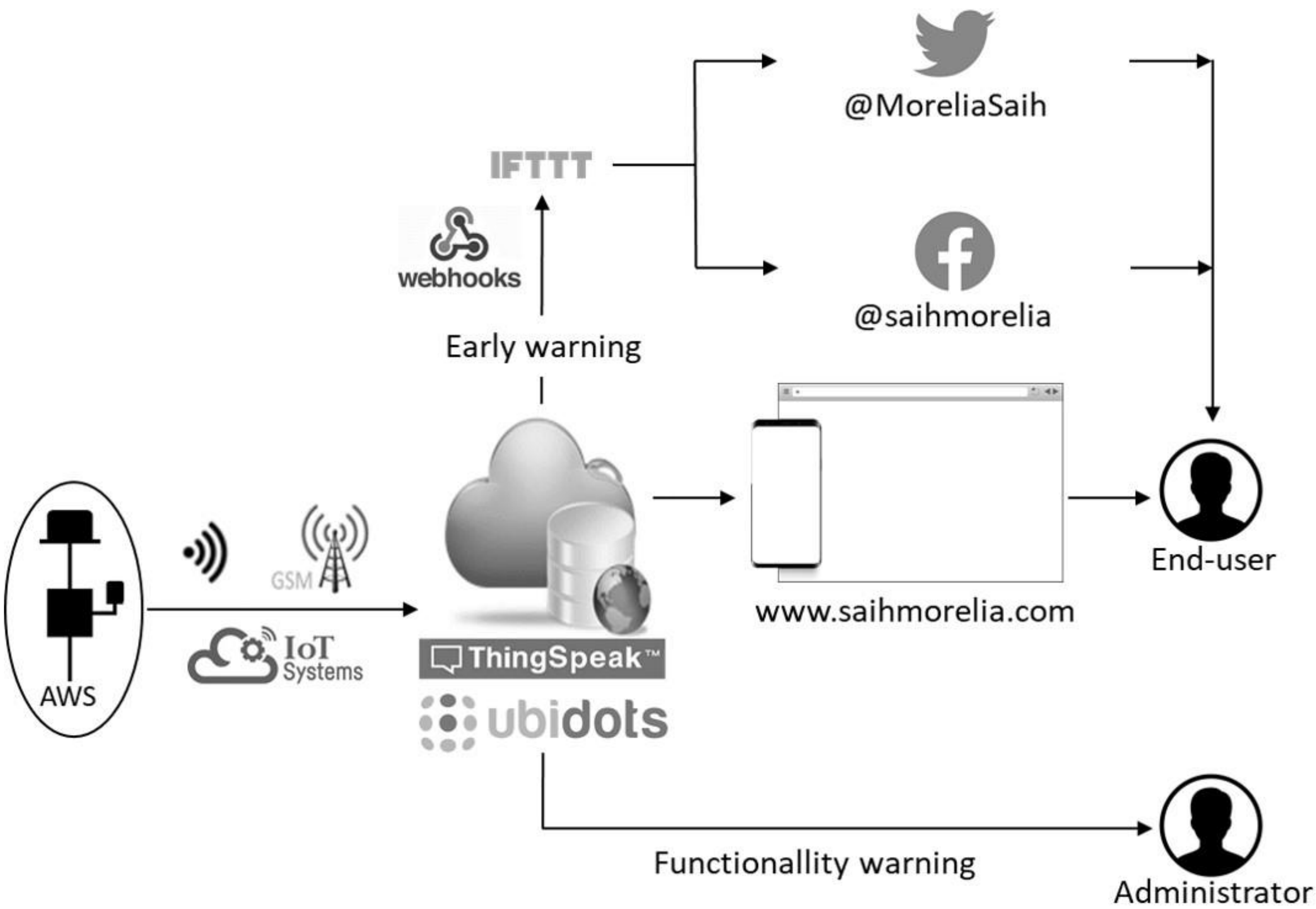

Figure 11. Automated Hydrological Information System (AHIS).

5. Conclusions

The characterization of the study area was carried out to identify the information systems that currently exist. These were subsequently analyzed mainly under the criteria of the definition of early warning systems, checking that they comply with the requirements of this type of information system.

Nowadays, there are low-cost technologies used to develop measurement devices. In addition, diverse IoT databases can be implemented with these devices to generate continuous and real-time information files. By incorporating these technologies, it is possible to produce websites where climate information is displayed, including Google APIS for temporal and spatial visualization.

An AHIS, which incorporates an early warning function, has been developed. However, this is not a proposal to reengineer the current systems but to generate an alternative one based on the characteristics of an automatic information system that also includes early warnings.

The Morelia Automated Hydrological Information System can be an opportunity for developing countries to monitor meteorological variables in real-time and generate information for environmental risk management (floods, droughts, climate change) at a low cost.

The system development consists of three main points: creating a measurement device, implementing an IoT database, and generating visualization platforms. The first step was to produce a low-cost measuring device capable of operating in remote areas in real-time to know the site's climate behavior and to send an alert about possible environmental risks. Two LCAWS were defined considering the above, one with Wi-Fi communication and the other with GSM communication. The GSM network can be used where it is impossible to connect to the internet to send the measured information by the LCAWS.

These devices with internet connectivity surpass previous forms of measuring the weather, so they must link with IoT databases. Implementing IoT databases improves information acquisition, analysis, and management due to the compatibility and simplicity of connecting with Arduino-based systems. These databases allow the transmission to websites through iFrames linked by API keys. Nowadays, there are plenty of web hosting services to create and maintain a site. In this case, Wix was selected.

The presentation of temporal data is easy for users to understand since it can be displayed in different time scales that facilitate analysis. Downloading information from the stations allows for the application of various tools for further examination of the data. Currently, cellphone use is increasing, which is why a mobile app was proposed. Users can easily access the information from an official application that redirects them to the website in a mobile format without the need for a computer or a mobile browser.

The display of information and its easy access is of great benefit to the users, considering that in seconds they can obtain real-time data from various sites in the study area. However, the relevance of using real-time information is to generate early warnings, which must be evident to users.

Warning systems are a possibility due to the use of IoT services such as ThingSpeak and Ubidots. Ultimately, they allow the analysis of information and immediately send alerts if it exceeds the tolerance ranges.

Author Contributions: Conceptualization, S.T.S.-Q. and J.M.; methodology, S.T.S.-Q.; software, D.R.-L.; validation, D.R.-L., F.J.D.-M. and S.T.S.-Q.; formal analysis, D.R.-L. and J.M.; investigation, D.R.-L. and J.M.; resources, D.R.-L.; writing—original draft preparation, J.M.; writing—review and editing, J.M., C.D.-S. and B.L.-L.; visualization, C.D.-S.; supervision, S.T.S.-Q.; project administration, S.T.S.-Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the Universidad Michoacana de San Nicolás de Hidalgo for their support in developing this manuscript. Thanks to the National Council of Humanities, Science, and Technology of Mexico (CONAHCYT).

Conflicts of Interest: The authors declare no conflict of interest.

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