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International Journal of
Electrical and Electronics Research (IJEER)
Case Study | Volume 12, Issue 4 | Pages 1407-1417 | e-ISSN: 2347-470X

An IoT Prototype for Water Quality Monitoring System with Case Study in NPIC Campus

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ABSTRACT- Water is one of the natural resources that may be found in the environment. It is the most essential element of life. All living things, including humans, depend on water to survive, as do other species. Regretfully, water contamination has become a significant worldwide issue because of industrialization and irresponsible consumption. Moreover, low-quality water is poisonous to entire ecosystems due to its hazardous chemical and microbial contents. The issue is made much more dangerous by the lack of accessible tools for monitoring water quality other than costly laboratory tests. In this study, we developed an integrated system to measure water quality using the Internet of Things. Among the sensors, the system makes use of are Turbidity, pH (potential of hydrogen), TDS (Total Dissolved Solids), and water temperature. The embedded system is involved in this project as well. It will help with the establishment of wireless data transmission and sensor device detection. We employed LoRa technology alongside a cellular network ensuring effective communication. Firebase was utilized as the backend platform to securely store and manage the sensor data. The information can be tracked *via* a mobile or online application. Based on the sensor data, the water environment's quality was assessed and problems with the water's quality were anticipated to prevent the spread of contamination.

Keywords: Internet of Things (IoT), Water Quality, Sensors, LoRa, Real-Time Data Transmission.

ARTICLE INFORMATION

Author(s): Seven Siren, Rothna Pec, Channareth Srun, Saran Meas, Virbora Ny, Sokheang Eang, and Puthiponareay Sari;

Received: 20/09/2024; **Accepted**: 06/11/2024; **Published**: 30/12/2024;
e-ISSN: 2347-470X;
Paper Id: IJEER 3009-30;
Citation: 10.37391/IJEER.120435
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-12/ijeer-120435.html

crossref member
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1. INTRODUCTION

Phnom Penh, the nation's capital, is now the focal point of all commercial and industrial activities as well as political, security, tourism, cultural heritage, and diplomatic centers [1]. The population density of this area quickly increased as individuals began to relocate from the provinces to the city to work [2], [3]. The Mekong River plays a crucial role in everyday life, especially for the people living in the city, ranging from daily-life consumption to general utilization such as cleaning, planting watering, and industrial usage [4]. Continuously assessing and analyzing the chemical and biological characteristics of water sources is important to evaluate the health of aquatic ecosystems and to ensure water safety for human consumption and other uses. For example, a crucial factor in the relationship between the terrestrial ecosystem and the land atmosphere is soil moisture, where high-quality soil moisture data collection is helpful for applications in scientific research or the creation of smart cities, such as weather forecasting, flood prediction, agricultural drought detection, precision agriculture, water resource management, and urban ecology [5], [6]. For daily usage and consumption, contaminated water poses a serious risk to the community and health because the water contains a variety of elements, including temperature, dissolved oxygen (DO), electrical conductivity, pH, and more [7]. The conventional approach to water quality monitoring is based on human intervention by collecting water samples from the field and conducting tests in the laboratories, which is difficult and impractical for measuring at multiple points, even though the sample data can be tested in the full range of physical, biological, and chemical parameters [8]. Another way for water-quality monitoring by probing various sensors is the use of offline and on-board data recording by a data logger that captures and stores data from the sensors for analysis and reporting. This technique also requires human intervention while retrieving the recorded data at the field. In addition, the results of laboratory-based tests involving multiple samples may not be obtained for several days, and the accuracy of certain parameters may be reduced due to sample water changes during the sampling process.

The IoT offers a revolutionary approach to overcoming the challenges associated with traditional water quality monitoring [9]. IoT systems employ a network of interconnected sensors strategically deployed in water bodies, enabling continuous data collection that is wirelessly transmitted to a central hub for real-time monitoring and analysis [10]. Currently, significant research findings have been achieved in the field of water quality monitoring that employs IoT and LoRa. As described in [11], the system facilitates remote data collection, storage, and dynamic monitoring through a network of multisensor nodes measuring parameters such as temperature, pH, turbidity, and conductivity. Data is transmitted via LoRaWAN technology to a gateway, which then converts the LoRa connection to an IP link and forwards the data to the Alibaba Cloud server. This configuration enables users to monitor and manage water quality in real-time through a specialized management platform. The system's signal reception strength within 2 Km remains above -81 dBm, and the average packet loss rate is only 0.94%. In [12], a LoRa-based IoT monitoring system was implemented in a carambola plantation in Indonesia. They achieved a reliable transmission range of 700 meters within the dense carambola forest, with an average system response time of 0.408 seconds. Other [13] proposes a smart monitoring system that integrates LoRa WAN technology with low-power wireless communication and IoT solutions. LoRa facilitates data transmission over distances of up to 30 miles, making it ideal for monitoring affected areas in Riau. The system employs sensors strategically positioned in regions previously impacted by fires to detect land and forest fires. Early detection is crucial for preventing more significant disasters. In [14], the system enables communication between an Android phone and a microprocessor (ESP32) through Wi-Fi at the transmitting end, where the ESP32 module interfaces with a LoRa module. At the receiving end, an additional ESP32 module is paired with another LoRa module that operates independently of Wi-Fi. The system was utilized to measure environmental temperature and humidity, detect fire, and control appliance switching. The results indicated a high level of effectiveness, achieving 90% accuracy in fire detection and 92.33% accuracy in switching functionality. Exploiting the IoT concept, this paper focuses on building a prototype for a water quality monitoring system with several sensors, a communication network, and software-enabled electronic devices, which allows users to visualize and exchange data with the sensing device in the field. The data can be periodically obtained with a predefined time interval configured by the user's demands [15].

The remainder of this paper is organized as follows: Section two describes the system architecture of the prototype, including the software interface, hardware, and software. Section three explains the deployment scenario on the NIPC (National Institute of Polytechnique of Cambodia) campus and the data collection results of the prototype. Section four provides the conclusion of the paper.

2. MATERIALS AND METHODS

The majority of research has been conducted recently on weather monitoring [16], [17]. The goal of this project is to use IoT technology to monitor water temperature, total dissolved solids, pH (hydrogen potential), and turbidity. IoT facilitates communication between people and technology [18]. Early on, RF, ZigBee, and Bluetooth were used to establish a wireless connection between the user and the system online. These technologies were found to have slow communication speeds and short communication ranges, though they could transfer a limited amount of data [19].

The system contains three important parts, such as the Main System, Data Integration & monitoring, and Nodes. In *figure 1*, it is the overall system block diagram. It includes a main system powered by AC and solar energy, featuring an RTC main controller and communication modules (Wi-Fi, LoRa, Cellular). Each node is equipped with an MCU, power board, and sensor interface to monitor temperature, pH, TDS, and turbidity, using LoRa for communication. The system's "Data Integration and Monitoring" component efficiently transmits sensor data to the main system, relays it through Cellular or Wi-Fi to the client interface, and utilizes Firebase for real-time data management and analysis.

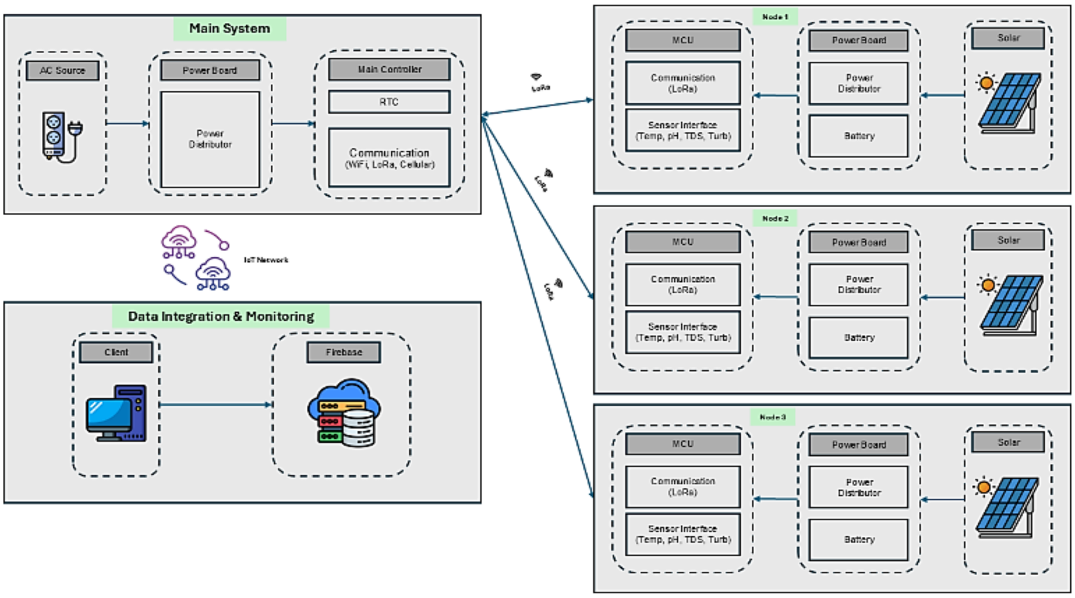

Figure 1. System Architecture of IoT-Prototyping System

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International Journal of
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Case Study | Volume 12, Issue 4 | Pages 1407-1417 | e-ISSN: 2347-470X

2.1. Node Design

The water quality monitoring nodes, situated in the sensing layer of the monitoring system, are strategically distributed throughout the target water area. Each node is assigned a unique ID and communicates with the gateway through various channels. The node design comprises four main components: the main control unit, water quality sensors, a power management module, and a LoRa RF. Among these, the main control unit and LoRa RF unit are the most essential. The main control unit is responsible for managing data collection from the water quality sensors, while the LoRa RF unit facilitates data transmission to the gateway.

2.1.1. Main Control Board

In the diagram for the main control board design, given the complexities of the water quality environment, multidimensional data is collected to enable a comprehensive analysis. This is accomplished using a combination of sensors: a pH sensor to measure acidity or alkalinity, a TDS sensor for assessing total dissolved solids (an indicative of water quality), a temperature sensor for monitoring the temperature of the liquid, and a turbidity sensor to gauge cloudiness or haziness (reflecting the presence of suspended particles) in the target water area.

The microcontroller used in this system is an Arduino Nano, built on the ATmega328 chip. This microcontroller is favored for its excellent balance of performance, power efficiency, and user-friendly programming capabilities. It is equipped with various peripheral interfaces, including UART, ADC, I2C, GPIO, and SPI, along with 32 kB of Flash memory and 2 kB of RAM [20], which are adequate for managing the sensors and the LoRa communication module. Additionally, its low power consumption makes it ideal for long-term monitoring applications. The microcontroller is responsible for data collection and processing, as well as for transmitting and receiving data packets via the RFM95 unit.

2.1.2. Water Quality Sensors

In this paper, four types of sensing parameters, including pH, turbidity, temperature, and TDS, are considered to measure the quality of water. The relationship between sensing parameters and the analog voltage used in firmware development and transmitted to the IoT platform is determined by a linear-interpolation equation with a corresponding slope value for each parameter. The linear-interpolation equation is given by $y = a_S x$, where y and x denote the sensing numeric value and analog input voltage in V, respectively. Here, a_S, the slope value in V^{-1} for each parameter (*i.e.*, $S \in \{pH, TDS\}$) is determined by

$$a_S = \frac{(y_1^S - y_0^S)}{x_1^S - x_0^S} \quad (1)$$

The initial values of y_1^S, y_0^S, x_1^S, and x_0^S used to calculate a_S is obtained from the technical specifications of each sensor [21], [22]. *Table 1* lists the computed slope values for sensing parameters.

Table 1. Slope Value for Sensing Parameters

Sensor (s)	y_1^S	y_0^S	x_1^S	x_0^S	a_S
pH	14	0	3	0	4.67
TDS	1000	0	2.3	0	434.78

For the pH sensor, the linear equation, $y = 4.67x$, is shown in *figure 2*. From this figure, the maximum range of analog voltage is from 0V to 3V resulting in a pH range between 0 to 14.

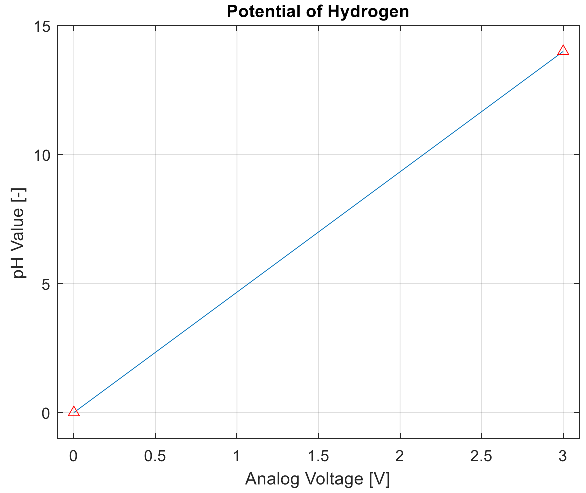

Figure 2. pH Model ranges between 0 to 14

Calibration of the sensors is crucial for ensuring data accuracy. The calibration process for the pH sensor involves preparing buffer solutions at pH 4.0, 7.0, and 10.0, which are verified using a high-precision meter. The sensor is rinsed with deionized water, dried, and then immersed in the pH 7.0 solution, allowing it to stabilize for 1–2 minutes. Once the reading is stable, the calibration is adjusted through the software interface to match the buffer's pH. This process is repeated for the pH 4.0 and 10.0 solutions to create a calibration curve, facilitating accurate linear interpolation. The sensor's accuracy is subsequently validated by testing it in solutions with known pH values. For TDS calibration, a standard NaCl solution of 1,000 ppm (mg/L) was prepared, representing a broad range of water quality levels. The sensor probe is rinsed with deionized water, dried, and immersed in the solution, allowing the reading to stabilize for 1–2 minutes. The Arduino software is then used to adjust the sensor output to the known TDS value. To improve accuracy, additional calibration points at 500 ppm and 1,500 ppm are included, ensuring reliable performance across varying TDS concentrations. For turbidity sensor calibration, a baseline for the sensor's raw readings is established first. The Arduino program reads the analog values from the turbidity sensor and displays them on the serial monitor. Calibration requires a water sample with a known turbidity value, starting with clear water—such as distilled or deionized water—which is assumed to have 0 NTU turbidity. This serves as the baseline. After recording the reading for clear water, turbidity solutions with known concentrations (*e.g.*, 10 NTU, 50 NTU, and 100 NTU) are prepared by adding specific substances to achieve the desired

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turbidity levels. For each solution, the sensor is allowed to stabilize before the analog reading is recorded from the serial monitor. The analog readings are then plotted on the x-axis of a graph, while the corresponding turbidity values (in NTU) are plotted on the *y-axis*. The relationship between the sensor's analog output and turbidity is generally linear, although this may vary depending on the specific setup and the characteristics of the water being tested.

$$\text{NTU} = m(\text{ADC\_READING}) + b \quad (2)$$

Where ***m*** is the slope, and ***b*** is the intercept.

2.1.3. Power Management at the Node

The system initiates with an MPPT (Maximum Power Point Tracking) solar charger, which efficiently optimizes energy capture from solar panels to charge a 3.7V battery [23]. This battery acts as the primary power source, supplying energy to a boost converter that elevates the voltage to the levels required by the connected components. Central to this configuration is the Arduino Nano, which receives power from the boost converter and distributes it to various sensors and modules [24]. The Arduino Nano supports two power branches: one delivers a regulated 5V to the sensors, while the other provides 3.3V to the LoRa Node. The LoRa Node is responsible for transmitting the collected sensor data over long distances, facilitating remote monitoring. This hierarchical power distribution ensures that each component operates within its specified voltage range, thereby enhancing the overall efficiency and reliability of the system. The power management framework for the Node is illustrated in *figure 3*.

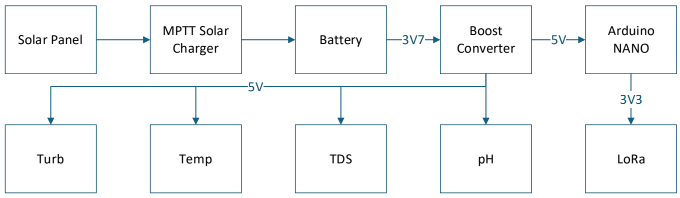

Figure 3. Power Management in Node

2.1.4. LoRa RF Unit

The LoRa RFM96 module, based on Semtech's SX1276 transceiver chip, represents the forefront of long-range communication technology, delivering exceptional range with minimal power consumption [25]. Its key features include adaptive data rate adjustment, which optimizes bandwidth utilization, and robust encryption algorithms that ensure secure data transmission. Despite advanced features, the module remains compact, ensuring versatility for integration across various applications. The LoRa RFM96 module is widely employed in industries such as smart agriculture, asset tracking, and wildlife conservation, enabling real-time monitoring and control over long distances. As the demand for effective long-range communication solutions grows, the LoRa RFM96 module continues to lead in innovation, enhancing connectivity in the IoT era [26].

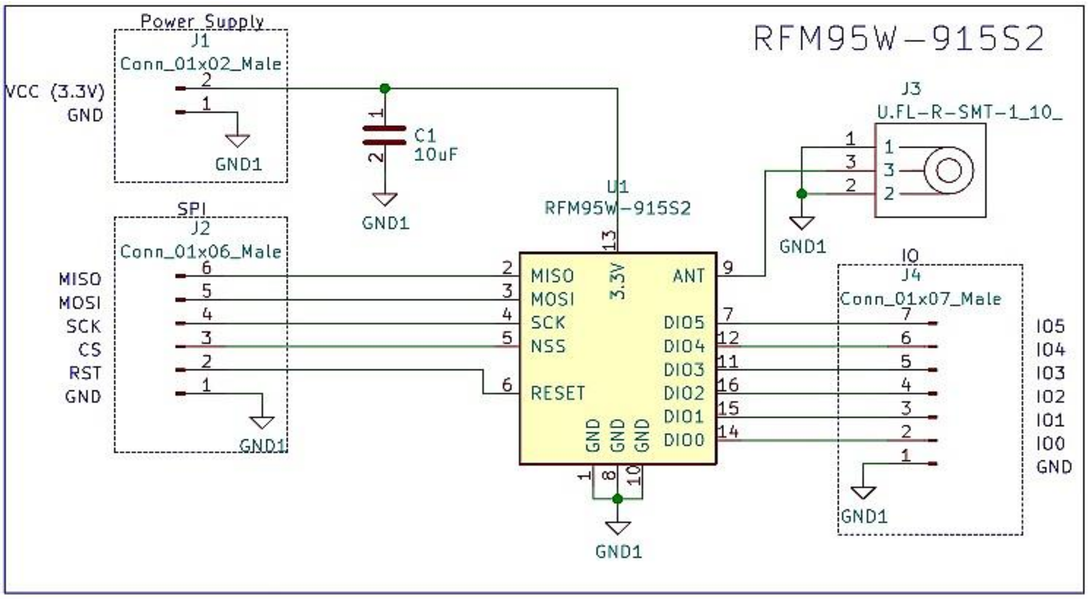

Figure 4. Schematic of RFM95 module

As shown in *figure 4*, the module is powered with 3.3V *via* a connector, with ground (GND) connected as well. A 10μF decoupling capacitor is used between VCC and GND to stabilize the power supply. SPI communication is established using four pins: MISO (Master-In-Slave-Out), MOSI (Master Out Slave In), SCK (Serial Clock), and NSS (Chip Select), connected to a dedicated connector. Additional pins include RESET for resetting the module and DIO0 to DIO3, which are general-purpose digital I/O pins used for control and status signals. These are connected to another connector. This setup is typical for connecting the RFM95W module with a microcontroller, utilizing SPI for communication and additional pins for control and status functions.

2.2. Gateway Design

The gateway functions as the central hub of the system, coordinating a comprehensive network of peripherals and modules to facilitate reliable data collection, processing, storage, display, and communication. The main system diagram is shown in *figure 5*. At its core, the ESP32 utilizes its built-in Wi-Fi and Bluetooth capabilities, while additional external modules enhance its overall functionality [27]. An SD card module provides ample local storage, ensuring that all sensor data—both raw and processed—is securely logged, even in the absence of network connectivity. This feature is crucial for applications that require historical data analysis or continuous monitoring without risk of data loss. Additionally, a Real-Time Clock (RTC) module, typically connected *via* I2C, guarantees precise timekeeping, enabling the ESP32 to accurately timestamp all data and maintain chronological integrity for time-sensitive applications. For real-time feedback and local monitoring, an OLED display, also interfaced via I2C, provides immediate visual updates of sensor readings, system status, and other vital information.

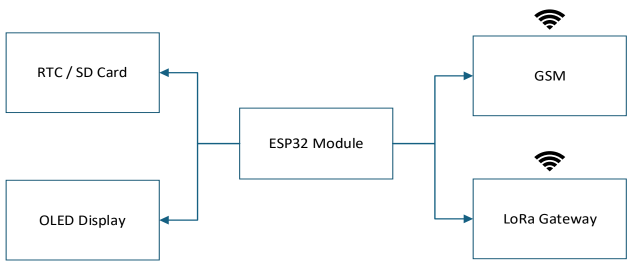

Figure 5. The Main System Block Diagram of Communication, Display Interface, and Data Storage

Communication is central to the versatility of this system, supported by multiple channels to ensure reliable connectivity. The GSM module plays a critical role in enabling long-range data transmission. It provides a reliable communication link between remote sensors and centralized servers, facilitating real-time access to water quality data. With its ability to operate over existing cellular networks, the GSM module ensures that data can be transmitted from even the most remote monitoring locations without the need for additional infrastructure [28]. The GSM module, connected through UART, facilitates cellular communication, allowing data transmission and command reception in remote locations lacking Wi-Fi infrastructure. This capability is essential for applications such as remote environmental monitoring or agriculture, where cellular coverage is often the primary connectivity option. Moreover, the LoRa Gateway introduces long-range, low-power wireless communication via UART or SPI, making it ideal for transmitting data across vast distances, particularly in rural or large deployment areas like smart agriculture and environmental monitoring. The ESP32 processes sensor data, displays it on the OLED screen, stores it on the SD card, and transmits it using the most suitable available channel—Wi-Fi or Cellular—ensuring that the data reaches a central server or cloud platform for further analysis.

The schematic is shown in *figure 6*. It integrated an RFM95W LoRa module into a system. The module is powered by connecting a 3.3V line to pin 15, with several GND pins (9, 10, 11, 12, 13) connected to the ground for proper grounding. For data communication, the SPI interface is utilized, where the Master-In-Slave-Out (MISO) is connected to pin 2, Master Out Slave In (MOSI) to pin 3, Serial Clock (SCK) to pin 5, and Slave Select (NSS) to pin 4. The reset function is managed via pin 6. The module also provides I/O connections available on DI00 through DI05, facilitating additional functionalities if needed. To stabilize the power supply, a 10uF capacitor is placed between the 3.3V line and the ground. This configuration enables the RFM95W module to operate efficiently for LoRa communication using the SPI protocol.

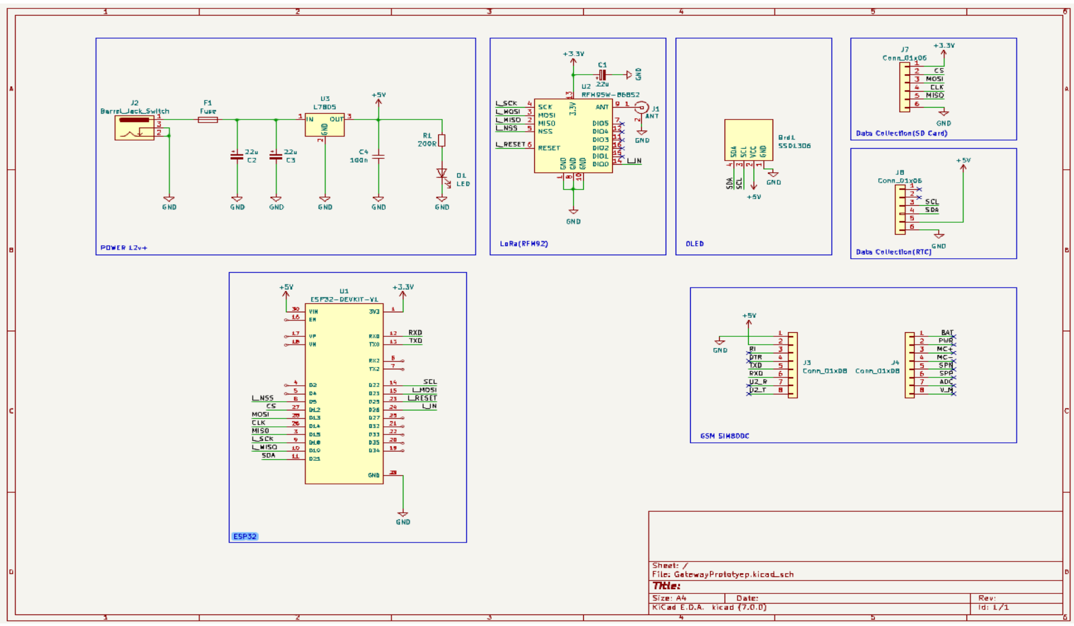

Figure 6. Schematic of Main System Design

International Journal of
Electrical and Electronics Research (IJEER)
Case Study | Volume 12, Issue 4 | Pages 1407-1417 | e-ISSN: 2347-470X

Power management in the main system is also a major concern. The 12V power supply powers the voltage regulator, which converts the 12V input to 5V and 3.3V output voltages. The 5V output powers the ESP32 microcontroller, the central component of the system responsible for managing all other components. An SD card is used to store data collected by the LoRa Gateway, while the real-time clock (RTC) ensures accurate timekeeping for time-stamping data. The 3.3V output powers the LoRa module (RFM96), enabling communication with other LoRa devices. If included, the OLED display provides real-time information such as current time, signal strength, and data usage, and the optional GSM module adds cellular connectivity for troubleshooting or as a backup when the LoRaWAN network is unavailable.

This power management system is designed to deliver efficient and reliable power to the main system. The voltage regulator ensures that each component receives the correct voltage, while the use of low-power components, like the ESP32 and RFM96 LoRa module, helps conserve battery life. Additionally, the system can be powered by various sources, such as a solar panel or battery, making it ideal for remote deployments. The power management framework for the Main System is illustrated in *figure 7*.

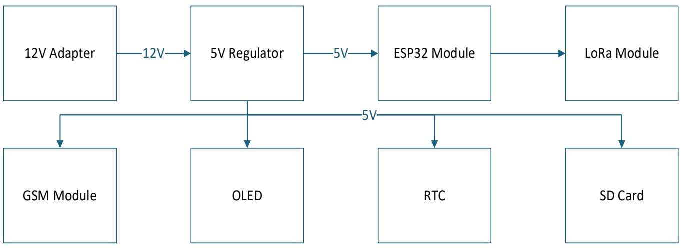

Figure 7. Power Management of Main System

2.3.Transport Layer Design

The transmission layer design of this system integrates the communication networking architecture with the LoRa gateway. This research utilizes a star networking architecture, as illustrated in *figure 8*. The Star network is acknowledged for its simplicity and low latency in data transmission [11]. Each LoRa node sends data from its sensors to the gateway every 10 seconds, enabling the gateway to receive real-time data from each node at this consistent interval. Importantly, LoRa gateways can be independently deployed without the need for reliance on third-party operators. In the context of the water quality monitoring system, the LoRa gateway acts as a central component of the star network, serving as a critical information exchange hub between data terminals and servers. The gateway connects to the cloud server via standard IP protocols, ensuring smooth data transfer. In addition, it supports several essential functions, including node access control, data packet analysis for node uploads, resource allocation and scheduling for uplink and downlink communications, encrypted user data transmission, and remote software upgrades.

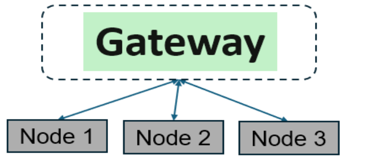

Figure 8. Three Nodes Communication with Gateway as a Star Network

2.4. System Interface

This research is developed on a web and mobile application platform that ensures seamless access for users across both computers and mobile devices. The system is designed for easy adoption, enabling users to effectively tackle various challenges related to water quality monitoring. The remote monitoring system at the application layer communicates with the cloud platform via the HTTP protocol, facilitating real-time data acquisition from underlying sensor networks. This architecture supports a range of functionalities, including real-time monitoring, equipment management, water quality alarms, and historical data analysis. As depicted in *figure 9*, it is a dashboard interface for water quality monitoring that features three nodes, each providing real-time readings for various parameters from the four sensors. It indicates the status of each node, showing whether readings are within normal ranges, and includes signal strength indicators to reflect wireless communication quality. Users can search for water quality data using node ID numbers or sensor names, enabling them to track real-time data collected by associated sensors. Additionally, the system visualizes historical data trends and includes an alarm feature that activates when a sensor's reading exceeds a threshold set by the administrator, triggering a notification that details the abnormal node ID and the specific parameter involved. This layout allows for easy tracking and assessment of water quality across different locations.

Figure 9. Dashboard Monitoring for Water Quality Monitoring

3. EXPERIMENT AND RESULT

3.1. Data Collection Experiment

To verify the accuracy of the data monitoring system, we conducted field tests at NPIC Lake, located at the National Polytechnic Institute of Cambodia. The lake encompasses an area of approximately 0.3 square kilometers and is home to a substantial population of egrets on the island situated at its center. This ecosystem serves multiple functions, including the collection of rainwater, support for aquaculture, and contribution to landscape ecology, thereby possessing significant value for water environmental protection. In *figure 10*, the actual node is displayed.

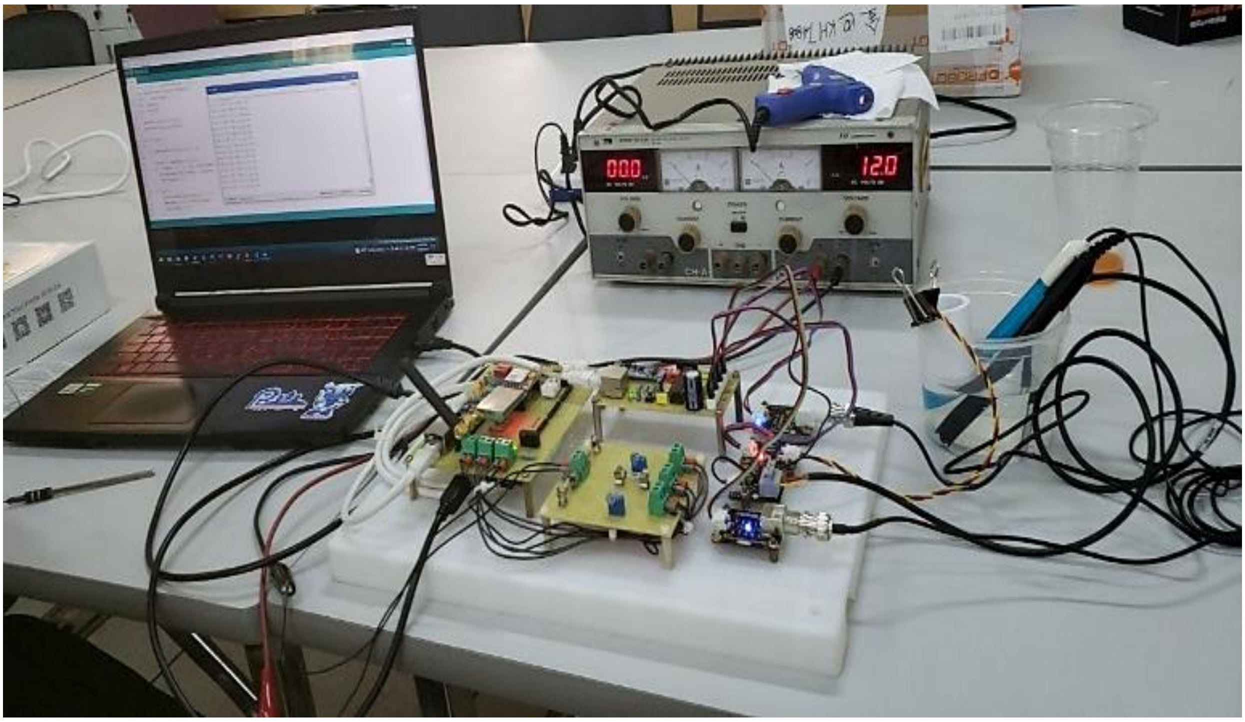

Figure 10. Physical diagram of Node Experiment

In the experiment, three monitoring nodes were strategically placed at various locations around NPIC Lake to collect real-time data on multiple water quality parameters, including pH, TDS, turbidity, and temperature. To assess the all-weather monitoring capability of our system under diverse meteorological conditions, measurements were recorded every minute during the rainy season, as well as at different times of the day—morning, noon, and night.

Table 2. Real-Time Water Quality Monitoring Data from Node 1

Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
pH	5.83	5.83	5.9	5.9	5.93	5.93	5.86	5.86	5.83	5.83
TDS	101.92	101.92	112.53	112.53	102.88	102.88	101.92	101.92	101.82	101.82
temp	28.49	28.5	28.44	28.49	28.5	28.44	28.49	28.5	28.5	28.5
turbidity	0.91	0.91	0.99	1.43	0.81	0.94	0.81	0.83	0.83	1.02

Although the precise location of the gateway on the campus is not disclosed, the accompanying diagram provides a detailed representation of the distances between each node and the central hub. As shown in *table 2*, it illustrates the data collection from Node 1. The pH levels range from 5.83 to 5.93, averaging approximately 5.87, indicating slightly acidic water with minimal variation, suggesting consistent acidity. TDS values vary from 101.82 to 112.53 mg/L, with an average of about 105.10 mg/L, reflecting moderate dissolved solids and showing more variability than pH. Temperature readings are consistent, ranging from 28.4°C to 28.5°C, with an average of approximately 28.5°C. Turbidity ranges from 0.91 to 1.02 NTU, averaging about 0.97 NTU, indicating relatively clear water.

Moreover, the data collection of all three nodes is shown in *figure 11*. The turbidity levels for three nodes are over multiple measurements. Each line represents a node: Node 1 (blue), Node 2 (orange), and Node 3 (green). The *x-axis* displays the measurement intervals, and the *y-axis* shows turbidity values. These visual highlights the differences and trends in turbidity across the nodes over time. All data collected by these nodes is transmitted to the central gateway, where it is stored on the gateway's memory card. This centralized data repository guarantees secure storage and immediate availability for analysis. The strategic positioning of these nodes enables researchers to systematically investigate the impact of distance on signal strength and data transmission efficiency within the LoRa network, ultimately informing future deployments and optimization strategies for similar monitoring systems.

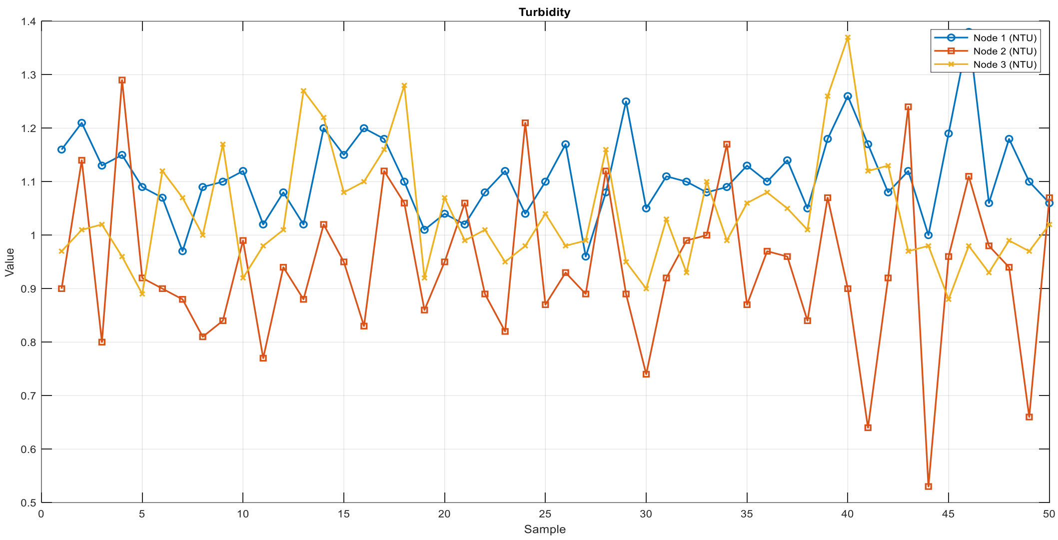

Figure 11. Historical data curve of remote monitoring of each Node

In comparison, the corresponding values from the handheld pH/ORP Model A8601 display slightly higher readings. The average pH from the node is approximately 5.84, while the A8601 averages around 6.05. As shown in *figure 12*, this indicates a systematic offset, with the node consistently recording lower pH values than the A8601. These differences highlight the importance of periodic calibration for the node's sensor to ensure its measurements align more closely with the established A8601 device. Overall, while the node demonstrates reliability, further calibration may enhance its accuracy in various applications.

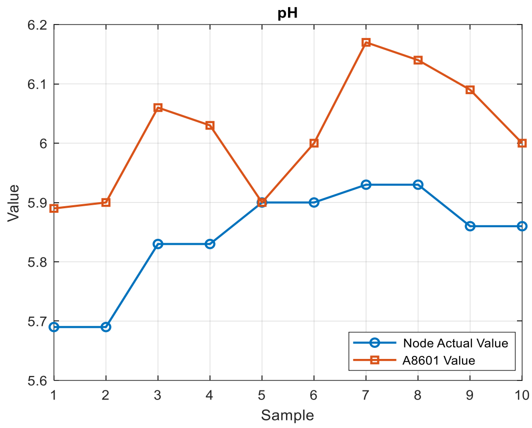

Figure 12. pH results compare with the A8601 handheld digital water pH meter

By analyzing the performance of the LoRa network in this real-world context, we can gain a deeper understanding of its capabilities and limitations. This insight is essential for enhancing the robustness and reliability of our water quality monitoring system. The distances from each node to the gateway are illustrated in *figure 13*, highlighting the varying transmission challenges and facilitating a comprehensive evaluation of the system's performance across different conditions.

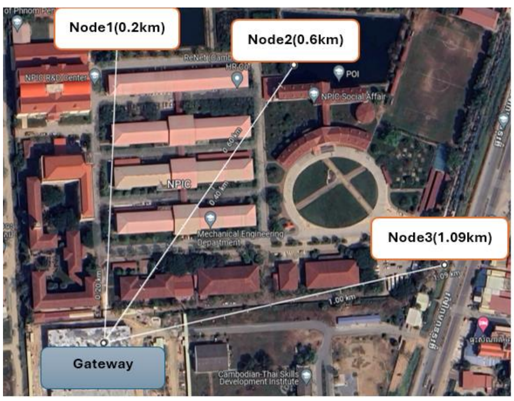

Figure 13. Distance of Each Node to Gateway Experiment

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3.2. Communication Quality Experiment

The communication framework of the LoRa (Long Range) network is meticulously designed to facilitate comprehensive water quality monitoring at NPIC Lake, incorporating multiple end-node devices strategically positioned at varying distances from a central LoRa gateway. Node 1 (Nx1), situated just 0.2 kilometers from the gateway, serves as the closest node responsible for real-time data collection on critical water quality parameters, including pH levels, dissolved oxygen, turbidity, and temperature. Its proximity ensures an exceptionally strong and stable connection to the gateway, allowing the system to leverage the LoRa technology's sensitivity of -70 dBm for reliable data transmission even under challenging environmental conditions. Node 2 (Nx2), located 0.6 kilometers from the gateway, mirrors the capabilities of Node 1 in data collection while operating at a slightly greater distance from the central hub. Despite this additional distance, Node 2 maintains robust communication with the gateway by utilizing the network's ability to optimize signal strength and transmission efficiency, thereby preserving data integrity. Node 3 (Nx3), positioned 1.09 kilometers away from the gateway, plays a pivotal role in assessing the LoRa network's long-range capabilities. Despite its distance from the central hub, Node 3 effectively demonstrates the network's resilience in transmitting data reliably, showcasing LoRa technology's capacity to overcome signal attenuation challenges while maintaining an effective sensitivity threshold of -82 dBm for accurate data reception.

The adherence to a sensitivity threshold of -82 dBm across all nodes ensures that even low-power signals are effectively detected and transmitted, enhancing the accuracy and reliability of the network in monitoring water quality parameters throughout NPIC Lake. This sensitivity standard is crucial for capturing subtle changes in environmental conditions and water quality metrics over time, thereby facilitating informed decision-making and proactive management strategies. The LoRa gateway functions as the central data aggregation point, consolidating information from all end-node devices before securely transmitting it to a central server for storage and analysis. This centralized approach enables comprehensive data collection and facilitates in-depth analysis of water quality trends, supporting researchers and environmentalists in monitoring the lake's ecological health and implementing targeted conservation measures as needed. By harnessing the capabilities of the LoRa network and maintaining stringent sensitivity standards across all nodes, stakeholders can gain valuable insights into the dynamics of NPIC Lake's ecosystem, promptly identify emerging environmental issues, and implement effective strategies to preserve and sustain the lake's ecological balance for future generations.

3.3. Sensors Value in User Interface

This project features a robust water quality monitoring system, meticulously designed to integrate advanced technologies with real-time data visualization for comprehensive water management. By utilizing both web and mobile application interfaces, the system ensures accessibility and usability for a diverse range of users, including researchers, environmentalists, local communities, and policymakers.

Figure 14. Real-Time Database in Firebase

At its core, the system collects essential water quality data from multiple nodes deployed across various water bodies. Firebase is integral to IoT water quality monitoring, offering real-time data synchronization and cloud storage [29]. Its real-time database ensures instant data updates from remote sensors, supporting timely monitoring and analysis. This enhances the system's efficiency and responsiveness, providing up-to-date insights into water quality metrics. This data is then transmitted to the Firebase Realtime Database, facilitating dynamic updates that reflect the current state of water quality. The user interface of the application is designed to be intuitive and user-friendly, featuring circular progress indicators for each water quality metric. These indicators offer a clear visual representation of the data, enabling users to evaluate the quality of water from each node swiftly. For instance, as illustrated in *figure 14,* the monitoring interface displays data from Node 1, displays data from Node 1, featuring key parameters such as temperature, pH, TDS, and turbidity. Users can easily switch between Node 1, Node 2, and Node 3 by clicking on each node, allowing for quick comparisons and assessments of water quality factors across different locations. Each data set includes a time stamp to indicate the date of the measurements, facilitating efficient real-time monitoring and analysis of water quality metrics.

3.4.Early Warning Alarm for Water Quality Monitoring

This paper primarily focuses on monitoring the water temperature, pH, conductivity, and turbidity of various water bodies. According to the water quality standards set by the Mekong River Commission (MRC) for landscape and recreational water, the water temperature should not exceed the average monthly temperature of the past decade by more than 4°C, the pH level must remain within the range of 6.5 to 8.5, and the turbidity of ornamental water bodies should not surpass 50 NTU [30]. Based on these standards and the average temperature in Cambodia over the past decade (approximately 25.1°C in November), this study establishes a threshold for water temperature in the node alarm program at below 20°C. The pH reference standard is set to be greater than 6 and less than 8.5, while the turbidity threshold is defined as less than 50 NTU.

Table 3. Average Response Time for Each Node

Item (threshold)	Test times	Node	Alarm response times	Average response time (s)
Temp(>20°C)	10	1	10	9.23
		2	10	9.46
		3	10	9.57
pH (pH<5.5 or pH>9)	10	1	10	9.23
		2	10	9.7
		3	10	9.40
Tur (>50 NTU)	10	1	10	9.6
		2	10	9.61
		3	10	9.21

The response speed and success rate of the system in issuing water pollution alarms are critical indicators of its reliability. To evaluate the response speed of the nodes to significant changes in water quality and the success rate of alarm notifications, human intervention was employed to alter the water quality parameters of the test solution. This involved conducting ten measurements across three groups of nodes and calculating the average response time for each group. The experimental results are presented in *table 3*, It indicates that when water quality parameters are artificially manipulated, the system effectively triggers alarms for abnormal water temperature, pH levels, and turbidity, successfully uploading this abnormal data to the equipment management platform. Notably, the alarm success rate across all nodes reached 100%, with a response time of under 10 seconds. These experimental results demonstrate that the system is sensitive to changes in water quality, providing managers with timely information to support the implementation of effective decontamination strategies.

4. CONCLUSION

In conclusion, the pressing challenge of water management requires careful analysis to prevent complications for both human populations and the environment. This study evaluated conventional water monitoring methods and identified significant drawbacks, including high costs and bulkiness. However, advancements on the Internet of Things (IoT) and low-power technologies have enabled effective monitoring solutions in aquatic environments. The system operates as a fully standalone unit powered by solar energy, requiring minimal maintenance.

The Water Monitoring System developed in this study offers continuous monitoring, real-time telemetry data transmission, and early warning notifications for water pollution. Experimental results demonstrate that the system achieves impressive accuracy: water temperature accuracy is ±0.14°C (relative error 0.31%), pH accuracy is ±0.08 (relative error 0.28%), TDS is ±0.04 mg/L (relative error 3.96%), and turbidity is ±0.49 NTU (relative error 0.71%). The system maintains a 100% communication success rate within 1.09 km, a packet loss rate under 10%, and a 100% alarm response rate with an average response time of less than 10 seconds.

These findings indicate that the proposed distributed water monitoring system provides accurate data, reliable transmission, and timely alerts—essential for effective water resource management. Future enhancements could include additional sensors for water level, rainfall, and air quality monitoring.

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