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IOT-MQTT PROTOCOL-BASED WATER SENSOR SYSTEM TO MONITOR CITARUM RIVER WATER QUALITY USING ARDUINO UNO R4 WIFI

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ABSTRACT

River water quality is critical for sustaining life, necessitating advanced monitoring technologies. This study presents a novel IoT-based water monitoring system using the Arduino Uno R4 WiFi and the MQTT protocol, offering significant improvements in real-time data acquisition, reliability, and accessibility. Unlike conventional systems, this approach uniquely integrates advanced microcontroller capabilities and efficient data transmission to address limitations in accuracy and usability in water quality monitoring. The system measures key indicators, including pH, temperature, total dissolved solids (TDS), and turbidity, and provides real-time updates via a solar-powered web interface. Using an exploratory sequential design, the study developed, calibrated, and tested the system, achieving high accuracy with relative errors of 2.50% for pH, 4.15% for temperature, 4.73% for TDS, and 3.08% for turbidity. Feedback from 59 residents near the Citarum River underscores the system's effectiveness and societal relevance, highlighting its potential to enhance public health, support sustainable environmental management, and set a new standard in water monitoring technology.

Keywords*: arduino uno R4 wifi, hiveMQ website, IoT project, message queuing telemetry transport (MQTT) protocol, water sensor system.*

I. INTRODUCTION

THE pollution levels of the Citarum River are extremely hazardous to individuals [1]. According to an article published by Aulia Putra Daulay in *Daily News Conservation FKT UGM* on June 20, 2020, titled *"Citarum River, the Predicate of Polluted Rivers in the World. What Is the Solution?"*, Green Cross Switzerland and the Blacksmith Institute confirmed in 2013 that the Citarum River is one of the most polluted and dirtiest places in the world. The quality of water flow along the river has deteriorated due to severe erosion and additional pollution from livestock manure, household waste, and industrial waste. Various toxic compounds have also appeared in the Citarum Basin, harming the region and affecting 35 million people across the 13 regencies and cities through which the water flows [2].

This situation is confirmed by the issuance of Presidential Regulation (Perpres) No. 15 of 2018 on the Acceleration of Pollution Control and Damage Management in the Citarum River Basin, which aims to speed up the river's recovery. The Minister of Environment and Forestry of the Republic of Indonesia, Siti Nurbaya Bakar, stated that the pollution burden of the Citarum River in the Cikapundung Sub-Watershed has reached 77,341.19 kg/day, while its capacity is only 19,335.30 kg/day, and must be urgently reduced [3]. Based on Open Data Jabar [4] in 2020, the Citarum River is the longest river in

TABLE 1
UNIT FOR MAGNETIC PROPERTIES

Parameter	Standard
pH unpolluted water	6,5 - 8,5
Maximum water hardness level	500 mg/liter
Water temperature normality	22°C - 28°C
Water turbidity	< 5 NTU
Dissolved oxygen in water	< 4 mg/ L

West Java, with a length of 3,332.97 kilometers, and serves as a source of drinking water for residents of Jakarta, Bekasi, Karawang, Purwakarta, and Bandung. However, due to urban expansion, rivers, particularly those near cities, are becoming increasingly polluted [5]. The pollution of the Citarum River has worsened with population growth. Every day, tens of thousands of tons of waste are dumped into the river, rendering the water hazardous to all forms of life. Agricultural areas near the contaminated river are also affected [6].

Manufacturing sectors such as chemical, textile, leather, paper, pharmaceutical, metal, agricultural, livestock farming, and food and beverage production predominate in the Citarum watershed region [7]. In addition to industrial factors, household waste also contributes significantly to the pollution of the Citarum River. To address this issue, a water monitoring system is needed to evaluate the river's water quality. The water monitoring system monitors the condition of the Citarum River and is integrated with community web-based devices and Citarum River officials, allowing them to recommend whether the river water is suitable for community use. Based on cloud data collected through this monitoring system, Citarum Harum officers can implement appropriate mitigation, prevention, and response measures. Meanwhile, residents of the Citarum River area can use the data to support efforts to maintain water quality.

Fadel and Shujaa [8] stated that the pH scale runs from 0 to 14, with an ideal range for drinking water between 6.5 and 8.5. Turbidity measures the amount of invisible suspended particles in water; the lower the turbidity, the cleaner the water. Additionally, the Indonesian Ministry of Health Regulation No. 492/MENKES/PER/IV/2010 [9] sets the drinking water quality standards. According to the regulation, the standard pH for drinking water is between 6.5 and 8.5, the water temperature should be within ±3°C of the ambient air temperature, total dissolved solids (TDS) should not exceed 500 mg/L, and turbidity should be less than 5 NTU. This study uses physical, chemical, and biological parameters for the water monitoring system. Table 1 presents the clean water quality standards according to Regulation No. 492/MENKES/PER/IV/2010.

With standards established through regulations, this product can serve as an accurate water monitoring instrument. The community surrounding the Citarum River can, therefore, engage in activities that utilize the river's water. Citarum Harum officers can investigate whether each parameter indicator meets the requirements for unpolluted water. This system supports the goal of clean water and adequate sanitation outlined in Sustainable Development Goal (SDG) number six. Additionally, it is essential for achieving the Citarum Harum program's target of reaching class II water quality (a Water Quality Index [IKA] of 60 points) in the Citarum River by 2025 [10].

The water monitoring system is not the first development in this research area. The logistics of water collection and analysis present the biggest challenge, as samples are often collected manually using small boats in very remote aquifers, relying on only a few samples [11]. IoT-based water quality monitoring offers a faster, more affordable, more effective solution, providing real-time results [12]. Arduino devices receive data from sensors that monitor the pH level, turbidity, temperature, and flow of water samples, and display the results on mobile devices using the Blynk app [13]. Although the research categorizes water quality for each parameter, it still requires the addition of a Wi-Fi module and separate Arduino modules to connect the water sensor tools to the website. Salih et al. (2019) monitored fish farms remotely with a system that was low-cost and highly reliable. Their system measured and monitored the pH and temperature of fish pond water in real time, but it used Bluetooth for communication between the smartphone and the sensory system, limiting its range. Another study used laboratory analysis of physical and chemical parameters to observe water quality in Tondano Lake, but it did not develop a real-time water monitoring system [15]. In the Cisadane River, physical parameters such as water temperature, total dissolved solids, total suspended solids, color, smell, and brightness of the water were tested [16].

Water monitoring systems can also use Arduino as the hardware. Such systems can support hydroponic farms by analyzing water quality parameters such as pH, temperature, and turbidity. However, this project lacked online data transmission, as the sensor results were only sent to an LCD connected to the microcontroller [17]. Another project, although similar, used Arduino as a microcontroller for a water monitoring system in aquaponics, focusing on controlling the pH and temperature of water [18]. Arduino-based water monitoring systems can also serve as controllers for drinking water systems by analyzing pH, total dissolved solids, and turbidity [19].

In addition to monitoring water quality, Arduino devices can be used to measure water flow in municipal waterworks [20]. A water monitoring system for the Citarum River has been developed by [21], analyzing pH, turbidity, and TDS using IoT technology and Arduino IDE. The results indicated that the water quality was below World Health Organization (WHO) standards. Furthermore, water monitoring systems have been used to support milkfish cultivation in Karawang using a wireless sensor network (WSN) [22]. A LoRa network combined with a fuzzy algorithm has also been tested in the Citarum River to analyze pH, turbidity, and TDS, using ESP32 as the microcontroller [23].

According to Mujib et al. [24], the Citarum River was used as a variable, and Arduino IDE hardware was employed with only three sensors: a temperature sensor, a pH sensor, and a turbidity sensor. The water monitoring system could detect water temperature, pH, oxidation-reduction potential, and conductivity [25]. However, the system used GSM for data transmission, which is now considered outdated, and the results were not calibrated with laboratory instruments. Therefore, no relative error with more accurate laboratory tools was reported.

Another study [26] proposed a system using four sensors—pH, turbidity, ultrasonic, and DHT-11—along with a microcontroller unit as the primary processing module. An ESP8266 Wi-Fi module (NodeMCU) was used for data transmission. The research employed an ESP8266 Wi-Fi module and an Arduino Mega, requiring two microcontrollers, but it did not report any calibration of the tools. The associated application could only be accessed via Android devices. Another research project measured water quality parameters including pH, conductivity, and temperature, using a GSM module for data transmission and LPC2148 along with ESP8266 microcontrollers [27]. However, that study only measured three parameters and used an older microcontroller.

To address the limitations of previous research, this study introduces a water monitoring system that uses the latest Arduino Uno R4 WiFi connected to the Message Queuing Telemetry Transport (MQTT) protocol and powered by a solar cell. It measures water quality parameters of the Citarum River, including pH, total dissolved solids (TDS), temperature, and turbidity. Furthermore, unlike previous research, this study compares project results with advanced laboratory tools to calculate relative errors and integrates Arduino with a solar-powered system.

The Arduino Uno is used in this research because it can be integrated with an ESP32-S3 module that connects to WiFi and enables real-time Internet of Things (IoT) connectivity with a website. Arduino Uno also offers a low-cost microcontroller that can be calibrated to demonstrate the accuracy of the Arduino Uno R4 WiFi tools. improves on previous models by combining two different microcontrollers with distinct functions into a single device. It also incorporates the MQTT protocol to enable cloud data transmission to website devices. MQTT is widely used in wireless applications due to its faster performance, lower bandwidth requirements, and reduced power consumption, with one of its key advantages being energy efficiency—especially when a cloud-based broker is used, as many experiments still rely on physical brokers for data transmission [28]. MQTT was chosen because it provides the fastest data transfer rate, with an average transmission time of 0.0197 seconds, compared to 0.169 seconds for HTTP and 2.211 seconds for HTTPS [29]. Among MQTT brokers, HiveMQ has the highest memory usage, up to 825 MB, compared to VerneMQ with up to 135 MB, EMQX with around 200 MB, and Mosquitto with approximately 11 MB [30]. Therefore, this study aims to enable Citarum River officers to take appropriate actions based on data obtained through the HiveMQ website, using a solar cell to power the Arduino Uno R4 and its four sensors.

This study aims to develop a water monitoring system by measuring pH, TDS, temperature, and

TABLE 2
LIKERT SCALE SCORING

1	2	3	4	5
Strongly disagree	disagree	neutral	agree	Strongly agree

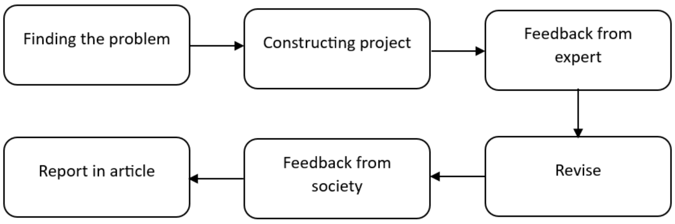

Figure 1. Research Process Chart

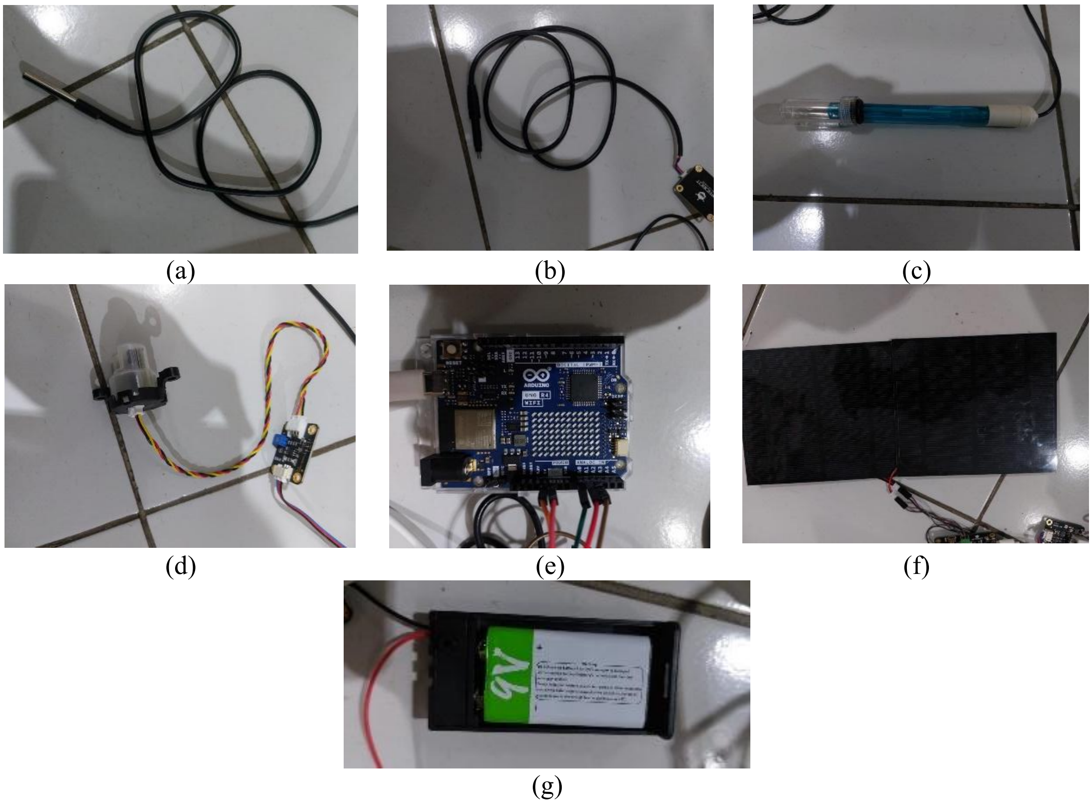

Figure 2. (a) Temperature Sensor, (b) TDS Sensor, (c) pH Sensor, (d) Turbidity Sensor, (e) Arduino Uno R4 WiFi, (f) Solar Cell, (g) Rechargeable Battery

turbidity. It contributes to monitoring the Citarum River online, allowing officers to assess water quality without manual inspections. Additionally, this study gathers feedback from the community regarding the water monitoring system. The study addresses three main questions: (1) How is the development of the water monitoring tools and website? (2) What is the percentage error level of the produced Arduino toolset? (3) What is the community's response to the water monitoring system?

II. RESEARCH METHOD

This study uses an experimental research design. As there have been no previous studies involving the Arduino Uno R4 WiFi integrated with the MQTT protocol applied to a real case, this study focuses on the Citarum River, recognized as one of the dirtiest rivers in the world. The MQTT protocol is selected because it is designed to send messages with a maximum size of 0–256 MB using minimal network resources, unlike the HTTP protocol [31]. Therefore, MQTT enables real-time data transmission and is more suitable for a monitoring system than HTTP. Before gathering feedback from the community, this project first received expert input. As this water monitoring system is intended for societal use in the Citarum River area, community feedback is essential. Feedback is collected using a Likert scale ranging from 1 to 5, as shown in Table 2.

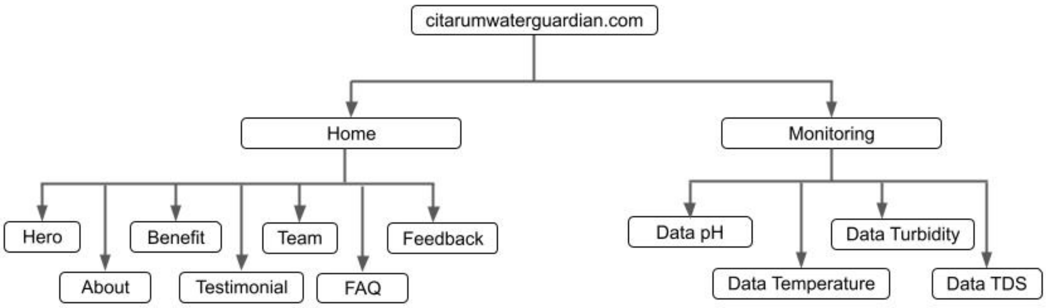

Figure 3. Website chart of the water monitoring system

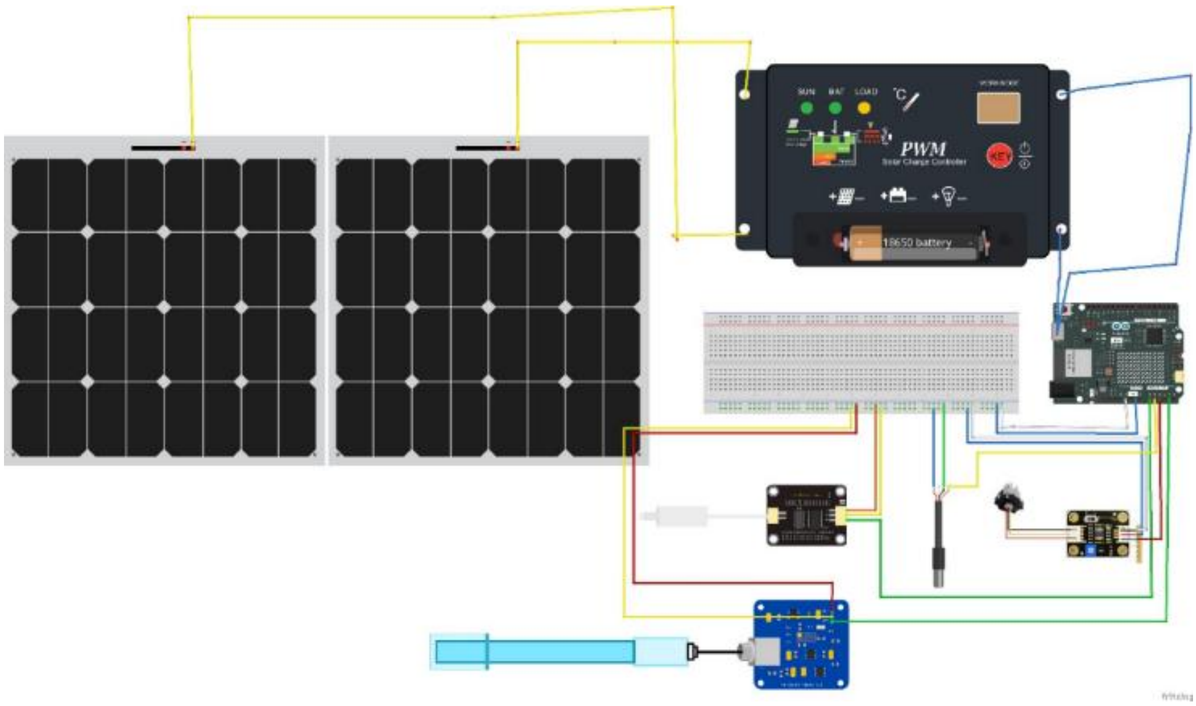

Figure 4. Arduino circuit designed in Fritzing

The questionnaire statements are provided in Indonesian to ensure respondents fully understand them. However, the statements are presented in English in this article. The detailed questionnaire is shown in Appendix B and includes 10 Likert-scale questions and 2 open-ended questions. Figure 1 presents the research process chart.

This water quality monitoring system is developed as a prototype. Previous systems focused mainly on fish farming and measured only pH or dissolved oxygen levels. In contrast, this research applies sensors that cover physical, chemical, and biological parameters. The prototype integrates the Arduino Uno with sensors connected via male-female jumper wires on a breadboard. The sensors include a pH sensor, turbidity sensor, water temperature sensor, and TDS sensor, all linked to the Arduino Uno through a laptop and activated using Arduino software coding. The components used in this project are shown in Figure 2.

The circuit used in this study is shown in the figure below, illustrating the Arduino circuit setup, the results, and the data transmission to the website developed with HiveMQ MQTT. In MQTT communication, "publisher" and "subscriber" refer to the names of the MQTT clients [28]. The Arduino input code is provided in Appendix A, which includes the manual calibration coding. The website structure is also presented in the appendix. Figure 3 shows the website chart developed for the water monitoring system.

the Arduino Uno R3, which is the commonly used model. However, connecting the results to the internet required an additional microcontroller, the ESP32 NodeMCU. By the end of the research, it was

TABLE 3
COORDINATES OF WATER SAMPLING LOCATIONS

Location	Coordinate	Area
1	(-6.9225534, 107.4826679)	Residential areas
2	(-6.9326154, 107.5060282)	Factories
3	(-6.9605107, 107.5340234)	Residential areas & factories.
4	(-6.9705792, 107.5416376)	Residential areas & public transportation terminal
5	(-6.9788552, 107.5540414)	Residential areas
6	(-6.9819638, 107.5577439)	Temporary waste disposal site
7	(-6.9875573, 107.5805638)	Factories

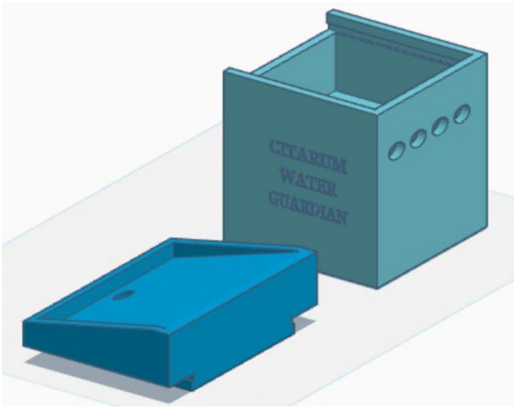

Figure 5. Design of the Arduino circuit cover

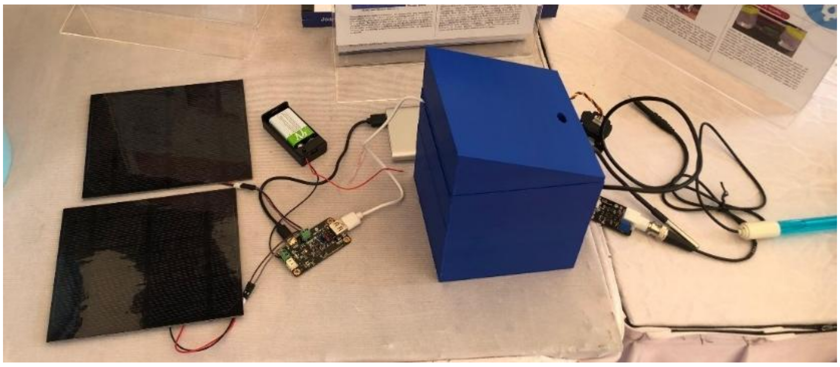
Figure 6. Real photo of the circuit

determined that the most suitable microcontroller for this system is the Arduino Uno R4 WiFi, the latest Arduino version launched in 2023, which integrates an ESP32 NodeMCU and can connect directly to the internet without needing an additional microcontroller. The Arduino is configured with four water sensors: a pH sensor, a temperature sensor, a total dissolved solids (TDS) sensor, and a turbidity sensor. Each sensor has three wires: one connected to the Arduino analog input pins A0, A1, A2, and A3, and the other two connected to the 5V and GND pins. However, since the Arduino Uno R4 WiFi has limited 5V and GND slots, a breadboard is used to expand the positive and negative connections. The water monitoring system circuit was designed using Fritzing software, as shown in Figure 4.

The Arduino Uno R4 WiFi circuit has only two power supply slots: 5V and GND. this study used a breadboard to connect the 5V and GND lines to the breadboard, allowing all positive and negative wires from the sensors to be connected to the Arduino Uno R4 WiFi. The connection between the solar cell and the Arduino is managed through a solar power manager. The Arduino operates using a rechargeable 9-volt battery, which is recharged by the solar cell and provides consistent power to the Arduino.

Water sensors require calibration. In this study, calibration was conducted using standard laboratory sensors. The calibration aimed to achieve a relative error of less than 10%. To protect the Arduino Uno R4 WiFi circuit, a waterproof plastic cover was designed using 3D modeling. Because Arduino is an electrical device that can be damaged by water exposure, a protective casing is necessary. The cover design was created using TinkerCad, and is shown in Figure 5.

The table containing the Arduino IDE input code for the five connected sensors, which communicate via the MQTT protocol, is provided. In the cover design, the light blue section encloses the Arduino circuit and water sensors, while the dark blue section holds the solar cell. With this setup, the Arduino circuit is powered independently by the solar cell, eliminating the need for an external power supply. The cover was 3D printed using an Ender 3D printer, with PLA+ as the primary material. The purpose of the design is to protect the components, especially the microcontrollers, from water exposure.

Data were collected from seven different locations along the Citarum River, representing various environments such as industrial areas, residential areas, and densely populated zones. The results obtained from the Arduino Uno R4 WiFi were compared to laboratory tools to calculate the relative error of the system, assessing its efficiency and validating the accuracy of the research product. This monitoring tool uses Arduino Uno hardware, which is integrated with Android devices in the system. The parameters used to determine water quality consist of scientific indicators, including physical, chemical, and biological parameters. These parameters assess the pH, water hardness, water temperature, and turbidity of the Citarum River water. Figure 6 shows a real photo of the circuit design.

After constructing the Arduino circuit, the water monitoring system was used to test water samples from the Citarum River. The sampling locations and their coordinates are shown in Table 3. The coordinates, obtained from Google Maps, represent areas likely contributing to water pollution.

III. Result and Discussion

A. *The Development of the Water Monitoring Tools Website*

The website developed for this project is named “Citarum Water Guardian.” The name was chosen because the website can be accessed by any type of smartphone, including both iOS and Android devices, through any search engine. The website includes several sections: Home Page, Monitoring Page, Login Page, Dashboard Page, Logs Data pH Page, Logs Data Temperature Page, Logs Data Total Dissolved Solids Page, Logs Data Turbidity Page, and Feedback Result Page. displayed categorize water quality into four categories: "clean water," "low pollutant," "moderate pollutant," and "high pollutant."

To develop the website, this research used Laravel, MQTT, MySQL, SB Admin Template, Impact Template, and Apex Chart, integrating the water monitoring system with the Arduino Uno R4 WiFi. The website displays real-time sensor results through MQTT-based messaging. The MQTT system must deliver comprehensive statistical data, including the most frequently used message topics, the total number of messages exchanged, the number of clients involved in sending and receiving messages, and the real-time ratio of subscribers to publishers [33]. Previous studies have also demonstrated the integration of the IoT with the MQTT protocol. One study used the ESP8266-12E microcontroller to bridge IoT devices and MQTT, enabling firmware file publishing [34]. Another study used the MQTT protocol to control a lamp through a website, achieving a light-on time of 0.36167 seconds and a light-off time of 0.42167 seconds [35]. In the healthcare sector, IoT integrated with MQTT is used to enhance technology performance by reading patients' vital signs [36].

The Dashboard display consists of three sections: Last Updated, Water Status, and Sensor Status. The Last Updated section shows the most recent time the data were sent by the sensors and received on the website. The Water Status section presents the current water quality status of the Citarum River based on four parameters transmitted by the sensors. The Sensor Status section indicates whether the sensors are currently connected or disconnected. Additionally, the Dashboard displays value data and charts for each sensor parameter: pH, Temperature, Total Dissolved Solids (TDS), and Turbidity. Each parameter has its own dedicated display on the Dashboard. Each view includes dynamic graphs that visualize changes in the parameter values of the Citarum River water over time. For example, the pH display allows users to monitor fluctuations in pH levels, providing a comprehensive understanding of water quality trends. With this information, users can effectively monitor the water quality of the Citarum River. The display of the “Dashboard Page” on the website is shown in Figure 7.

B. *The Measurement of The Percentage Error of The Arduino*

The Arduino-based water monitoring system was tested and compared with laboratory tools. The laboratory tools used were the 4-in-1 pH TDS Temperature Meter Tester (KT-686) and the EZO Turbidity Sensor. The results were evaluated by calculating the percentage error using (1).

$$percentage\ error = \frac{Actul\ value\ observer - expected\ value}{expected\ value} \times 100\% \quad (1)$$

TABLE 4
LABORATORY TOOL RESULTS

Water sample	Laboratory Tools			
	pH	Temperature (°C)	Total Dissolved Solid (mg/L)	Turbidity (NTU)
1	6.20	28.00	65.00	80.40
2	6.73	27.00	63.00	73.40
3	6.30	27.00	87.00	74.80
4	5.96	26.90	87.00	73.70
5	6.33	26.90	55.00	74.40
6	6.12	26.67	85.00	98.40
7	6.36	26.60	55.00	23.70

TABLE 5
RESULTS FROM ARDUINO TOOLS

Water sample	Arduino Tools			
	pH	Temperature (°C)	Total Dissolved Solid (mg/L)	Turbidity (NTU)
1	6.40	29.00	67.00	79.00
2	6.63	29.00	65.00	74.87
3	6.32	29.00	81.40	76.67
4	6.31	27.61	84.20	75.90
5	6.51	27.30	52.30	76.20
6	6.31	27.60	80.40	102.30
7	6.44	27.50	51.90	25.30

TABLE 6
RESULTS FROM PRASAD [25]

Source	Readings			
	pH	Temperature (°C)	Total Dissolved Solid (mg/L)	Turbidity (NTU)
Rewa River	7.7 – 8.2 pH	20-30°C	190-220 mV	70-80 uS/cm
Central Tap Water	7.7 – 8.1 pH	20-30°C	300-600 mV	55-70 uS/cm
Sigatoka coast	7.7 – 7.9 pH	20-30°C	100-150 mV	50-60 mS/cm
Nabukulau Creek	7.7 – 7.9 pH	20-30°C	0 to -3 mV	42-45 mS/cm

TABLE 7
PERCENTAGE ERROR RESULTS

Water sample	Percentage Error			
	pH	Temperature (%)	Total Dissolved Solid (%)	Turbidity (%)
1	3.13%	3.45%	2.99%	1.77%
2	1.51%	6.90%	3.08%	1.96%
3	0.32%	6.90%	6.88%	2.44%
4	5.55%	2.57%	3.33%	2.90%
5	2.75%	2.56%	5.16%	2.36%
6	3.01%	3.37%	5.72%	3.81%
7	1.24%	3.27%	5.97%	6.32%
Average	2.50%	4.15%	4.73%	3.08%

TABLE 8
BOX'S TEST OF EQUALITY OF COVARIANCE MATRICES

Box's Test of Equality of Covariance Matrices	
Box's M	9.153
F	0.574
df1	10
df2	688.446
Sig.	0.836

TABLE 9
TESTS OF BETWEEN-SUBJECTS EFFECTS

Source	Dependent Variable	Sig.
Corrected model	pH	0.220^{ns}
	Temperature	0.007**
	TDS	0.786^{ns}
	Turbidity	0.896^{ns}

To calculate the percentage error, the researcher must determine the actual value and the expected value. In this case, the "expected value" refers to the measurements obtained using the laboratory tools. The laboratory results for water quality parameters—pH, temperature, total dissolved solids, and turbidity—are presented in Table 4.

After the water samples were tested using laboratory tools, the same samples were tested using the Arduino-based system developed in this study. The Arduino values are considered the "actual values" for the percentage error calculation. The measurements from the Arduino water sensors using the same water samples are presented in Table 5.

The findings were compared to the Indonesian government regulations on river water quality [38]. Based on the results from both Arduino and laboratory tools measuring pH, temperature, total dissolved solids, and turbidity, several parameters were found to deviate from the standard criteria. Significant differences were observed in turbidity measurements, particularly for water sample 5, which showed the highest turbidity. Total dissolved solids also exhibited notable variations; for example, water samples 1 and 2 had relatively similar values, while samples 3, 4, and 6 showed closely grouped values, and samples 5 and 7 had the lowest values. Meanwhile, pH and temperature measurements among the samples showed no significant differences.

To strengthen the findings, the results were compared with other studies on river water quality. A study by Prasad [25] measured water quality parameters such as temperature, pH, oxidation-reduction potential (ORP), and conductivity from various sources. The results are shown in Table 6.

The results shown in Table 6 do not fully represent the actual condition of the water sources. Additionally, the measurements obtained by the tools reflect an uncertainty range across all parameters and were not calibrated. As a result, the findings could not meet the requirements for percentage error analysis. In contrast, our findings have been calibrated using laboratory tools to accurately measure the percentage error and improve the validity of the research. Table 7 presents the percentage error results.

To obtain rigorous and validated findings regarding the effectiveness of the tools, a statistical analysis was conducted. An independent T-test was performed to compare the Arduino tool measurements and laboratory tool measurements across pH, temperature, TDS, and turbidity parameters. The results of the Box's Test of Equality of Covariance Matrices are presented in Table 8.

The results indicate that the significance value is greater than 0.05, meaning there is no significant difference between the control (laboratory tools) and the experimental group (Arduino tools). This finding validates that the Arduino tools developed in this research are statistically consistent with laboratory measurements. However, the MANOVA test also provides a comparison for each parameter individually, as shown in Table 9.

The results reveal the comparison of each parameter between the Arduino tools and laboratory tools. The water parameters of pH, TDS, and turbidity show significance values greater than 0.05, indicating no significant difference between the two measurement tools. However, the temperature parameter shows a significance value less than 0.05, suggesting a difference between the Arduino tools and laboratory tools. Therefore, the temperature parameter requires further improvement to reduce discrepancies. Calculating the percentage error is essential to assess the accuracy of the measurements. A smaller percentage error indicates less measurement bias [39]. Measurement uncertainty may also occur due to the sampling network design, which represents only a subset of the entire population [40].

Previous studies have evaluated similar system developments. Hong et al. [29] demonstrated the practicality of installing an Arduino-based sensor system for monitoring water quality. Their system was proven reliable but remained dependent on human intervention and was prone to data errors. The Arduino Mega 2560, used in their IoT platform (GPSB), significantly enhanced processing capacity at the cost of a slight increase in power consumption. It employed a highly reliable duty cycle mechanism with various fail-safes to ensure system stability and achieve low power consumption while controlling water turbidity [42]. Miry and Aramice [43] developed an IoT-based platform called ThingSpeak to monitor and analyze water quality. It offers analytical tools and visualizations using MATLAB programming, testing water samples through sensor fusion techniques such as TDS and turbidity analysis, and uploading the results online. The IFTTT protocol was also used to send user warnings. Waterproof sensors, implemented with an Arduino NodeMCU board, monitored vital parameters such as liquid level, temperature, and pH while the tanks were in use. The sensors were connected to Blynk, a smartphone app that enabled remote monitoring via a Wi-Fi connection [44]. Additionally, a GSM module-based monitoring system allows users to check water quality automatically via mobile phones, storing and transmitting data wirelessly as the sensors detect the parameters [45].

The MQTT protocol successfully transmitted messages from the microcontrollers to the website in real time. However, several issues related to MQTT were identified. Since MQTT operates on a distributed architecture, it requires multiple brokers and various communication standards, leading to increased security risks and greater complexity in security management. Furthermore, MQTT has inherent security limitations, relying on plaintext username and password authentication, which is less secure [46]. Another issue arises with the microcontrollers, which require a constant power supply. To address this, the study successfully used solar cells to power the microcontroller through a rechargeable battery. However, a single solar cell was insufficient to recharge the battery quickly. Therefore, additional solar cells were incorporated to provide enough energy for efficient battery recharging.

C. Society Feedback

Feedback was gathered from people living near the Citarum River regarding the water monitoring system. A total of 59 responses were collected from residents in the surrounding area. The feedback indicated a positive response to the water monitoring system. Many respondents mentioned that the system would help them utilize the river water more safely for agriculture and fisheries purposes, as reflected in the open-ended questions. Additionally, the water monitoring system was recognized for raising public awareness about preventing water pollution, highlighting the river's importance for human, animal, and plant life. The website also enables the community to submit inquiries and feedback regarding the monitoring system tools, making it easier for residents to contribute suggestions for improving the system's quality.

Today, society places increasing importance on technologies that can protect various forms of privacy, including informational, physical, and psychological privacy [47]. When a monitoring system is perceived as beneficial, the public response tends to be positive, particularly among elderly individuals with low information literacy [48]. Water is used by society for several purposes, such as fish farming, where maintaining uncontaminated water quality is crucial for both fish health and human consumption [49]. Additionally, household water use requires careful attention to contamination by bacteria and other harmful substances to safeguard health [50].

The survey responses offer valuable insights into public perceptions of the water quality monitoring system implemented to support the "Citarum Harum" program. Most respondents viewed the system positively, highlighting its effectiveness, reliability, and ease of access through the website. Many indicated that the system plays a significant role in raising awareness about river sustainability and addressing pollution challenges in the Citarum River. This feedback reflects the system's alignment with public expectations and its contribution to environmental sustainability initiatives. Respondents also acknowledged the tangible benefits provided by the system, such as offering reliable water quality data and promoting cleaner water conditions in the Citarum River. Some participants mentioned that the monitoring system could help identify pollution sources and support informed decision-making to mitigate environmental damage. However, a few responses were neutral or expressed skepticism, suggesting potential gaps in meeting broader community expectations or communicating system results effectively.

Several participants recommended improvements, including fostering collaboration with government agencies and local organizations to enhance the system's impact. They also suggested integrating public education campaigns with the monitoring results to empower communities and encourage proactive environmental actions. These suggestions emphasize the importance of combining technical monitoring with community engagement and actionable interventions.

Overall, the feedback indicates that while the monitoring system has been well-received and represents a positive step forward, there remains room for improvement. Incorporating public suggestions—such as collaborative efforts and broader outreach initiatives—could strengthen the system's effectiveness and ensure its long-term sustainability as a tool for protecting the Citarum River.

IV. CONCLUSION

All of the parameter sensors successfully operated, with an average relative error below 5%. The water monitoring system received positive feedback from residents living near the Citarum River, highlighting its potential to improve water quality for agriculture, fisheries, and household needs. The system also fosters greater awareness of the importance of preventing water pollution, given the river's vital role in supporting human, animal, and plant life. Addressing concerns related to privacy and ensuring that the water remains free from contaminants is crucial for maximizing the system's benefits and meeting community expectations.

However, this study has several limitations. The monitoring system only identifies water quality but does not detect pollution sources or provide interventions for cleaning the water. The monitored parameters are also limited. Furthermore, issues related to backend management and data privacy for the Arduino-based tools were not addressed. Therefore, future research is recommended to develop IoT-based systems for cleaning waste originating from factories or residential areas and to create more advanced water quality monitoring tools. These tools could include additional parameters such as dissolved oxygen and nitrate levels and utilize alternative communication technologies, such as LoRaWAN or NB-IoT, to improve the system's range and reliability.

This work contributes practical tools and knowledge that can help protect river ecosystems and surrounding environments. The water monitoring system can be implemented across multiple rivers in Indonesia to prevent further river pollution. Additionally, the monitoring system can serve as a tool for supervising factory waste disposal activities. This product can function as an accurate water monitoring solution, adhering to regulatory standards. The West Java Provincial Government could adopt this system to monitor the Citarum River, as it currently lacks a real-time, web-accessible river water monitoring system. Through this system, Citarum Harum officers can respond promptly if any parameter indicators deviate from unpolluted water standards. Furthermore, communities around the Citarum River can continue to safely utilize the river for various activities.

Theoretically, this product can serve as a reference for further product development by other researchers working with Arduino tools and additional parameters for monitoring other rivers in Indonesia or abroad. This product also contributes to Sustainable Development Goal (SDG) 6: Clean Water and Proper Sanitation. It can help prevent the worsening of water pollution and support efforts to ensure that no other rivers in Indonesia experience pollution similar to that of the Citarum River. Additionally, the product can function as a monitoring tool for supervising factory waste disposal activities.

In the field of education, this tool can be used as a STEM-based science learning medium (Science, Technology, Engineering, and Mathematics), aligned with 21st-century skill demands—4C (Communication, Creativity, Critical Thinking, and Collaboration)—and Education for Sustainable Development (ESD). It can also support undergraduate theses, master's theses, or dissertation research.

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