

Research Article

A Solar Powered Ultrasonic Water Level Monitoring System with IoT Type for Small-Scale Agricultural Water Management

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ABSTRACT

Article history:

Received: 2025-10-10

Revised: 2025-12-08

Accepted: 2025-12-15

Keywords:

IoT water management;
 Ultrasonic level sensor;
 Solar IoT system;
 Real-time monitoring;
 Sustainable farming

This research aims to develop and evaluate the performance of an ultrasonic water level meter prototype by applying solar power and an IoT network communication system to support the management of small water resources in community-level agricultural areas. The prototype is designed to be low-cost to implement non-contact measurements and to be able to transmit real-time data to a central server and display results on a mobile application. There are 5 units that have been installed in agricultural areas in lower northeastern Thailand to create a network of water databases reflecting the situation from multiple sources simultaneously. Laboratory testing results showed an average measurement error of 1.36%, which was within acceptable limits while field testing with five agencies, totaling 20 times, indicated an average success rate of 90.2%, with the water level measurement accuracy at 92.5%, ease of installation and practical use at 100%, and data transmission continuity and power durability at 88.3%. These results confirm the potential of combining low-cost sensor technologies, renewable energy, and IoT to create a collaborative water management network prototype across multiple water bodies, and this prototype is practical and field-ready.

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1. Introduction

Local water management is critical for the agriculture sector because it is Thailand's major water consumer, accounting for around 70% of overall water consumption (Thai National Committee on Irrigation and Drainage, 2024). Most rural areas rely on small water sources and reserves for off-season cultivation. These sources not only serve as storage to meet water demands during the dry season but also serve as a crucial mechanism for maintaining continuous agricultural production, which impacts food security and farmers' incomes in the region, particularly in the Northeast, the country's largest agricultural region (National Statistical Office, 2024). The region has been

reported to be continuously at a high risk of drought (Chatklang *et al.*, 2024). This causes the area to be highly vulnerable to climate fluctuations. Recent drought index research indicates that the trend of consecutive dry days is increasing in the Northeast (Oliveira-Júnior *et al.*, 2025). Consequently, it has a direct influence on field crop productivity and the availability of reserve water supplies. Furthermore, an examination of water usage efficiency in Thailand revealed that it has fallen by more than 21% in recent years while the level of water stress has risen from 9.68% to 13.8% in numerous river basins (Theprasit *et al.*, 2025). This indicates greater pressure on the water system in the cultivation area.

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Cite this article as:

Kunlerd, A., Nabumroong, B., Vongvas, N., Lakonpol, T., Ruttanaprasert, R. and Burana, K. 2026. A Solar Powered Ultrasonic Water Level Monitoring System with IoT Type for Small-Scale Agricultural Water Management. *Recent Science and Technology* 18(2): e269459.

<https://doi.org/10.65411/rst.2026.269459>

Despite the importance of water management, remote areas continue to face structural and practical limitations. Limited personnel are available, while water sources are numerous and widely dispersed. This causes the impossibility of continuously and consistently monitoring water levels at all sources. Moreover, daily field visits are nearly impossible, leading to individual water users utilizing water as needed without coordinated planning. Furthermore, there is no centralized database that clearly reflects the water level situation in each area and how much water remains. These problems lead to unbalanced water usage, the risk of water shortages before the end of the growing season, and the possibility of inequitable in water distribution to various stakeholders. The previous research has attempted to apply IoT technology and information systems to support water management. It has been found that measurement accuracy and support for predictive analysis could be increased. However, most of the research still has been focused on development in the context of large-scale irrigation systems or industrial applications rather than community-level agricultural areas (Mu and Antwi-Afari, 2023). Moreover, some research showed that the utilization of IoT in conjunction with data analytics could actually improve water management, yet it was limited to the individual plot level and did not cover linking data from multiple water sources to a central system (Ngamsin *et al.*, 2024). Furthermore, research on flood monitoring systems using low-cost sensors has highlighted the potential of IoT technology in the field, but it has focused solely on warning of floods and has not evolved to support collaborative water allocation in agricultural areas (Choosumrong *et al.*, 2025). In addition to the work that applies IoT to directly measure water levels, several recent studies have applied GIS and remote sensing technologies to support water management, such as drought-risk area assessment, reservoir condition analysis, and spatial mapping (Kumar *et al.*, 2024; Rabie *et al.*, 2025). This offers an in-depth overview of the watershed, although the main limitation is that it is unable to evaluate water levels in minor community water sources in real time. It relies on satellite imagery with a relatively long data collection period, making it unsuitable for daily, local decision-making. Meanwhile, research is underway on the application of AI to forecast water levels or analyze risks (Azad *et al.*, 2025; Panta *et al.*, 2025). Despite its potential for in-depth data analysis, it relies on data from existing monitoring stations, causing it to be inapplicable to areas without basic water level monitoring systems. A review of research reveals that there is no multi-point water-level network that transmits data to a central server that is low-power and suitable for rural contexts where electricity and internet are lacking. Furthermore, there is no system that is able to be applied to support integrated, multi-source water management at the community level. Therefore, despite research demonstrating progress in the use of IoT and intelligent systems for water management, there has been no development of a prototype

multi-point water level monitoring network connected to a central system to serve as a centralized database for simultaneous water management from multiple water sources in rural areas. This is a key gap that this research aims to address and further develop.

To address the aforementioned issue, this research aims (1) to develop a prototype ultrasonic water level meter that is able to measure water levels without contact and transmit data via an IoT network to a central server in real time, with display results via a mobile phone application to enable users to monitor water level situations from multiple sources in the same system; and (2) to test the prototype's performance at both the laboratory and field levels. The 5 prototypes were installed in agricultural areas in the lower northeastern region to evaluate their accuracy, data transmission stability, and suitability for practical use. The resulting data had the potential to support community and local government decision-making, including collaborative water management across multiple water sources.

2. Materials and Methods

2.1 Population and samples

The population of this research was community-level agricultural water resource management personnel who were the target users of the prototype system. The sample consisted of 5 field officers from 5 provinces: Surin, Buriram, Sisaket, Roi Et, and Kalasin. The population was specifically selected based on the criteria that participants were required to be officers of agencies directly involved in water level monitoring, water resource management, and water management in the area, with more than 5 years of experience in this field to ensure that participants understood the actual working process and were able to evaluate the efficiency of the prototype system.

2.2 Design of research instruments

In this study, the research instruments were developed in two main parts: The first was the design and development of an ultrasonic sensor-based water level measuring device, and the second was the development of a usability assessment form for field officers. The details of the procedures are described as follows.

2.2.1 Design and development of an ultrasonic sensor based water level measuring device

This research referenced the embedded system design methodology (Marwedel, 2011) framework as the main framework for prototype development. However, some steps were modified and expanded to be consistent with the context of rural agricultural areas with limitations in communication signals, electricity, and variable field environments. Specifically, steps included the survey of actual site conditions, energy-oriented design for solar cell systems, adaptation of the architecture to support multiple networks, and testing of the

system under real weather conditions. Details of the process in each step are presented in the following subsections.

1) Determination of requirements: Field visits with local government officials revealed that one field officer was responsible for multiple agricultural water sources that were dispersed and far apart. This physical survey to obtain real-time water level data found its limitations of time, distance, and budget. This resulted in farmers lacking information on water usage situations without coordinating plans and being unaware of trends in water level decline, leading to problems of water running out before plants reach their full growth stage and inadequate water use. To address this issue, the system's functional requirements were defined as (1) continuously measuring water levels in the field by applying a non-contact method; (2) transmitting real-time or semi-real-time data to the cloud via a rurally accessible communication network (3G/4G); and 3) displaying and alerting via a mobile application to support operational decision-making by officials and water users.

2) Components of the system included a 40-watt solar panel and a 12V 15Ah battery for power and backup, a charging control system, and electrical protection circuits for enhanced safety, a voltage converter circuit to power the NodeMCU ESP8266 microcontroller, which served as the sensor processor and control unit, a 3G/4G router module for mobile network data communication, and an HC-SR04 ultrasonic sensor for non-contact water level measurement. According to the equipment specifications, the system had a total power consumption of approximately 3–4 watts in continuous operation, which was equivalent to approximately 72–96 Wh per day. A 40-watt solar panel can produce approximately 160–200 Wh per day under average sunlight conditions of 4–5 hours per day. A 12V 15Ah battery had an energy capacity of approximately 180 Wh, which, according to rough calculations, was able to support the system operation for approximately 36–48 hours in the absence of sunlight. This numerical analysis was implemented to support the selection of solar panel and battery sizes for rural applications.

3) Prototype development and functional testing: Once the system components were as specified, the entire device was assembled into a prototype water level meter, starting with the installation of an electrical circuit between the solar panels, charge controller, and battery to test its ability to supply continuous power. Afterwards, the voltage converter circuit was connected to the NodeMCU ESP8266 board and the HC-SR04 ultrasonic sensor to control the distance measurement and convert the value to water level. The circuit connection is shown in Figure 1. Programming was carried out with Arduino IDE by developing a set of commands for reading values from sensors. This showed the performance of preliminary processing and sending data via HTTP request to the Ubuntu server, which was installed to act as a cloud server, communicating via a 3G/4G router module to support work in areas without a LAN network

and displaying the results via mobile applications. The system architecture is shown in Figure 2.

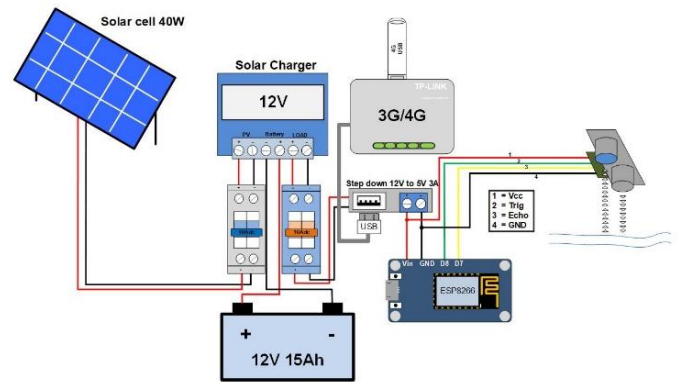


Figure 1 Circuit architecture.



Figure 2 Overall system architecture.

The system accuracy test was performed in a laboratory, which applied a 20-liter water tank with a water level scale marked on the tank wall in centimeters as a ground truth. The water level was then controlled by adding and releasing it in stages, with a level change range of every 5 centimeters, totaling at least 15 measurement points in each cycle. Afterwards, the experiment was repeated 3 times to obtain reliable values. After adding or releasing water at each water level point, a 10-15 second delay was set to allow the water surface to settle before recording the experimental equipment's readings. The system was set to read values continuously every 1 second for 30 seconds per water level. The acquired data was subsequently applied to generate an average value that represented the actual measured water level. The values read from the device were compared with the standard values from the water tank scale, and the error value was calculated according to Equation (1). This step was tested by 3 experts who have knowledge of embedded systems and data communication.

$$\text{Error (\%)} = \frac{|\text{Measured} - \text{Actual}|}{\text{Actual}} \times 100 \quad (1)$$

4) Improvement and validation: After the prototype passed laboratory testing, the water level meter was installed and tested in 5 provinces before being handed over to officials for field system readiness inspection. Following that, it was necessary to transfer knowledge and teach the field staff how to operate the machine in detail, which included checking the equipment's status, reading values through the application, and performing basic maintenance. The installation location map is displayed in Figure 3.

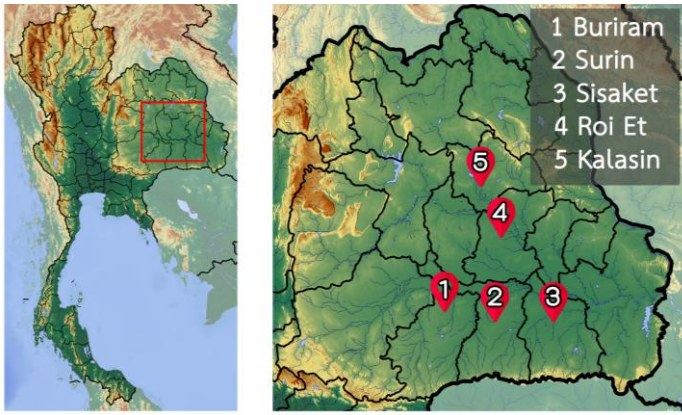


Figure 3 Water level sensor installation map.

2.2.2 Design and validation of the evaluation questionnaire for field officers: The test was designed to reflect the system's performance in terms of water level measurement accuracy, data transmission stability, ease of installation and usage, and suitability for usage in real field conditions. The test format applied field testing methodologies, defining specific test items such as calibration measurements, results presentation on applications, and continuous operation with solar power. The test results were recorded in a pass/fail format to avoid subjective evaluations and to obtain factual information about the system's operation. The test was reviewed by 3 experts in the field of computer technology with over 10 years of experience to check the content validity and appropriateness of the test items (IOC) before being used with field personnel.

2.3 Data collection

After the installation of the equipment, the performance was continuously monitored for a period of one month. The system was set to transmit water level data and timestamps to a central server at fixed intervals every day, while also recording the power system operation status and data transmission. Field personnel performed inspections 7 times a week. This test consisted of monitoring the actual water level at the water source, comparing the values with the data displayed on the application, verifying the solar panel power stability, and assessing the availability of equipment at each location. The evaluation variables included (1) the measured water level, (2) the data transmission status, and (3) the power system status. The evaluation criteria were established as the functional criteria of the system, including the continuity of data transmission, daily availability, and the accuracy of the values displayed on the system compared to field inspections. After the test period, 5 operators completed an online questionnaire to evaluate the ease of installation, usage, and suitability of the system in the actual field.

2.4 Data analysis

Data analysis was performed by utilizing descriptive statistics to summarize the test results from 5 field operators who continuously evaluated the prototype system 4 times (total

of 20 datasets) in quantitative terms by calculating the number of times the system could operate according to the criteria (frequency) and converting the results into percentage of success (percentage) in each evaluation item, which is calculated from Equation (2).

$$\text{Success Rate (\%)} = \frac{\text{Passed Tests}}{\text{Total Tests}} \times 100 \quad (2)$$

3. Results and Discussion

3.1 Laboratory test results for prototype water level meter

The accuracy results that are presented in this section are derived from the laboratory calibration process described in section 2.2.1, which involved testing the prototype in a controlled environment using a 20 L water tank with 15 water level measurement points and repeatable measurements for reliability. It found that the device was able to measure water level values close to the actual values from the standard scale, with an error value in the range of 0.2–4.0 % and an average error value of approximately 1.36 %. The experimental results indicated that the error tended to be higher at low water levels (e.g., 5 cm) and decreased with increasing water levels, with the error values being less than 2% at water levels of 20–50 cm, which was considered acceptable. The experimental results are shown in Table 1.

From Figure 4(a), the graph comparing the actual water level with the measured value indicates a clear linear relationship, where the measured value frequently remains near the reference line of the actual value almost throughout the measurement range. While Figure 4(b) demonstrates the percentage error plot at each point, it indicates the distribution pattern of error values, which, although they appear slightly higher during low water levels, when the water level increases, the error values become stable and remain low.

From the research results, it could be discussed that the accuracy of the developed ultrasonic water level meter reflected that the device was at a low average error value (approximately 1.36%), which was considered acceptable for prototype usage. Several worldwide studies pointed to the same tendency, notably in low-cost laboratory testing of devices with errors in the range of 1-5% (Ding *et al.*, 2025; Masoudimoghaddam *et al.*, 2024). It indicated that the developed instrument had performance consistent with academic standards. When considering the results at each point, it was found that the error tended to be higher at shallow water levels, especially in the range of 5 centimeters, where the maximum error value was up to 4%, which was a common result found in ultrasonic devices caused by entering the dead zone of the sensor and incomplete reflection of sound waves. This observation is consistent with the experimental results of Kim *et al.* (2024) and Pereira *et al.* (2022), who reported that the accuracy of ultrasonic measurements

decreased significantly when measurements were performed at low water levels. Furthermore, the research of Duangso *et al.* (2025) confirmed this observation by finding that the measurements in open channels increased errors in shallow water and intermittent flow. In terms of error-causing factors, it was possibly due to the variation of the speed of sound in air depending on temperature and humidity, which was possibly an important variable affecting the accuracy of the measurement,

including interference from air bubbles at the water surface and reflections from the walls of the water tank, which cause the signal to deviate from the true value (Yusupov *et al.*, 2023). In addition, the physical design of the device, including the sensor mounting angle, directly affected the quality of the wave reflection (Mydlarz *et al.*, 2024), requiring the use of multi-point calibration and temperature compensation to increase the stability of the measured values.

Table 1 Laboratory calibration and performance test results of the water level sensor.

Measurement Point	Actual Water Level (cm)	Measured Water Level (cm)	Error (cm)	Error (%)
1.	5	5.2	0.2	4.0
2.	10	9.8	-0.2	2.0
3.	15	15.3	0.3	2.0
4.	20	19.7	-0.3	1.5
5.	25	24.9	-0.1	0.4
6.	30	30.2	0.2	0.7
7.	35	35.5	0.5	1.4
8.	40	39.8	-0.2	0.5
9.	45	45.4	0.4	0.9
10.	50	50.1	0.1	0.2

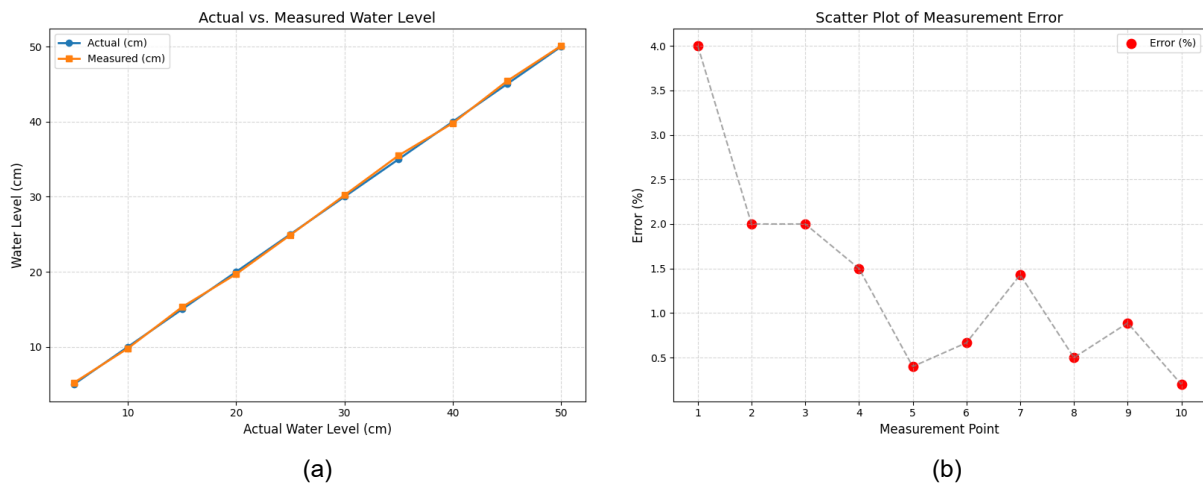


Figure 4 Laboratory calibration results: Actual vs. measured water levels.

In laboratory testing, the system was calibrated by comparing the readings to the actual values from a specified scale in a water tank as per the procedure in section 2.2.1, which gave an average error of 1.36%. However, the experiment was not designed to collect a large amount of data for generating a calibration curve or regression equation capable of reporting R^2 values and uncertainty analysis according to metric calibration standards. This research primarily focuses on evaluating the functional accuracy of the prototype at the laboratory and field level and thus applies the average of repeated measurements as a representative of the initial calibration results. This limitation is identified as part of the

research scope, and it is proposed to conduct metric calibration in future research in case a commercial system is developed.

Based on the experimental results and sensor characteristics, the overall measurement error was able to be explained through a factor analysis framework. It was found that changes in temperature and humidity, which affected the speed of sound waves in air, possibly caused errors in the range of approximately 0.1–0.3% according to the device specifications, while multipath reflections and sensor dead zones were important factors that increased the errors, especially in shallow water, which was consistent with the high errors found in the experiments. Water surface turbulence also causes instability in the reflected signal and may add additional errors. A sensor

mounting angle deviating from the perpendicular by 90 degrees caused the sound wave travel distance to be inaccurate and caused the measured value to deviate from the true value. All these factors were consistent with the average error of 1.36% found experimentally and were within the expected range for low-cost ultrasonic devices.

3.2 Field test results

Figure 5 shows the development results of a prototype water level meter installed in an agricultural area. The system consists of a solar panel for power supply and a control box containing a microcontroller circuit and a data communication module. It is linked to a mobile phone application to display the water level value in real time.



Figure 5 Field installation results.

The field test results with 5 agencies' personnel, 20 times per item (data recorded once per week for each person over a period of 1 month), found that the prototype water level meter was at an average success rate of 90.2%, with the most effective aspects being ease of installation and readiness of the device in real-world conditions, with a success rate of 95%. Subsequently, it was the accuracy of water level measurement compared to the water level pole with a success rate of 92.5%, while the continuity of data transmission and power durability was at an average success rate of 88.3%, indicating that the system effectively worked. The test details are shown in Table 2.

The field test results were able to be discussed, and the average success rate of 90.2% reflects the effectiveness of system design that focuses on suitability to the real context of agricultural areas. The ease of installation and practicality score of 100% is attributed to the design's simplified structure and modular approach, facilitating users to assemble and maintain. This is in line with the trend of developing field water measurement systems that focus on low-cost IoT and user-friendly design (James *et al.*, 2021). Meanwhile, the accuracy of water level measurement of 92.5% is explained by field calibration and design to reduce the interference of reflected signal by adjusting the installation angle to 90° to the water surface. This allows the sound wave reflection to be aligned with the receiver, which reduces the error from false echo, thus making the value obtained close to the measurement standard

(Gao *et al.*, 2021; Tawalbeh *et al.*, 2023). The data transmission continuity and power durability scores of 88.3% indicate limitations of relying on solar power during inclement weather conditions, especially on cloudy or rainy days. This finding is consistent with the report by Qian *et al.* (2023), who studied a wireless water quality monitoring system powered by solar panels and found that the intensity of the generated electrical energy depends on solar radiation. When sunlight decreases or during cloudy days, the system's performance declines, requiring the use of backup battery management to maintain continuous operation. However, the developed system could continue to operate with backup power, which is in line with technical proposals to increase the reliability of environmental IoT networks (Ajibola and Ogbolumani, 2024). Overall, the success of this field test is not solely due to the sensor's accuracy but also to the system's integrated design of power, communication, and ease of use.

In field tests, the system was configured to transmit data once a day to accommodate power constraints and signal instability in rural areas. This resulted in insufficiently detailed time-series logs for calculating network metrics such as RSSI, latency, and packet loss, or statistical values such as mean, standard deviation, and scatter. Evaluation of system stability and communication quality was therefore performed using functional performance checks, including daily transmission success, system availability, and events where the system was unable to transmit due to signal or power factors. This approach is consistent with the nature of IoT prototype testing in rural areas, which focuses on verifying real-world performance rather than collecting in-depth network statistics, which is in line with research by Zubaidah *et al.* (2025), where system evaluation also relied on functional indicators like transmission success and operational continuity rather than detailed network-level metrics.

Field testing results revealed that the main causes of data loss were both network and power factors. In rural areas, unstable mobile network signals led to intermittent dropouts and data packet loss. This is consistent with findings from field IoT research that indicated weak signals and limited telecommunications infrastructure were key factors in data loss in sensor systems. Additionally, during the rainy season, when rainfall lasted for up to 7 days, solar panel power generation dropped significantly to the point where it was insufficient to charge the batteries, causing the system to temporarily stop transmitting data before resuming operation when sufficient sunlight was available the next day. The data during this period were recorded based on observations between the research team and field personnel. This limitation highlights the requirement for more efficient energy management systems, such as applying high-capacity batteries or hybrid wind power systems, or adjusting the transmission interval based on remaining power levels, as well as increasing the number of cell

towers or using communication modules that support frequency bands suitable for rural areas, to enhance network stability and reduce future transmission losses.

Table 2 Field performance test results of the water level sensor (20 trials).

No	Evaluation Item	Pass (Times)	Fail (Times)	Success Rate (%)
Aspect 1: Accuracy of water level measurement				
1.	The system display corresponds to the staff gauge (error not exceeding ± 1 cm or $\pm 2\%$).	19	1	95.0
2.	Repeated measurements (3 times) yield similar results (standard deviation ≤ 0.5 cm).	18	2	90.0
Total		37	3	92.5
Aspect 2: Data transmission continuity and power durability				
3.	The system records data at least once daily for 30 consecutive days.	17	3	85.0
4.	The system records data $\geq 95\%$ of the total weekly time.	18	2	90.0
5.	No data gaps exceeding one day.	18	2	90
Total		53	7	88.3
Aspect 3: Power Durability				
6.	The system operates continuously every night (verified by morning data transmissions).	17	3	85.0
7.	The system maintains data transmission $\geq 90\%$ during consecutive cloudy or rainy days.	18	2	90.0
8.	The system operates for at least 24 hours without sunlight (e.g., during continuous rainfall).	18	2	90.0
Total		53	7	88.3
Aspect 4: Ease of installation and practicality				
9.	The device can be fully installed according to the manual within ≤ 60 minutes.	5	0	100.0
10.	The sensor head remains in proper condition with no obstructions or abnormal water disturbances during readings, verified weekly.	19	1	95.0
Total		24	1	96.0
All 10 Evaluation Items		167	18	90.2

4. Conclusion

This research successfully develops a prototype ultrasonic water level measurement system that combines solar power, non-contact measurement, and real-time data communication via an IoT infrastructure. The novelty of this work lies in the system's design to operate in a multi-point network, which has the ability to link water level data from multiple water sources to a central server simultaneously, even in rural areas lacking electrical infrastructure and stable internet signals. In addition, the system is also designed to be low-power and capable of continuous data transmission under remote agricultural conditions. Laboratory calibration and field sensor deployment verified the prototype's accuracy, achieving an accuracy of 92.5

percent. The system's IoT architecture enables continuous data transmission with an average success rate of 88.3 percent. From the installation of 5 prototype locations in the lower northeastern region, data from all locations was linked to a central system, creating a prototype water level data network for integrated water management at the community level. This network is usable to provide a real-time overview of water situations in multiple areas and support planning for water transfers between water sources when a particular area has insufficient water.

According to input from field users, the system promotes interagency collaboration, lessens the workload associated with field water level monitoring, and offers dependable daily data.

Users still point out issues with field equipment deterioration, though, and they demand the system be able to self-monitor and notify users when equipment malfunctions. This is an important direction for future development, including the application of artificial intelligence technology to analyze water level data, such as water level forecasting to assess water volume trends and shortage risks. The detection of abnormal signals in the devices and predictive energy management enable the system to adjust the operating mode, adjust the data transmission cycle, or increase the energy storage according to the sunlight and weather conditions. After the field test is completed, this research will be applied to a group of farmers in an agricultural area, and the implementation details will be presented in a future article.

5. Acknowledgments

This research project is supported by Thailand Science Research and Innovation (TSRI). Contract No. FRB650059/SRN/06.

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