Implementation of Wireless Sensor Technology Based on LoRa for River Water Quality Monitoring System to Detect Water Pollution

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***Abstract*— River water pollution has become an increasingly serious environmental issue due to rising human activities such as the disposal of domestic, industrial, and agricultural waste. The impact of this pollution can damage aquatic ecosystems and pose health risks to humans. Therefore, an effective, efficient, and real-time water quality monitoring system is needed. This study aims to develop a water quality monitoring system using multiple sensors with communication based on LoRa (Long Range) technology. The system consists of a sensor node capable of measuring several key water quality parameters, namely pH, temperature, turbidity, and TDS (Total Dissolved Solids). The data obtained from the sensors is transmitted wirelessly to a zinc node connected to the internet, allowing real-time display on a website. In addition, the system is equipped with an automatic alert feature via WhatsApp when any water quality parameter exceeds a certain threshold. Tests were conducted on sensor accuracy, LoRa connectivity, and the overall water quality monitoring system. The results show that the system can accurately detect changes in water quality and provide timely warnings. This system is expected to support environmental conservation efforts by offering early warnings of potential river water pollution.**

***Keywords*— LoRa, River Pollution, Sensors, Water Quality, WhatsApp Notification.**

I. INTRODUCTION

Rivers are a vital water resource for human life and other living things. However, human activities in recent years have caused many rivers to become polluted. According to the Central Statistics Agency (2023), most rivers in Indonesia were polluted in 2022. Of the 111 rivers identified, only 8.1% met quality standards [1]. The main causes of river pollution are the discharge of industrial waste, household waste, agricultural waste, and mining activities. Other causes include waste disposal, transportation activities, natural changes, and the use of chemicals along rivers that are not in accordance with the river's carrying capacity [2].

One of the main challenges in overcoming water pollution is the lack of an adequate monitoring system. Manual water quality monitoring is often unable to provide fast and accurate data. River water pollution can come from various sources, including domestic, industrial, and agricultural waste [3]. River water pollution is defined as the entry of living things, substances, energy, and other components into the water resulting in a decrease in water quality to the point where it cannot function according to its intended purpose [4]. Therefore, continuous water quality monitoring is very important to detect and address pollution before it causes a greater impact. This monitoring is carried out to ensure that the water source is safe for consumption and can be used for human and animal needs [5]. Regulations made by the Minister of Health of the Republic of Indonesia No. 416 of 1990 have stipulated that good water quality for daily use regarding the parameters of pH, temperature, and water turbidity [6].

Previous research conducted by Trisiani Dewi Hendrawati, Nirfan Maulana, and Adnan Rafi Al Tahtawi in 2019 was a journal entitled "River Water Quality Monitoring System in Industrial Areas Based on WSN and IoT". With the results of testing the entire system carried out in four stages. The first stage is testing the pH electrode probe sensor, GE Turbidity, and Dallas DS18B20 with water that has been provided with a comparison tool. This is done to determine the difference in error values between the designed tool and the measuring tool. The second stage is testing the WSN network using the NRF24L01 radio frequency module between the base and the node using a star network topology. The third stage is testing the monitoring system integrated into the browser interface and storing sensor data in the database using ESP8266. The fourth stage is testing the implementation system of the designed tool by measuring river water quality (system implementation) to determine the overall performance of the designed tool [7].

In 2023, Nadia Wartiningrum, Dadan Nur Ramadan, and Indriani Dyah Irawati also conducted a study entitled "Implementation of a LoRa-Based Water Quality Monitoring System in Tilapia Ponds." With two test results, namely the sensor reading accuracy test and the data transfer speed test. Where the pH sensor test results were 1.82%, the turbidity sensor was 4.12%, and the temperature sensor was 0.459% so that it could be used to monitor pond water quality in Nganjat Village properly. The hardware design at the location has worked well with a design that adjusts to the water level, so that the sensor can still read water quality when the water is full or low [8].

Based on the problem of river water pollution, the Implementation of LoRa-Based Wireless Sensor Technology was developed in a Water Quality Monitoring System for River Water Pollution Detection. The use of multisensors whose communication utilizes LoRa technology allows sensors in certain locations to be wirelessly connected to each other for data collection and transmission to the monitoring center. Long Range for long-distance communication and uses relatively low power and is resistant to interference and minimizes current consumption [9]. In this study, water quality monitoring was carried out using a website that was connected to the river water pollution detection system. With this system, users or residents around the river environment can monitor water conditions remotely without having to visit the physical location [10]. The parameters used in this study were checking pH levels, temperature, water turbidity, and TDS (Total Dissolved Solids). Solar panels were also added to the design to be implemented, the use of solar panels saves maintenance costs and is flexible because it can be carried anywhere and only requires sunlight for its operation. This system provides benefits to the environment by enabling early detection of potential pollution, so that mitigation measures can be taken immediately to maintain a healthy aquatic ecosystem.

The water quality parameter threshold in the river water quality monitoring system in this study uses the Republic of Indonesia Health Government Regulation Number 32 of 2017 concerning Environmental Health Quality Standards and Water Health Requirements for Sanitation Hygiene Purposes, Swimming Pools, Solus Per Aqua and Public Baths as a reference. Water for sanitation hygiene purposes is used for maintaining personal hygiene such as bathing and brushing teeth, as well as for washing food ingredients, eating utensils, and clothes. The water quality threshold table according to the Republic of Indonesia Health Government Regulation Number 32 of 2017 [3], as stated in Table 1 as follows.

TABLE I
WATER QUALITY THRESHOLD

Parameter	Unit	Quality Standard (maximum content)
pH	mg/l	6.5 - 8.5
Temperature	°C	°C deviation$\pm$3
Turbidity	NTU	25
TDS	mg/l	1000

II. METHOD

A. System Block Diagram

In this study, the river is the object of research. This system is designed to monitor water quality by detecting parameters such as pH, temperature, water turbidity, and TDS (Total Dissolved Solids). The system is also equipped with the ability to provide notifications if the value of these parameters exceeds a predetermined threshold. The ESP32 microcontroller is used to process data from various installed sensors, while data communication is carried out using the LoRa SX1278 module to enable efficient long-distance data transmission. The use of multisensors whose communication utilizes LoRa technology was chosen because it is power efficient, wide range, and data efficiency, making it suitable for monitoring water quality in remote locations with real-time access.

Figure 1 shows a general system block diagram of the "Water Quality Monitoring System for River Water Pollution Detection", as follows.

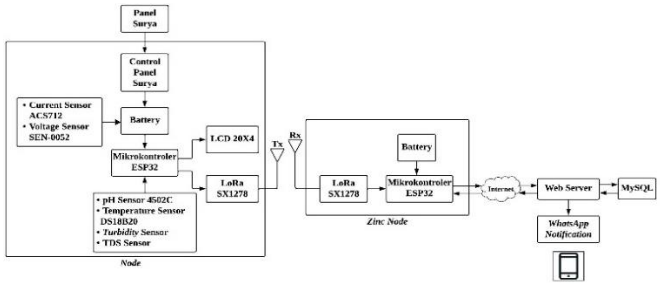

Figure 1. System Block Diagram

B. System Flowchart

The following is the overall system flow diagram shown in Figure 2 below.

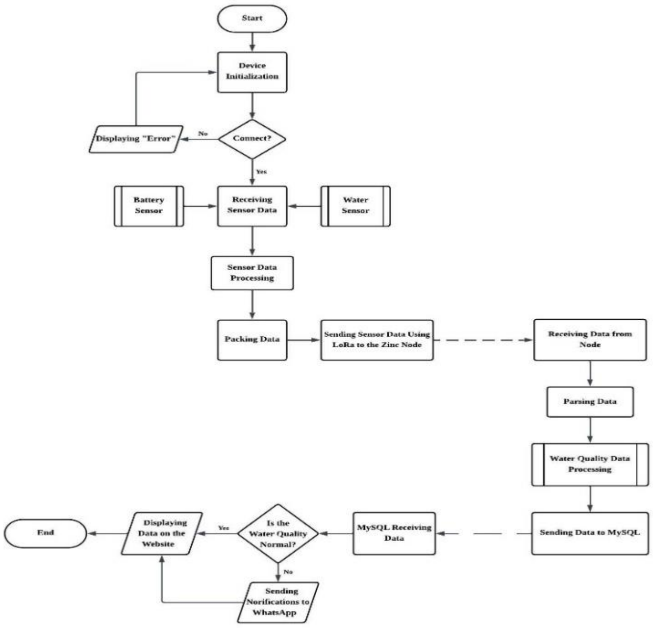

Figure 2. Overall System Flowchart

Based on Figure 2 which explains the overall system flow diagram, the description for each block is as follows:

1. The water quality monitoring system begins when the device is turned on or restarted. This is the initial step that triggers the entire automated monitoring process, which will be carried out by a microcontroller-based system such as the ESP32.
2. Initialization of the microcontroller device or system begins to ensure the device is ready for operation. The system will check for any errors during initiation, such as sensor failures or network errors, and then display them on the LCD.
3. The system takes readings from two types of sensors, there is a battery sensor and also a water sensor consisting of several sensors to measure water quality parameters such as pH, temperature, turbidity, and TDS.

4. Data from all connected sensors is collected and received by the microcontroller as input for further processing.
5. The processed data is packaged into a string format so that it can be sent over the LoRa network.
6. The packed data is sent via LoRa (Long Range) wireless communication from the measuring node to the Zinc Node as the receiver.
7. On the receiving end (Zinc Node or Gateway), data sent by the measuring node is received for further processing. This gateway is connected to a backend system (server or database).
8. After the data is separated, the system will analyze the water quality based on the predetermined normal threshold.
9. The processed data is then sent and stored in a MySQL database.
10. The system will evaluate whether the measured water parameters are still within the range considered safe.
11. If the water doesn't meet quality standards, the system automatically sends a notification message to the user's WhatsApp (usually via the WhatsApp API). This notification contains parameter data and a warning for further action.
12. All data that is successfully collected, whether normal or not, will be displayed on the website dashboard.
13. One cycle of the monitoring process is complete.

C. *Water Quality Parameter Thresholds in the System*

In the designed water quality monitoring system, the threshold for each sensor parameter is adjusted based on practical needs in the field and the Indonesian Government Regulation on Health Number 32 of 2017 as a reference. Specifically for the temperature and TDS parameters, adjustments were made because rivers in tropical regions such as Indonesia naturally have temperatures ranging from 20°C to 30°C and dissolved solids (TDS) content that varies depending on soil minerals and activities around the river. Temperatures above 30°C can negatively impact the balance of the aquatic ecosystem, while TDS in the range of 300–500 mg/L is still considered normal for natural waters but can still be an early indicator of pollution from agricultural or domestic waste. These adjustments were made to make the system more adaptive to local environmental conditions and able to provide relevant warnings. The water quality thresholds in this adjusted system are listed in Table 2.

TABLE II
THRESHOLD LIMITS OF WATER QUALITY PARAMETERS IN THE SYSTEM

Parameter	Sensor Type	Usefulness	Normal Threshold
pH	pH Sensor	Measuring the acidity/alkalinity of water.	6.5 - 8.5
Temperature	Temperature Sensor	Measuring water temperature to monitor ecosystem changes.	20°C - 30°C
Turbidity	Turbidity Sensor	Measures the amount of suspended particles in water.	< 25 NTU
TDS	TDS Sensor	Measuring the concentration of dissolved substances in water.	300 - 500 mg/L

D. *Hardware System Design*

The design of the tool that will be implemented for the water quality monitoring system and river water pollution detection is shown in Figures 3, 4 and 5.

Figure 3. Overall Tool

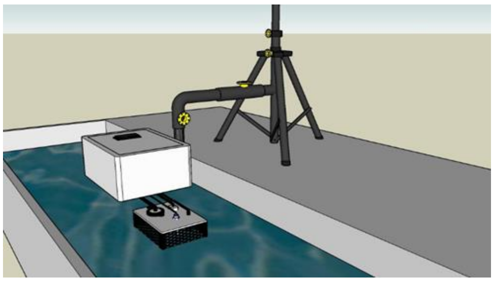

Figure 4. Side View of the Tool

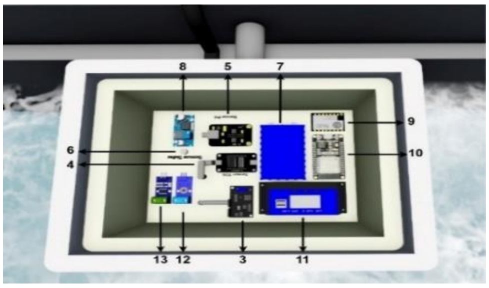

Figure 5. Top View of the Box

The location of the components in the box according to Figure 5 is shown in Table 3.

TABLE III
COMPONENT LOCATION

No.	Component
1.	Turbidity Sensor
2.	TDS Sensor
3.	pH Sensor 4502C
4.	DS18B20 Temperature Sensor
5.	LiFePO4 Battery BMS
6.	*Step Down*LM2596
7.	LoRa SX1278
8.	ESP32 microcontroller
9.	*Control*Solar Panels
10.	ACS712 Current Sensor
11.	SEN0052 Voltage Sensor

There is electronic design in the system which is done by creating a schematic for each component so that it becomes one in the Tx and Rx system. The schematic design was made using Fritzing and draw.io software. The following is a series of systems used in this research which are shown in Figure 6 and Figure 7.

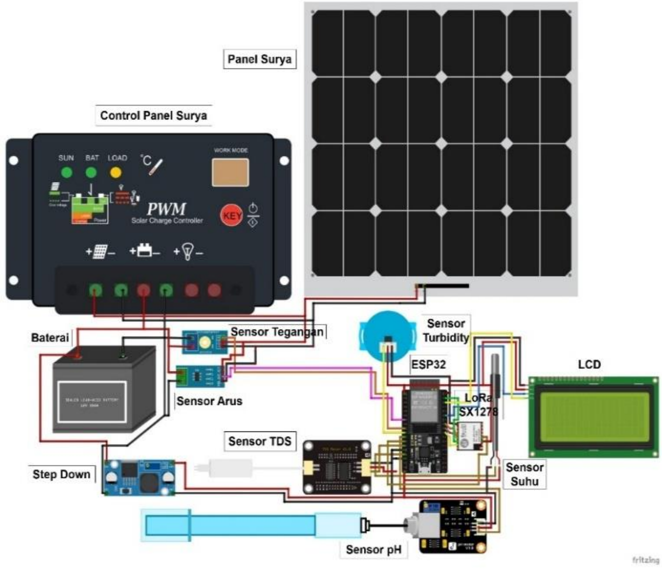

Figure 6. System Electronic Circuit in Tx

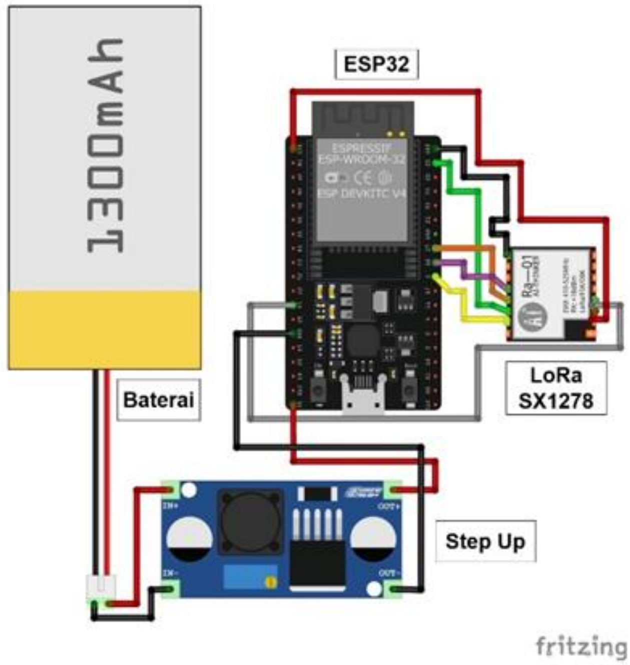

Figure 7. System Electronic Circuit on Rx

E. Software System Design

The website used in this study displays data from pH, temperature, water turbidity, and TDS (Total Dissolved Solids) sensor readings. Users can view real-time changes in water quality parameters on the website, along with graphs of sensor readings, and battery voltage and current. The website layout after logging in is shown in Figure 8 below.

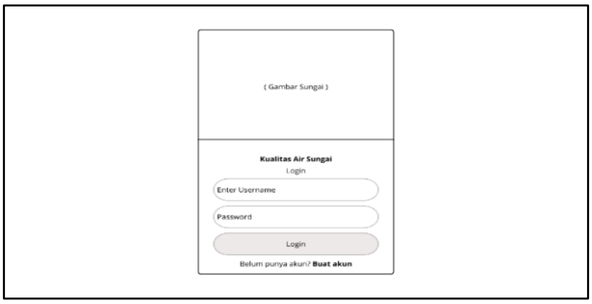

Figure 8. Login Page View

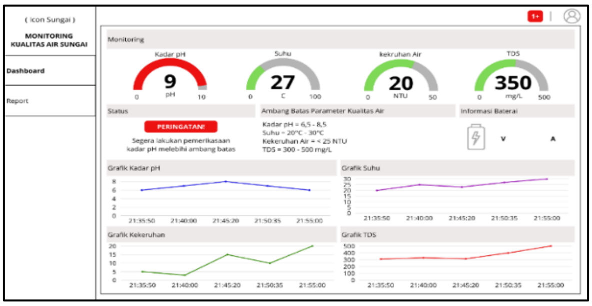

Figure 9. Dashboard Page View

Figure 9 is a website layout on the dashboard page that can monitor four water quality parameters, namely pH value, temperature, water turbidity, and TDS (Total Dissolved Solids).

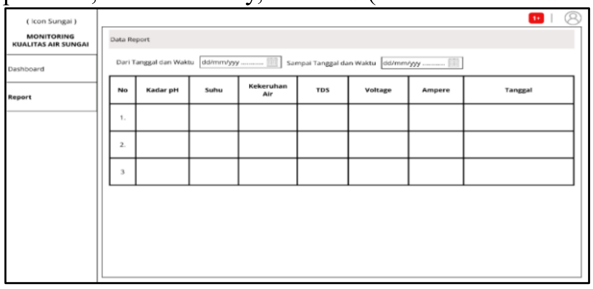

Figure 10. Report Page View

Figure 10 shows the website layout on the report page. The report page displays complete data stored by time. The data on the report page can be used to view measurement history, perform analysis, or review water conditions from previous periods.

WhatsApp notifications will also be sent, containing real-time water quality parameter values exceeding thresholds, so users can take immediate action. A screenshot of the WhatsApp notification is shown in Figure 11 below.

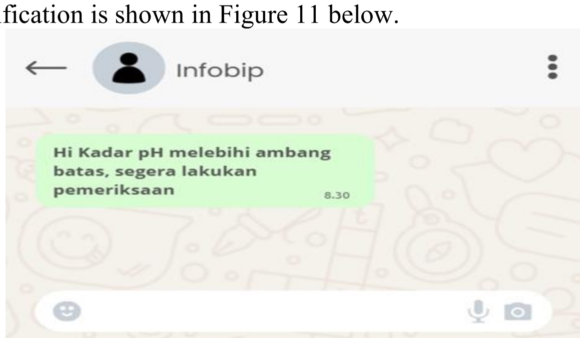

Figure 11. WhatsApp Notification Display

III. RESULTS AND DISCUSSION

A. Hardware System Implementation

The result of hardware implementation is a comprehensive series of components in accordance with the plans that have been designed. In this system there is a series of Nodes as Tx (transmitter) which have been designed as shown in Figure 12, Figure 13 and Figure 14 as follows.

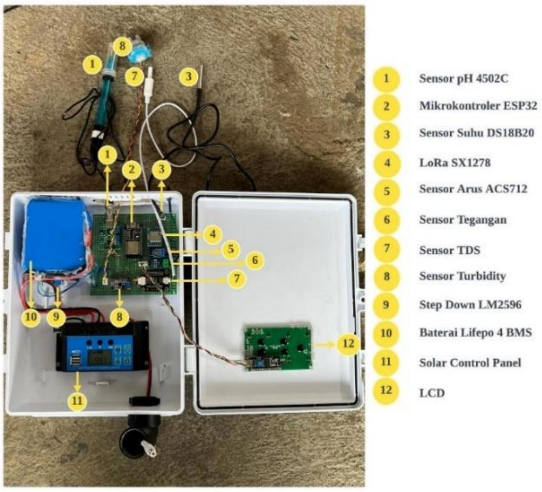

Figure 12. Front View of the Tx System Box Result

Figure 13. Side View of the Tx System Box Result

Figure 14. Result of the Tx System Box External View

The results of the Tx system box are shown from the side, showing the LoRa antenna and holes for the sensors to exit into the water surface, and on the outside, an LCD is visible to display the sensor values.

There is also a Zinc node as an Rx (receiver) that has been designed which is shown in Figure 15, Figure 16 and Figure 17 as follows.

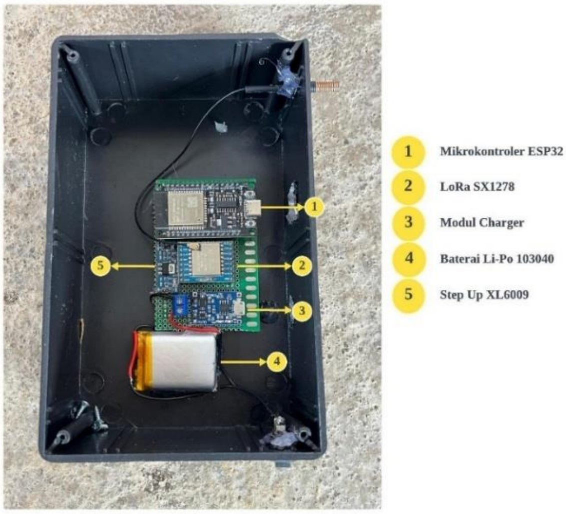

Figure 15. Top View of the Rx System Box Results

Figure 16. Top View of the Rx System Box Results

Figure 17. Side View of the Rx System Box Results

The results of the Rx system box can be seen from the top, showing the switch to activate and deactivate the Rx system and from the side you can see the LoRa antenna, a large hole for the USB cable to the ESP32 and a small hole for the USB cable to the battery charger module.

B. Software System Implementation

The results of the Rx system box can be seen from the top, showing the switch to activate and deactivate the Rx system and from the side you can see the LoRa antenna, a large hole for the USB cable to the ESP32 and a small hole for the USB cable to the battery charger module.

The software implementation resulted in a website that allows users and residents living near the river to remotely monitor water conditions without having to physically visit the site. The website's results are as follows:

1. Login page

   Figure 18 shows the website's login screen. This website has two user types: Admin and Viewer. Admin users have full access to the dashboard and report pages, and will automatically receive notifications via WhatsApp when changes in water quality parameters exceed the threshold. Admins can log in by entering the username "admin" and password "admin."

   Users as Viewers only have access to view the dashboard page and need to register an account first before being able to log in to the website by creating their own username and password.

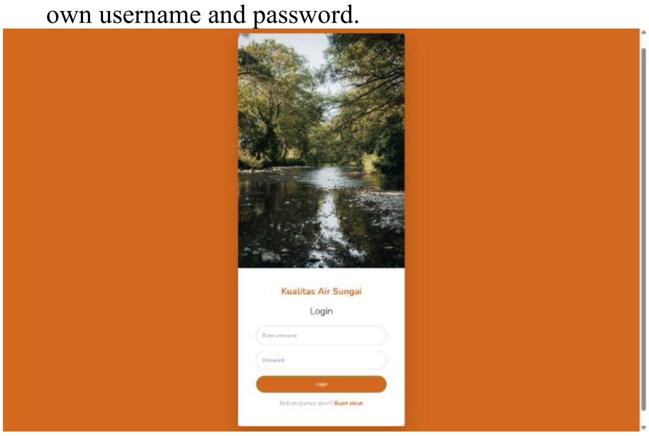

Figure 18. Login Page Display Results

2. Dashboard Page

   Figures 19 and 20 show the website's dashboard display. This page displays the pH, temperature, water turbidity, and TDS (Total Dissolved Solids) sensor readings for user monitoring. Users can also view graphs of the pH, temperature, water turbidity, and TDS (Total Dissolved Solids) sensor readings.

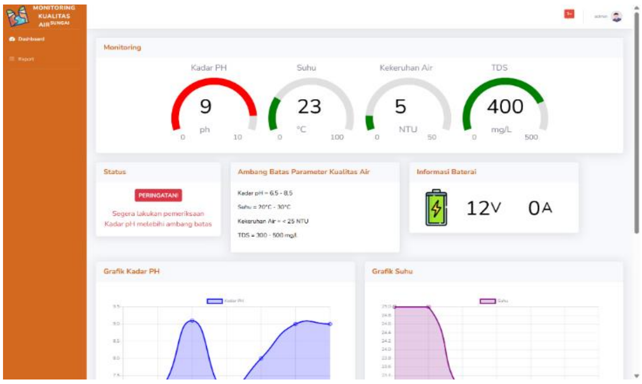

Figure 19. Dashboard Page Display Results

Figure 20. Graphic Display on the Dashboard Page

There is a status of the sensor reading, if the sensor reading exceeds the threshold, it will say "Warning" and the display will be red as shown in Figure 21. Meanwhile, if the sensor reading is in the normal range, it will say "normal" and the display will be green as shown in Figure 22. Information regarding the threshold of water quality parameters and battery information will also appear on this dashboard page.

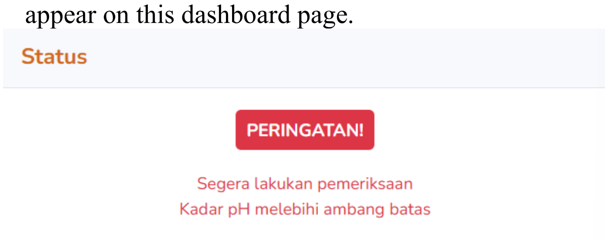

Figure 21. Warning Status Display

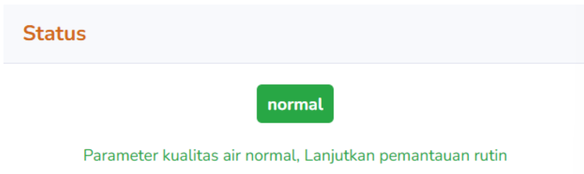

Figure 22. Normal Status Display

The dashboard page also displays notifications regarding water quality parameters that exceed the threshold shown in Figure 23.

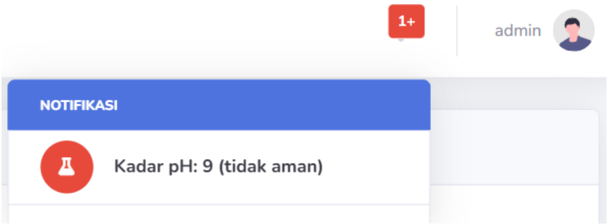

Figure 23. Notification Display on the Dashboard Page

3. Report Page
   Figure 24 shows the website's display on the report page. At the top of the page, there is a time range selection feature with two input columns: "From Date and Time" and "To Date and Time," which allow users to filter data based on a specific period. Below it, there is a table displaying the monitored parameters: pH, temperature, water turbidity, TDS (Total Dissolved Solids), as well as information regarding the system's voltage and current (amperage), complete with the data recording time.

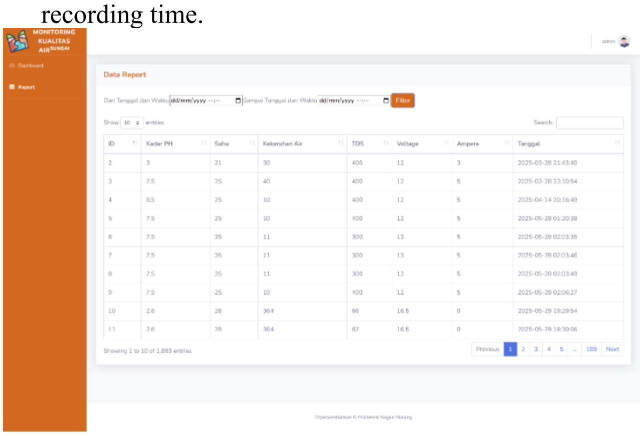

Figure 24. Report Page Display Results

This website is also connected to the user's Whatsapp which sends warning notifications if the water quality parameters exceed the thresholds shown in Figure 25.

Figure 25. WhatsApp Notification Results

Notifications sent via WhatsApp messages are automatically received only by users acting as Admins whose phone numbers have been previously registered in the system. This setting aims to ensure that information related to water quality parameters, such as pH levels, temperature, water turbidity, and TDS (Total Dissolved Solids) is received exclusively by Admins. In addition, each notification message is also equipped with a link http://147.139.172.97/iot_kualitasair/index.php to the monitoring page that can be accessed directly by Admins to check conditions in real time and take necessary actions quickly and accurately.

C. *LoRa Connectivity Testing*

The LoRa communication testing method was carried out using a distance and signal stability testing approach. The sensor node was configured to periodically transmit water quality data using the LoRa SX1278 module with a spread factor of 7 and a bandwidth of 125 kHz. Testing was conducted at several points with varying distances (5 m to 50 m). RSSI values were recorded to assess effective range and signal quality.

The connectivity testing process of the SX1278 LoRa module as a wireless communication medium between the sender (Tx) and receiver (Rx). Testing is carried out to ensure that data can be sent and received properly without interference. The location of the LoRa connectivity test is shown in Figure 26.

Figure 26. LoRa Connectivity Testing Location

Figure 26 shows the location of the LoRa connectivity test conducted on Jl. Sasando, Telasih, Kepuharjo, Karangploso District, Malang Regency. The starting point of the test was calculated at 0 meters to 50 meters from the starting point where the Tx was located. The RSSI value can be seen on the Rx device serial monitor as shown in Figure 27. From the test results, there are differences in RSSI values at each predetermined distance as listed in Table 4.


```
Received packet: ' with RSSI -114
Received message: WQ#128|PH:4.0|TEMP:25.7|TURB:100.0|TDS:0|VOLT:9.9|CURR:0.13|WARN:pH:4.0 OUT_OF_RANGE;TURB:100.0 TOO_HIGH;TDS:0 OUT_OF_RANGE;
Parsed values:
Packet ID: 128
pH: 4.00
Temperature: 25.70
Turbidity: 100.00
TDS: 0
Voltage: 9.90
Current: 0.13
Warnings: pH:4.0 OUT_OF_RANGE;TURB:100.0 TOO_HIGH;TDS:0 OUT_OF_RANGE;
Sending data to API: http://147.139.172.97/iot_kualitasair/kirimdata.php?kadarPH=4.00&suhu=25.70&kekeruhanAir=100.00&TDS=0&voltage=9.90&ampere=0.13
HTTP Response code: 200
Response:
```

Figure 27. Serial Monitor Data LoRa test results at a distance of 40 meters

TABLE IV
LORA CONNECTIVITY TESTING FOR DATA TRANSMISSION FROM TX TO RX

No.	Spread Factor	Bandwidth	Distance	RSSI value	Average
1.	7	125 kHz	5 meters	-54 dBm -56 dBm -59 dBm -63 dBm -66 dBm	-59.6

RSSI value (dBm)

No.	Spread Factor	Bandwidth	Distance	RSSI value	Average
2.			10 meters	-70 dBm -72 dBm -74 dBm -75 dBm -76 dBm	-73.4
3.			20 meters	-101 dBm -104 dBm -105 dBm -105 dBm -106 dBm	-104.2
4.			30 meters	-107 dBm -107 dBm -109 dBm -111 dBm -113 dBm	-109.4
5.			40 meters	-114 dBm -115 dBm -117dBm -119dBm -120dBm	-117
6.			50 meters	-120 dBm -122 dBm -122 dBm -123 dBm -124 dBm	-122.2

The difference in RSSI values at each distance can be presented in graphical form in Figure 28.

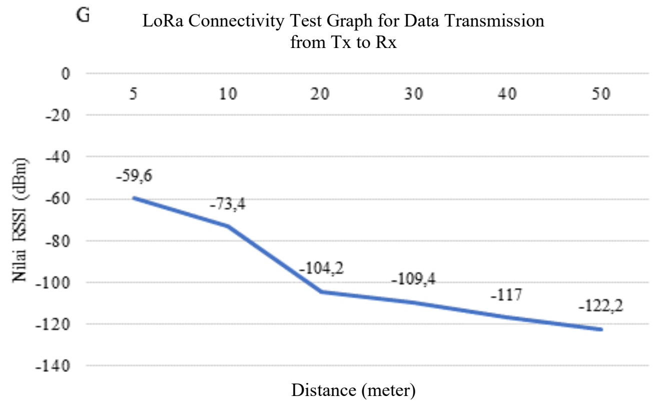

Figure 28. LoRa Connectivity Test Graph for Data Transmission from Tx to Rx

D. Overall System Testing

Overall system testing is carried out to ensure that all components, both hardware and software, are able to operate in an integrated manner and carry out their functions according to the specifications and objectives of the system that have been previously designed.

This test was conducted twice daily, in the morning and afternoon, to collect water quality samples for river pollution detection, with each session lasting 15 minutes. This time was chosen to obtain a snapshot of water conditions at two different times, considering that water quality can change depending on environmental activity and weather conditions. This allowed the system to be tested in two different situations to determine the stability and accuracy of sensor readings. The overall system test is shown in Figure 29.

Figure 29. Overall System Testing

The results of the overall system testing in the morning and afternoon are shown in Table 5 and Table 6 as follows.

TABLE V
RESULTS OF THE ENTIRE SYSTEM TESTING IN THE MORNING

No	Waktu	pH	Suhu (°C)	Kekeruhan air (NTU)	TDS (mg/L)	Status Kualitas Air	Data Tampil di *Website*	Notifikasi *WhatsApp* terkirim
1.	08.36.50	9.1	23	5	235	pH dan TDS melebihi ambang batas	Ya	Ya
2.	08.39.40	8.4	23	5	235	pH dan TDS melebihi ambang batas	Ya	Ya
3.	08.42.54	8.7	23	5	236	pH dan TDS melebihi ambang batas	Ya	Ya
4.	08.45.50	8.6	23	6	235	pH dan TDS melebihi ambang batas	Ya	Ya
5.	08.48.53	8.7	23	6	236	pH dan TDS melebihi ambang batas	Ya	Ya

TABLE VI
RESULTS OF THE ENTIRE SYSTEM TESTING DURING THE DAY

No	Waktu	pH	Suhu (°C)	Kekeruhan air (NTU)	TDS (mg/L)	Status Kualitas Air	Data Tampil di *Website*	Notifikasi *WhatsApp* terkirim
1.	11.55.35	9	25	5	239	pH dan TDS melebihi ambang batas	Ya	Ya
2.	11.58.12	8.9	25	5	243	pH dan TDS melebihi ambang batas	Ya	Ya
3.	12.01.54	8.9	25	6	247	pH dan TDS melebihi ambang batas	Ya	Ya
4.	12.04.50	9	25	6	242	pH dan TDS melebihi ambang batas	Ya	Ya
5.	12.07.33	9.3	25	5	246	pH dan TDS melebihi ambang batas	Ya	Ya

IV. CONCLUSION

Based on the results of the tests that have been carried out with the title of the Final Project "Implementation of LoRa-Based Wireless Sensor Technology in a Water Quality Monitoring System for Detecting River Water Pollution" it can be concluded that the system has been successfully developed to monitor river water quality using multisensors whose communication utilizes LoRa technology. The collected data is sent wirelessly via the LoRa SX1278 module. The website created is able to display monitoring data directly and send notifications to the user's WhatsApp if parameters are found that exceed the water quality parameter threshold. This simplifies the monitoring process without having to go directly to the location, making it more practical and faster in detecting pollution. Testing is carried out twice a day, namely in the morning and afternoon, with a duration of 15 minutes each. The sensor is able to read water parameters at different times, and all data is successfully sent and displayed via the website and WhatsApp notifications without any problems, indicating that the system is running according to its expected function.

REFERENCES

[1] DM Yusuf "Most Rivers in Indonesia Are Polluted, What Impact Does This Have on Drinking Water Supply?", 2023.

[2] PPID. 2023. River Pollution: Causes and Solutions [Online]. [Accessed: November 17, 2024].

[3] Government Regulation of the Republic of Indonesia Number 32 of 2017 on Health [Online]. Available: https://peraturan.bpk.go.id. [Accessed: November 18, 2024].

[4] MRA Budiman "Analysis of the Carrying Capacity of the Kenali Besar River Water Pollution Load on Domestic Wastewater from Residential Areas in Alam Barajo District", Batanghari University, 2021.

[5] TD Hendrawati, N. Maulana, and ARA Tahtawi, "River Water Quality Monitoring System in Industrial Areas Based on WSN and IoT", Computer Engineering Study Program, Sukabumi Polytechnic, 2019.

[6] TD Hendrawati, N. Maulana, and ARA Tahtawi "River Water Quality Monitoring System in Industrial Areas Based on WSN and IoT", Computer Engineering Study Program, Sukabumi Polytechnic, 2019.

[7] TD Hendrawati, N. Maulana, and ARA Tahtawi "River Water Quality Monitoring System in Industrial Areas Based on WSN and IoT", Computer Engineering Study Program, Sukabumi Polytechnic, 2019.

[8] AZ Anam and FAG Rakha "Android-Based Monitoring and Control of Water Temperature and Water Turbidity in Hot Springs", Department of Electrical Engineering, State Polytechnic of Malang, 2023.

[9] EA Prastyo "Working Principle of LoRa SX1278", 2022.

[10] MN Gani, R. Hanifatunnisa, R. Hasanah, M. Yamin, and DS Rohman, "LoRa Technology-Based Water Quality Monitoring with the Naïve Bayes Method", Department of Electrical Engineering, Bandung State Polytechnic, 2024.

[11] S. N. S. Taha, N. A. A. Hamid, M. F. M. Zain, and N. H. M. Saad, "Implementation of LoRa in River Water Quality Monitoring," in Proc. Int. Conf. on Advanced Intelligent Robotics and Ocean Engineering (ICAROB), 2022, pp. 1–6, doi: 10.5954/ICAROB.2022.OS22-2.

[12] M. H. F. M. Reduan, N. A. A. Rahman, and A. Z. Ahmad, "Water Quality Monitoring System Based on Microcontroller and LoRa," Malaysian Journal of Science and Advanced Technology, vol. 1, no. 2, pp. 1–8, 2025, doi: 10.56532/mjsat.v1i2.6.

[13] D. Perdana, J. Naufal, and I. Alinursafa, "Performance Evaluation of River Water Quality Monitoring Using LoRa Connectivity with Fuzzy Algorithm," International Journal of Computers Communications & Control, vol. 16, no. 4, pp. 1–12, 2021, doi: 10.15837/ijccc.2021.4.4226.

[14] A. M. Santos et al., "Evaluation of LoRa Network Performance for Water Quality Monitoring Systems," Applied Sciences, vol. 14, no. 16, p. 7136, 2024, doi: 10.3390/app14167136.

[15] J. C. Moreno, L. Pérez, and A. García, "Implementation of a Dynamic LoRa Network for Real-Time Monitoring of Water Quality," Designs, vol. 9, no. 4, p. 96, 2025, doi: 10.3390/designs9040096.