IoT-Based Real-Time Water Quality Monitoring System in Water Treatment Plants

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Abstract: This paper presents an IoT-based real-time water quality monitoring system designed for deployment in water treatment plants. The system continuously monitors five critical water quality parameters — turbidity, pH, total dissolved solids (TDS), temperature, and soil moisture — using dedicated sensors interfaced with a Raspberry Pi 4 Model B single-board computer. An MCP3008 analog-to-digital converter (ADC) facilitates the interfacing of analog sensors with the digital processing platform. Real-time sensor data is displayed on a 16×2 LCD, stored on a micro-SD card, and transmitted via a GSM/GPRS module as SMS alerts when threshold violations are detected. Data is simultaneously uploaded to the ThingSpeak IoT cloud platform. Experimental results demonstrate reliable sensor performance, prompt threshold detection within 2 seconds, and automated pump control, confirming the system's suitability for practical water treatment plant applications at an estimated hardware cost of USD 150–200.

Keywords: IoT; water quality monitoring; Raspberry Pi; turbidity; pH; TDS; GSM/GPRS; relay control; MCP3008; real-time monitoring.

I. Introduction

Water is one of the most indispensable natural resources on Earth, forming the biological foundation upon which all life depends. The availability of safe, clean water is not merely a convenience but a prerequisite for the preservation of public health, agricultural productivity, and industrial functioning. As global population growth, urbanization, and erratic climate patterns place increasing pressure on freshwater resources, maintaining consistent water quality throughout the treatment and distribution chain has become one of the defining engineering challenges of the twenty-first century.

Water treatment plants form the critical interface between raw natural water sources and the public. These facilities receive water from rivers, reservoirs, lakes, or underground aquifers, and subject it to carefully controlled processes including coagulation, flocculation, sedimentation, filtration, and disinfection. The effectiveness of these treatment stages depends critically on the ability of plant operators to monitor key water quality parameters throughout the treatment process.

Historically, water quality monitoring has relied on manual sampling techniques, where trained operators collect water samples at regular intervals for laboratory analysis. While this approach can deliver high analytical accuracy, its practical utility is severely compromised by the time delay between a water quality deviation and the availability of results — often ranging from one to several hours. During this interval, contamination events or equipment malfunctions may go undetected.

The proliferation of Internet of Things (IoT) technology has created a compelling new paradigm for continuous, automated, real-time environmental monitoring. IoT-enabled sensor systems can be deployed throughout a treatment plant to collect measurements at intervals of seconds or minutes, evaluate data against safe operating thresholds, and immediately trigger alert and control responses whenever an anomaly is detected **[1].** Single-board computers, particularly the Raspberry Pi family, have emerged as ideal platforms for IoT applications in the industrial monitoring domain, combining a powerful processor, extensive GPIO connectivity, built-in networking, and broad software library support in a compact, low-cost form factor.

This paper presents the design, implementation, and experimental validation of a comprehensive IoT-based water quality monitoring system integrating five sensor types — turbidity, pH, TDS, temperature, and soil moisture — with a Raspberry Pi 4 Model B, 16×2 LCD display, active buzzer, relay-controlled pump, micro-SD data logger, and GSM/GPRS communication module.

II. Related Work

Considerable research has been conducted on IoT-based water quality monitoring systems. Guna Selvi et al. **[2]** proposed an IoT-based system for smart cities using pH and temperature sensors connected to a cloud platform. Kakkar et al. **[3]** combined IoT sensors with machine learning algorithms to detect water contamination automatically, achieving sigificantly improved detection accuracy.

Sanya et al. **[4]** developed a smart monitoring system measuring pH, turbidity, and temperature via IoT sensors, achieving early pollution detection and reducing manual testing needs. Tyagi et al. **[5]** proposed an IoT-based water quality and level monitoring system showing effective remote-area monitoring. Shilwant et al. **[6]** conducted a comparative study finding that IoT systems provide faster results and superior real-time monitoring capability over traditional laboratory testing.

Existing systems commonly suffer from high costs, limited scalability, and restricted sensor ranges. The present work addresses these gaps by providing a multi-parameter, low-cost, fully automated system with local alerting, cloud connectivity, and GSM-based remote notification.

III. System Architecture

The overall system architecture is centered on the Raspberry Pi 4 Model B as the central processing unit, interfacing with all sensors, the MCP3008 ADC, the LCD display, the micro-SD card, the buzzer, the relay module, and the GSM/GPRS module. Analog sensors (turbidity, TDS, soil moisture) connect through the MCP3008 8-channel, 10-bit ADC via SPI. The DS18B20 temperature sensor connects directly via the 1-Wire GPIO protocol. The pH sensor communicates via UART at 9600 baud. The relay module enables automated control of the DC water pump in response to threshold violations. The complete system block diagram is shown in Fig. 1.

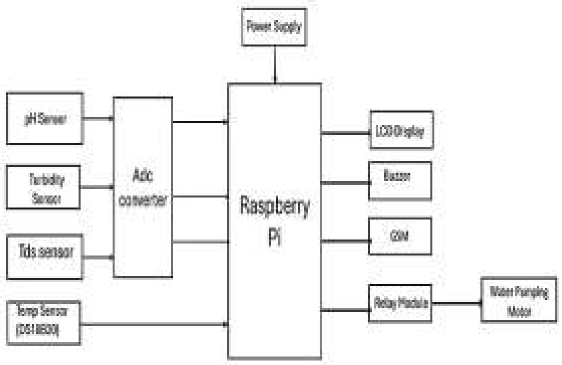

Fig. 1. Block Diagram of the Proposed IoT-Based Water Quality Monitoring System.

A. Advantages of the Proposed System

- Continuous real-time monitoring of five water quality parameters simultaneously without manual intervention.
- Cost-effective alternative to PLC/SCADA systems — hardware cost USD 150–200, approximately 95% reduction.
- Multi-channel alert outputs: audible buzzer, local LCD display, relay-controlled pump, and remote GSM/GPRS SMS.
- Timestamped CSV data logging for historical analysis and regulatory compliance reporting.
- Headless remote operation via RealVNC eliminates the need for a dedicated monitor at the plant site.
- Easy expansion: additional sensors or cloud modules can be integrated with minimal modification.

IV. HARDWARE DESCRIPTION

The following hardware components constitute the proposed IoT-based water quality monitoring system.

A. Raspberry Pi 4 Model B

The Raspberry Pi 4 Model B serves as the central processing and control unit. It features a Broadcom BCM2711 Quad-core Cortex-A72 64-bit processor at 1.8 GHz, up to 8 GB LPDDR4 RAM, a 40-pin GPIO header supporting SPI, I2C, UART, and 1-Wire protocols, dual micro-HDMI outputs, USB 3.0 ports, and a micro-SD card slot. The board runs Raspberry Pi OS (Raspbian) and supports Python development, making it ideal for IoT-based sensor interfacing, data processing, and automated control applications. Table I summarizes the key specifications.

TABLE I. RASPBERRY PI 4 MODEL B KEY SPECIFICATIONS

Parameter	Specification
Processor	Broadcom BCM2711, Quad-core Cortex-A72 @ 1.8 GHz
RAM	2 GB / 4 GB / 8 GB LPDDR4-3200 SDRAM
Storage	Micro-SD card slot
Connectivity	Wi-Fi, Bluetooth 5.0, Gigabit Ethernet
GPIO	40-pin header (SPI, I2C, UART, PWM, 1-Wire)
Power Input	5V DC via USB-C connector (min. 3A)

B. Turbidity Sensor (DFRobot)

Turbidity is the cloudiness or haziness of a fluid caused by suspended particles, measured in Nephelometric Turbidity Units (NTU). The DFRobot turbidity sensor measures water quality by detecting light transmittance and scattering. As turbidity increases, transmitted light decreases, producing a proportional analog voltage output (0–4.5 V). The sensor connects to the Raspberry Pi via MCP3008 ADC Channel 1. An alert is triggered when the ADC value exceeds 700 (approximately 4 NTU).

C. TDS Sensor (Keyestudio TDS Meter V1.0)

The TDS meter measures the concentration of dissolved salts, minerals, and metals in water using the electrical conductivity principle. The sensor is connected to MCP3008 ADC Channel 2. Safe drinking water requires TDS below 500 ppm; an alert is triggered when the ADC value exceeds 500.

D. pH Sensor PCB Module

The pH sensor PCB module measures the acidity or alkalinity of a water sample by evaluating hydrogen ion activity on a scale of 0 to 14. The safe pH range for potable water is 6.5–8.5 per WHO standards **[11].** The module communicates via UART at 9600 baud; serial data is parsed using regular expressions in the Python firmware. An alert is triggered if pH falls below 6.0 or exceeds 8.0.

E. DS18B20 Temperature Sensor

The DS18B20 is a digital temperature sensor measuring −55°C to +125°C with ±0.5°C accuracy using the 1-Wire protocol **[9].** Each sensor has a unique 64-bit serial code enabling multiple sensors on a single data line. The waterproof probe connects directly to GPIO pin 4. An alert is triggered if temperature exceeds 28°C.

F. Soil Moisture Sensor (FC-28)

The FC-28 soil moisture sensor detects moisture conditions in the surrounding installation area using capacitance or resistivity measurement, indicating potential pipe leakage or flooding. The analog output is read via MCP3008 Channel 0. An alert is triggered when the ADC value falls below 300, indicating excessive moisture.

G. GSM/GPRS Module (SIM800L)

The SIM800L is a compact GSM/GPRS module operating on the 850/900/1800/1900 MHz bands, supporting SMS transmission, voice calls, and GPRS data connectivity. It communicates with the Raspberry Pi via UART at /dev/ttyS0, using AT commands to send SMS alerts when water quality parameters exceed safe thresholds. It also supports HTTP POST requests for data upload to the ThingSpeak cloud platform. Table II summarizes the active buzzer specifications used alongside the GSM module.

TABLE II. ACTIVE BUZZER SPECIFICATIONS

Parameter	Value
Rated Voltage	5V DC
Operating Voltage	4–8V DC
Rated Current	< 30 mA
Sound Type	Continuous Beep
Resonant Frequency	~2300 Hz

H. MCP3008 8-Channel ADC

The MCP3008 is an 8-channel, 10-bit Analog-to-Digital Converter with SPI-compatible serial interface **[10].** It bridges the Raspberry Pi — which has no built-in ADC — and the analog sensors, converting voltage signals (0 V to VDD) into 10-bit digital values (0–1023). Channels 0, 1, and 2 are used for soil moisture, turbidity, and TDS respectively. SPI lines: MOSI (GPIO 10), MISO (GPIO 9), CLK (GPIO 11), CE0 (GPIO 8).

I. Relay Module and DC Water Pump

A two-channel relay module provides electrically isolated switching, allowing the low-voltage Raspberry Pi to safely control the DC water pump. When the GPIO control pin is driven HIGH, the relay coil is energized and the normally open (NO) contact closes. The mini submersible DC pump operates on 3–6V DC and is activated or deactivated automatically in response to sensor threshold exceedances, preventing contaminated water from advancing through treatment stages.

V. System Implementation

A. Circuit Connections

Table III provides the complete circuit connection summary, showing how the Raspberry Pi interfaces with all sensors and external components using different communication protocols.

TABLE III. Circuit Connection Summary

Component	Interface	Raspberry Pi Pin / Port
MCP3008 ADC	SPI (Bus 0)	GPIO 10(MOSI),9(MISO),11(CLK),8(CE0)
DS18B20 Sensor	1-Wire	GPIO 4 (4.7 kΩ pull-up to 3.3V)
LCD (I2C)	I2C	GPIO 2(SDA), GPIO 3(SCL), Addr 0x27
pH Sensor	UART	GPIO 14(TX), 15(RX) → /dev/serial0
Active Buzzer	GPIO Out	GPIO 21
Relay – Water Pump	GPIO Out	GPIO 17
Relay – Outer	GPIO Out	GPIO 18
GSM/GPRS Module	UART	GPIO 14/15 → /dev/ttyS0
Turbidity (Analog)	SPI/ADC	MCP3008 Channel 1
TDS (Analog)	SPI/ADC	MCP3008 Channel 2
Soil Moisture (Analog)	SPI/ADC	MCP3008 Channel 0

B. Communication Protocol Analysis

Table IV presents a comparative overview of the communication protocols selected for this system. SPI was selected for the MCP3008 ADC due to its synchronous clocking and high noise immunity in electrically noisy industrial environments. I2C minimizes LCD pin usage to two lines. UART suits the commercial pH module which ships with its own serial firmware. The 1-Wire protocol requires only a single signal wire, advantageous for future multi-point temperature monitoring deployments.

TABLE IV. Communication Protocol Comparison

Protocol	Speed	Wires	Primary Use in System
SPI	Up to 1.35 MHz	4+CS	MCP3008 ADC: turbidity, TDS, soil moisture
I2C	100–400 kHz	2	16×2 LCD display output
UART	9600 bps	2	pH sensor; GSM/GPRS module
1-Wire	15.4 kbps	1+GND	DS18B20 temperature sensor

C. Software Architecture

The monitoring application is developed in Python 3.x as a single-threaded main loop with modular helper functions per sensor. Key libraries include: spidev (SPI/MCP3008), RPi.GPIO (buzzer and relay control), RPLCD (I2C LCD), pyserial (UART/pH), requests (ThingSpeak HTTP POST), csv and datetime (data logging), and re (pH stream parsing).

The application is registered as a systemd service with Restart=always, ensuring automatic restart after any crash. All sensor read operations are wrapped in try-except blocks to handle intermittent disconnections gracefully. The Raspberry Pi hardware watchdog timer (bcm2835_wdt, 15-second timeout) automatically reboots the system if the application hangs.

D. System Operating Flow

The system follows a continuous monitoring loop: (1) Initialize all components (GPIO, SPI, UART, LCD); (2) Read sensor data from all channels; (3) Process and convert raw values to physical units using calibration equations; (4) Display readings on LCD; (5) Log timestamped readings to micro-SD CSV file; (6) Compare values with predefined thresholds; (7) If abnormal: activate buzzer, display alert on LCD, trigger relay; (8) Upload data to ThingSpeak every 15 seconds; (9) Sleep 2 seconds; (10) Repeat indefinitely.

VI. Results and Discussion

A. Hardware Setup and Remote Access

The complete hardware assembly integrates the Raspberry Pi 4 Model B, all five sensors, the MCP3008 ADC, 16×2 I2C LCD, active buzzer, two-channel relay module, DC water pump, and GSM/GPRS module. All components are assembled on a breadboard base powered by a 5V/3A USB-C supply. Since the Raspberry Pi operates in headless mode, remote desktop access is established via Advanced IP Scanner (for IP discovery) and RealVNC Viewer, enabling wireless monitoring and control without a dedicated monitor at the plant site.

B. Sensor Performance Evaluation

The system was tested using two water samples representing normal and abnormal conditions. Sample 1 produced stable, consistent readings within all safe thresholds without triggering any alerts. Sample 2 simulated threshold violations and confirmed prompt automated responses across all channels. Table V summarizes the sensor test results.

TABLE V. Sensor Sample Test Results — Normal vs. Abnormal Conditions

Parameter	Safe Range	Sample 1 (Normal)	Sample 2 (Abnormal)	Status
Turbidity	0–4 NTU	1.2 NTU (ADC:654)	6.8 NTU (ADC:>700)	Normal/Alert
pH	6.0–8.0	7.2	37.65 (out of range)	Normal/Alert
TDS	0–500 ppm	320 ppm (ADC:0)	720 ppm (ADC:>500)	Normal/Alert

Temperature	< 28°C	24.5°C	29.375°C	Normal/Alert
Soil Moisture	ADC > 300	ADC: 600	ADC: 1010 (Wet)	Normal/Alert

C. System Response Time Validation

When abnormal sensor conditions were introduced, the system demonstrated prompt and reliable automated responses across all four output channels simultaneously. The buzzer activated within 2 seconds, the LCD updated within 1 second, the relay executed a 3-second activation cycle, and the GSM/GPRS module transmitted an SMS within 10 seconds of the threshold violation. Table VI summarizes the response time validation results.

TABLE VI. SYSTEM RESPONSE TIME VALIDATION RESULTS

Output Channel	Response Time	Status
Buzzer Alert	< 2 seconds	PASS
LCD Display Update	< 1 second (immediate)	PASS
Relay Activation	3-second cycle	PASS
GSM/SMS Alert	< 10 seconds	PASS

D. Data Logging Verification

The data logging functionality was verified by examining CSV log files written to the micro-SD card. The Python firmware appends one row per monitoring cycle, recording all five sensor readings with accurate timestamps. Over 360 timestamped entries were recorded per hour with no missed cycles and no data loss under either normal or alert conditions. Log file structure: Timestamp | Temperature (°C) | Soil Moisture | Turbidity | TDS | pH | Alert Status.

E. Applications

- Municipal water treatment plants: automated potable water quality compliance monitoring.
- Industrial wastewater treatment: real-time effluent parameter monitoring before discharge.
- Irrigation and agricultural water management: pH, TDS, and turbidity monitoring in canals and ponds.
- Aquaponics, hydroponics, and aquaculture: precise monitoring of parameters critical to aquatic life.
- Drinking water storage tanks and distribution networks: contamination event detection.
- Reservoirs, dams, and unmanned water supply stations: GSM-based remote alerting.

VII. FUTURE SCOPE

The proposed system can be further enhanced in several directions. Cloud integration with platforms such as AWS IoT Core, Google Cloud IoT, or MQTT brokers would enable centralized monitoring and real-time visualization via web and mobile dashboards. Machine learning integration using historical sensor data to train predictive models such as Random Forest or LSTM **[7]** could enable anomaly detection before parameters reach critical levels.

Additional sensors for dissolved oxygen, conductivity, nitrate/nitrite, and heavy metal detection would provide more comprehensive water quality assessment. A custom PCB design would replace the breadboard prototype for field-ready deployment. A mobile application for operators and integration with solar or renewable energy sources for off-grid deployment represent further future enhancements.

VIII. CONCLUSION

This paper has presented an IoT-based real-time water quality monitoring system successfully designed, developed, and experimentally validated for water treatment plant applications. The system continuously monitors turbidity, pH, TDS, temperature, and soil moisture by integrating multiple sensors with a Raspberry Pi 4 Model B controller and MCP3008 ADC. Python-based firmware provides robust real-time data acquisition, threshold comparison, LCD display, micro-SD card logging, relay-based pump control, buzzer alerting, and GSM/GPRS remote SMS notification.

Experimental results confirm that the system reliably detects abnormal water quality conditions within 2 seconds and triggers appropriate automated responses promptly. The estimated hardware cost of USD 150–200 represents a reduction of approximately 95% compared to equivalent SCADA-based monitoring systems, demonstrating that IoT solutions incorporating readily available microprocessor platforms and low-cost sensors can deliver significant operational benefits for water treatment plant monitoring applications without requiring specialized instrumentation engineering expertise.

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