

# Edge-Enabled Dual-Mode IoT System for Water and Environmental Monitoring with Smart Alerts

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**Abstract-** The problem of water quality deterioration and the environmental pollution is a burning issue that endangers the health of the population, the level of agricultural activity, and the sustainable development. Traditional methods of water quality monitoring are based on manual sampling or cloud-based Internet of Things (IoT) that constantly transmits raw sensor data, thereby causing a greater latency, the increase in network traffic, and a high reliance on the stable internet connection. To overcome these shortcomings, this paper introduces an edge-based dual-mode IoT system of real-time water quality and environment monitoring with smart alert messages. The suggested system incorporates the sensors to measure water quality parameters such as pH, turbidity, total dissolved solids, electrical conductivity and temperature as well as environmental parameters such as air temperature, humidity and atmospheric pressure. The Raspberry Pi Pico 2W is a data processing board that features edge-level data processing with filtering, sliding-window averaging, and threshold analysis to achieve rapid detection of anomalies without constant cloud communication. The two-mode Wi-Fi and GSM communications are used to guarantee the security of data transmission in the areas where the network covers are insufficient. Processed data are visualized through the Blynk IoT platform, while local alerts are generated using RGB LEDs and a buzzer. The system is cost-effective, scalable, and suitable for deployment in both rural and urban environments.

**Keywords** - IoT, Edge Processing, Dual-Mode Communication, Water Quality Monitoring Environmental Monitoring, Blynk Dashboard, Smart Alerts, raspberry pi.

## I. INTRODUCTION

The high rate of population growth, industrialization and environmental pollution have significantly affected the supply and quality of water resource throughout the global world. The constant control of water quality and other environmental conditions is essential to safeguard and improve the health of the population, preserve the balance in the environment, and guarantee sustainable development. Traditional methods of water quality are based on the ability to collect samples manually and further analyze the data. These methods are both time consuming and expensive and cannot be used in online applications [1], [2].

Internet of Things (IoT) technology has been invented, which has made it possible to create the Internet-based monitoring systems that utilize a variety of connected sensors and controllers to monitor different environmental parameters. The IoT-based systems can be used to provide continuous monitoring of such parameters as pH values, turbidity, conductivity, and temperatures levels, as well as guaranteeing online monitoring through cloud-based systems [3]-[6]. These technologies have been widely used in marine surveillance and environmental-friendly uses towards improving water quality measurements [7].

However, Nevertheless, in the majority of classic IoT monitoring systems, cloud systems are important in processing the data and the raw data of the sensors

are continuously relayed to the cloud to be processed. This has created high bandwidth usage in the networks, power consumption and latency in identifying abnormal situations, particularly in the places where the internet connectivity is poor [8].

To overcome the limitations, To get around these shortcomings, edge computing has been suggested as an effective means of processing the data of the sensors. With edge-enabled IoT, it is possible to implement several processing tasks such as filtering, aggregation, as well as abnormality detection, which leads to the efficient response time and network overhead [9]-[11]. The most recent IoT architectures have been created to include cloud and edge technologies to have efficient and scalable IoT systems, particularly when to process massive data on the environment [12], [13].

In this paper, an edge-enabled dual-mode IoT system to operate on real-time water quality and environmental monitoring is proposed based on the developments of IoT technologies. The proposed IoT system will involve the use of different sensors to monitor the water and environmental qualities and use edge technology to process the data in an efficient manner. An effective transmission of data will be performed with the help of a dual-mode communication protocol and the alert mechanisms will be employed to respond in case of abnormal situation as soon as possible.

The rest of this paper is organized as follows: Section 2 discusses the related works on IoT-based water and environmental monitoring systems. Section 3 introduces the overall system architecture and components. Section 4 discusses the proposed edge-enabled dual-mode monitoring system. Section 5 results and discussion, and finally, Section 6 concludes the paper.

## II. RELATED WORKS

There are a number of research studies that have been carried out to explore the potential of IoT technologies in environmental monitoring and smart development of infrastructure. The first studies have been carried out to explore the opportunities of the

IoT architectures and frameworks to help connect great quantities of sensors to implement smart cities and industries [14], [15]. The structures and designs have been established to integrate cloud platforms and distributed sensors to enable data gathering and real-time tracking in different locations.

Architectures of fog and edge computing have been designed to support the capabilities of IoT technologies in different applications such as the development of middle layers between sensors and cloud servers. The architectures have been designed in order to improve the potential of IoT technologies in regards to faster processing, reduced latency and increased scalability of IoT applications [16]–[18].

A number of research studies have been performed to examine the possibilities offered by the IoT technologies to support the creation of intelligent and precise environmental monitoring systems, as well as, the incorporation of machine learning and intelligent data processing technologies. The technologies have been designed to increase the precision of the different environmental monitoring systems and assist in forecasting analysis in the detection of abnormal environmental conditions [19].

This term, “interconnected smart devices” was originally coined in terms of the Internet of Things, to make smart devices available to facilitate the communication between physical objects and digital systems, the foundation of the modern IoT-based monitoring infrastructures [20]. The word has also been expanded to include smart gateways, cloud-based communication systems, and smart management within the context of IoT settings based on the findings of recent research studies [21]–[23].

Within the framework of water quality, a number of intelligent water quality monitoring systems have been proposed, with sensor networks and embedded controllers to measure the parameters of pH, turbidity and temperature in real time environments [24], [25]. The implementation of energy-efficient communication mechanisms in the

framework of IoT-based monitoring systems has enhanced the overall lifetime of the latter [26].

Despite the fact that such systems enhance monitoring within the environment, majority of them apply cloud-based processing and single-mode communication which are discussed in the proposed IoT-based monitoring system.

### III. DESCRIPTION OF THE SYSTEM

In this section, the design and operation of the proposed edge-enabled dual-mode IoT system of monitoring water quality and environmental factors are highlighted. The system has been established to provide real time monitoring, intelligence, communication and alert. The system has been developed with different layers including sensing, edge processing, communication, alerting and cloud visualization which assist the system in being efficient.

#### Overall System Overview

The system is constantly monitoring both water quality and environmental factors using an integrated set of sensors. The sensors are collecting data, which is processed using a Raspberry Pi Pico 2W. The system does not rely on continuously sending data to the cloud. Instead, the system is analyzing the data to identify any abnormal conditions. Only important data is sent.

To ensure that communication is reliable in any environment, the system relies on dual-mode connectivity using Wi-Fi and GSM. The data is displayed on a Blynk IoT platform, while local alert devices are used to send instant alerts when there is an abnormal condition.

#### Sensing Unit

The sensing unit is tasked with the role of acquiring physical values associated with water quality and environmental factors. The sensing unit is made up of the following sensors:

#### Water Quality Sensors:

The sensors are employed to detect pH, turbidity, total dissolved solids, electrical conductivity, and

water temperature. The values are used to determine the suitability of the water for drinking, agricultural, and other uses.

#### Environmental Sensors:

The sensors are employed to measure air temperature, humidity, and atmospheric pressure. The values are used to determine the environmental conditions surrounding the water.

The output of the sensors is conditioned and connected to the Raspberry Pi Pico 2W using the corresponding communication protocols such as ADC, I2C, UART, or RS485.

#### Edge Processing Unit

The primary edge processing controller of the system is the Raspberry Pi Pico 2W. It takes the data through sensors and performs edge processing prior to transmission of the data. The edge processing includes the removal of noise, averaging of the sliding window and the detection of a threshold.

The system can identify the abnormal conditions like change in pH or turbidity by local analysis of the data without necessarily having to be linked to the cloud.

#### Communication Unit

Communication unit ensures that the edge device transfers data to the cloud platform. The system to be proposed has two communication modes to ensure reliability:

#### Wi-Fi Communication:

Raspberry Pi Pico 2W Wi-Fi features are used as the main communication channel of the transmission of processed data to the cloud.

#### GSM Communication:

The external GSM module serves as a backup communication system in the areas where Wi-Fi connectivity is not possible.

#### Alert and Notification Unit

In order to be notified of the abnormal situation in real time, the system includes the local and remote notification systems:

### Local Notification Systems:

The system also incorporates the use of RGB LEDs in notifying the user of the system color status, and a buzzer that is used to alert the user of abnormal water or environmental conditions.

### Remote Notification Systems:

The processed information is sent to the cloud where notifications are sent to the user in the Blynk IoT dashboard.

The notification systems would enable timely response even in situations where internet connectivity is low.

### Cloud and Visualization Unit

The cloud system will be used in data visualization, data storage, and interaction. The information leaving the edge device is displayed in real time on the Blynk IoT platform. The user can view the real-time values, analyze the trends, and get notifications on their mobile devices.

The system has the ability to visualize the data, which makes it possible to monitor the water safety and environmental health conditions from a distance.

## IV. PROPOSED SYSTEM

The proposed system presents an edge-enabled and communication-resilient framework for the IoT that enhances the efficiency of water and environmental monitoring. The proposed system will ensure the reduction of network dependency, the increase of response time, and the provision of a reliable notification generation system through the extension of the capabilities of the existing water and environmental monitoring IoT systems. The practical hardware implementation of the proposed system is shown in Figure 1.

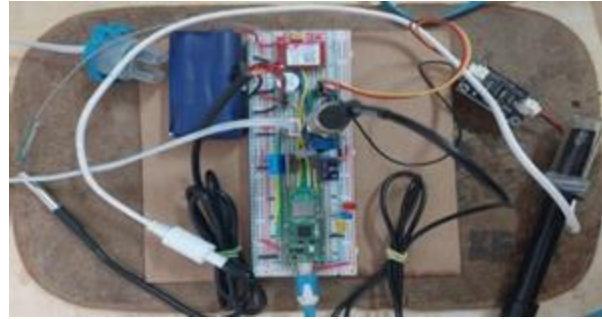


Fig.1: Hardware implementation of the proposed edge-enabled water and environmental monitoring system

### Edge-Level Intelligence for Anomaly Detection

The main significance of the proposed system is in the execution of data processing at the edge level.

The proposed system does not rely on the continuous transfer of raw sensor data to the cloud. Rather, the system uses a Raspberry Pi Pico 2W for data analysis at the location of the sensing point.

The sensor data is processed through filtering and sliding window average techniques to remove noise and make the data stable. A decision mechanism based on a threshold is used for real-time detection of abnormal data. The sliding window average is calculated as:

$$\bar{x}(k) = \frac{1}{N} \sum_{i=k-N+1}^k x(i)$$

An abnormal event is defined when the level of deviation is beyond a threshold value:

$$E(k) = \begin{cases} 1, & |x(k) - \bar{x}(k)| > \tau \\ 0, & \text{otherwise} \end{cases}$$

It is an edge-based decision-making process that enables faster recognition of critical situations and avoids any needless data transmissions.

In addition to the anomaly detection, the sensor level calibration and estimation of parameters are also

done on the edge to ensure that the water quality indicator is measured accurately.

In the case of the pH sensor, the 12-bit ADC of the controller converts the analog voltage signal of the sensing probe to a digital signal. The conversion equation of ADC to voltage is:

$$V_{out} = \frac{ADC_{value}}{4095} \times V_{ref}$$

where  $V_{ref}=3.3V$ . The pH value is then determined using a linear calibration model:

$$pH = m \times V_{out} + c$$

where  $m$  and  $c$  are experimentally determined calibration constants.

On the same note, in the case of the TDS sensor, the output voltage is ADC converted as:

$$V_{out} = \frac{ADC_{value}}{2^n - 1} \times V_{ref}$$

where  $n=12$ . The electrical conductivity (EC) is estimated as:

$$EC = m \times V_{out} + c$$

The total dissolved solids (TDS) concentration is then computed using:

$$TDS = k \times EC$$

where  $k$  is the TDS conversion factor determined during calibration.

By performing these calculations, the system can guarantee that the parameters are properly estimated prior to the anomaly detection and communication process and hence enhance reliability and reduce reliance on cloud computing. Figure 2 shows the general workflow of how the system is going to operate.

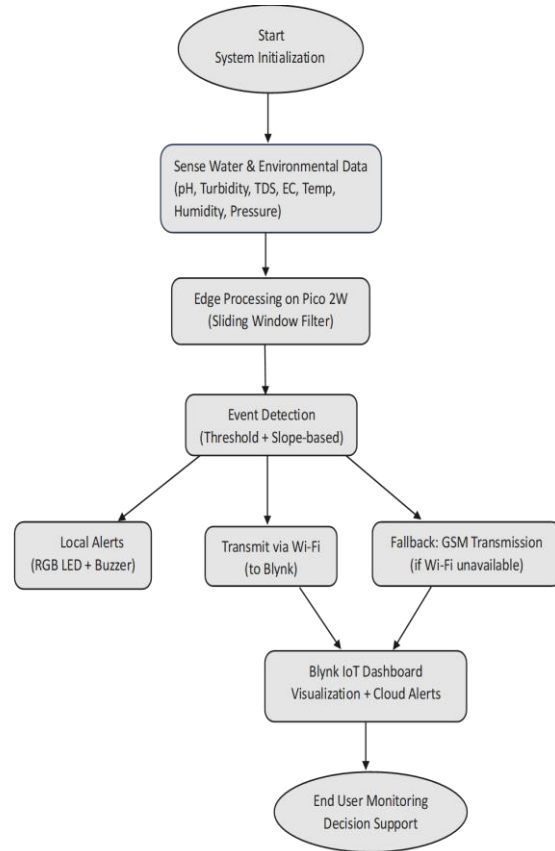


Figure .2: Processes flow of the edge-based anomaly detection and communication process

### Event-Driven and Dual-Mode Communication Strategy

To ensure greater efficiency and reliability of communication, the proposed system is based on the event-driven mechanism of data transmission and on dual-mode connectivity. In a normal condition, data on the sensors is summarized and sent at fixed intervals by the system. But when the abnormal events are detected at the edge, a notification of the alert data is sent out immediately. The primary communication mode is utilized through the use of Wi-Fi and the secondary communication mode is utilized through the use of GSM module when there is no reliable Wi-Fi connection. This two-way communication solution allows continuous flow of information and functionality of the system even in those regions where network connectivity is low, which is a major disadvantage of the current cloud-based IoT systems.

### Integrated Smart Alert Mechanism

The suggested system employs an inbuilt smart warning system to give a satisfactory notification regarding abnormal water and environmental conditions. The proposed system also consists of local and cloud notifications as opposed to the existing system, which relies solely on cloud notifications.

Local notifications are achieved through the use of RGB LEDs and a buzzer to provide instant visual and auditory notifications at the monitoring station. At the same time, the processed notification data is sent to the cloud and displayed on the IoT dashboard for remote monitoring and notification.

### Reduced Network Load and Energy Optimization

The system proposed is aimed at minimizing the use of the network and maximizing the use of energy through local processing and event-based communication. The proposed system minimizes the overhead of wireless communications since only the necessary information will be sent rather than sending raw sensor data.

It is not only that the bandwidth is saved, but the power consumption of the communication modules is also less hence making the system more energy-efficient. This is more so in remote locations where power and network resources are scarce.

## V. RESULTS AND DISCUSSION

### Experimental Setup

The design of the edge-enabled dual-mode IoT water quality monitoring system was developed using Raspberry Pi Pico 2W as the main controller. The system is a combination of various water quality and environmental sensors, which include:

- pH sensor
- TDS sensor
- Turbidity sensor
- DS18B20 water temperature sensor
- DHT11 humidity and air temperature sensor
- Barometric pressure sensor

The sensors were tested in normal drinking water and standard environmental conditions. The system was able to conduct real-time data acquisition, edge processing, anomaly detection, and cloud transmission.

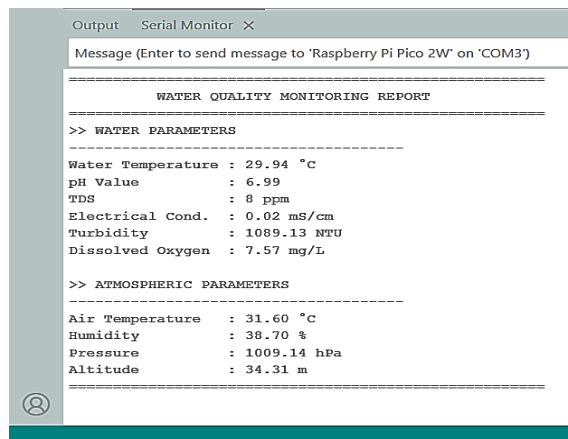


Fig.3: Real-time sensor readings displayed on the serial monitor during experimental validation

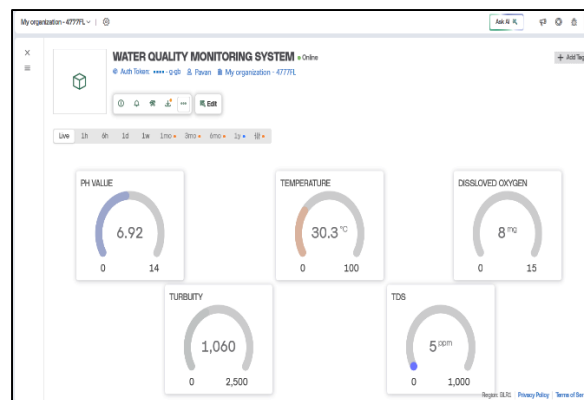


Fig.4: Blynk dashboard displaying real-time pH, TDS, temperature, turbidity, and dissolved oxygen values

### Observed Sensor Values

The values of the sensor readings measured from the system are given in Table 1 below:

Table 1: Measured Sensor Parameters

Parameter	Measured Value
pH	6.55
TDS	26 ppm
Water Temperature	26–29 °C

Humidity	57.5 %
Pressure	1016.69 hPa
Dissolved Oxygen	7.92 mg/L
Turbidity	Raw ADC: 900–1900

### Comparison with Standard Reference Values

The sensor readings were compared with the WHO and BIS (IS 10500) guidelines for drinking water to check the accuracy of the system.

Table 2: Theoretical vs Practical Comparison

Parameter	Standard Value	Measured Value	Status
pH	6.5 – 8.5	6.55	Within Acceptable Range
TDS	< 500 ppm	26 ppm	Excellent Quality
Turbidity	< 5 NTU	ADC 900–1900	Requires Calibration for NTU Conversion
Dissolved Oxygen	6 – 8 mg/L	7.92 mg/L	Within Standard Limits
Temperature	~25°C	26°C	Slight Variation Observed
Pressure	~1013 hPa	1016.69 hPa	Within Normal Atmospheric Range

The results show that the values of the measured parameters are within acceptable ranges, proving the functionality of the sensors and the edge-level processing.

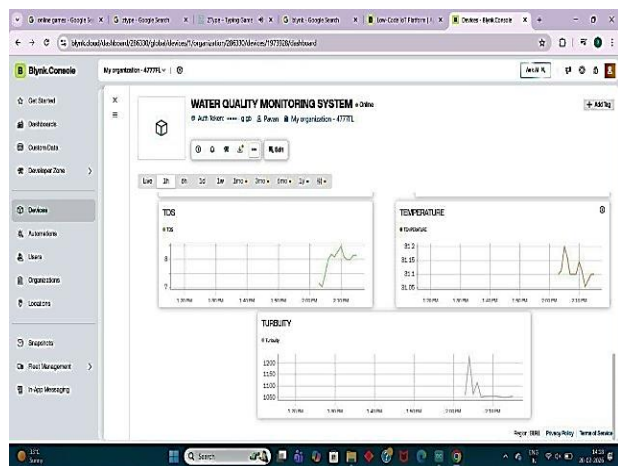
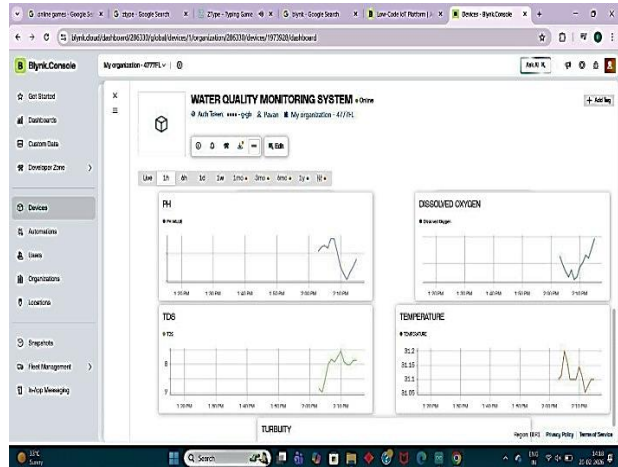


Fig.5: Time-series graphical representation of monitored water quality parameters

### Parameter-wise Discussion

#### pH Sensor:

The pH reading of 6.55 is within the acceptable drinking water standards (6.5-8.5 pH). This shows that the water sample is slightly acidic but safe for drinking.

#### TDS Sensor:

The TDS reading of 26 ppm is low, and the dissolved solid content is relatively pure.

#### Dissolved Oxygen:

The DO level reading of 7.92 mg/L is nearly equal to the standard saturation level at room temperature, which shows that the water sample has sufficient oxygen.

### Turbidity Sensor:

The turbidity sensor gives raw ADC readings between 900 and 1900. However, since the sensor gives analog output and not NTU values, calibration is necessary to obtain readings in standardized units of NTU. Further calibration with standard water samples will give more accurate results.

### Environmental Parameters:

The humidity and atmospheric pressure readings are within the standard ranges of environmental parameters, which confirms proper integration of environmental sensors into the system.

## System Performance Analysis

The experimental validation verifies that:

- The edge-level sliding window averaging successfully removed sensor noise.
- The threshold-based anomaly detection system facilitated real-time event detection.
- The dual-mode communication system (Wi-Fi and GSM) maintained uninterrupted data transfer.
- The local alert systems immediately reacted to anomalies.
- The network bandwidth was conserved by transmitting processed event data.

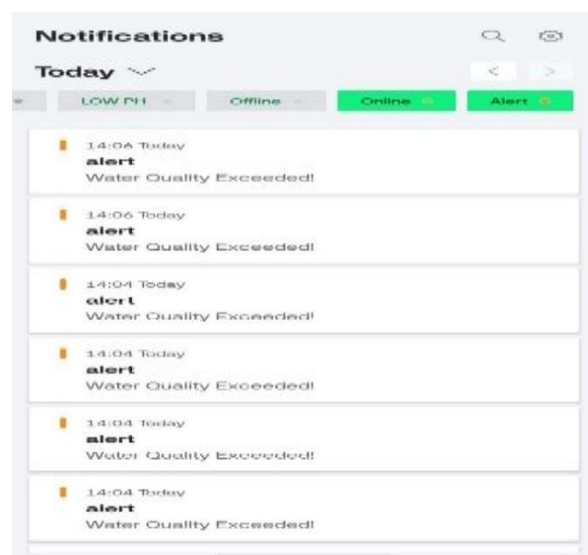


Fig.6: Alert notification generated through Blynk when water quality exceeds safe limits

Fig.7: GSM-based SMS alert containing real-time parameter values during abnormal conditions

## VI. CONCLUSION

This paper has demonstrated an edge-enabled dual-mode IoT system for the integrated monitoring of water quality and environmental factors with smart alert functionality. The proposed system architecture overcomes the drawbacks of the traditional cloud-based monitoring system by incorporating multi-parameter sensing, edge-level processing, and robust communication. The system enables real-time decision-making by performing sliding window averaging and threshold anomaly detection at the edge device.

Additional parameters of water quality like pH, turbidity, total dissolved solids, conductivity and temperature together with environmental parameters like atmospheric pressure, humidity, and temperature give the full situational awareness. The local processing done by the use of Raspberry Pi Pico 2W microcontroller with 2W increases the reaction time of the system and minimizes the latency. Also, the dual-mode communication system that uses Wi-Fi as the main and GSM as the secondary communication system will provide the reliability of the data transfer in the areas with untrustworthy connection.

The implementation of the local alerting system (RGB LEDs and buzzer) and cloud-based visualization with the help of the IoT dashboard will increase the reliability and responsiveness of the system under abnormal conditions. The proposed system has been demonstrated to have improved operational efficiency and scalability through the minimization of network dependency and optimization of data transmission to be deployed in rural, urban and industrial applications.

In conclusion, the suggested framework is a viable, affordable, and scalable solution to real-time water and environmental monitoring, thereby providing sustainable resource management and environmental safety.

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