ECE 445

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Design Document

Water Quality Monitoring System

Group #63

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1 Introduction

1.1 Problem

Water pollution is a growing global concern, with industrial waste, agricultural runoff, and inadequate infrastructure contributing to the degradation of freshwater ecosystems. According to the United States Environmental Protection Agency (EPA), nutrient pollution from agricultural runoff is one of the most widespread and challenging environmental problems, affecting rivers, lakes, and reservoirs [10]. These pollutants can have devastating effects on aquatic life, particularly in controlled environments such as fish tanks and fish farms, where maintaining optimal water quality is critical for the health and survival of fish populations.

Traditional methods of monitoring water quality, such as manual sampling and laboratory testing, are time-consuming, labor-intensive, and often fail to provide real-time data. This delay in detecting contamination can lead to irreversible damage to aquatic ecosystems and economic losses for fish farmers. For example, the Food and Agriculture Organization (FAO) highlights that poor water quality is a leading cause of fish mortality in aquaculture, resulting in significant financial losses for farmers [4]. Furthermore, the lack of affordable and scalable solutions for real-time water quality monitoring exacerbates the problem, especially in remote or resource-constrained areas. Without timely intervention, pollutants can accumulate to dangerous levels, leading to fish mortality, ecosystem imbalance, and potential risks to human health if contaminated water is consumed. Therefore, there is an urgent need for an efficient, cost-effective, and scalable system that can continuously monitor water quality parameters and provide actionable insights to prevent contamination and ensure the safety of aquatic environments.

1.2 Solution

We propose an IoT-based water quality monitoring system designed to provide real-time, actionable insights into maintaining water quality. Our solution features a custom PCB that integrates the ESP32 microcontroller, sensors for pH, turbidity, temperature, dissolved oxygen, and power/communication circuits, ensuring a compact and reliable design. The system measures and estimates critical water parameters in real time and transmits data wirelessly to a cloud dashboard for remote monitoring. Additionally, the system will be low-cost, portable, and scalable, making it suitable for fish tanks. By combining affordability, real-time data, and ease of use, our solution empowers communities to monitor water quality proactively and prevent contamination risks.

1.3 Visual Aid

Figure 1 is a visual overview of our water quality system.

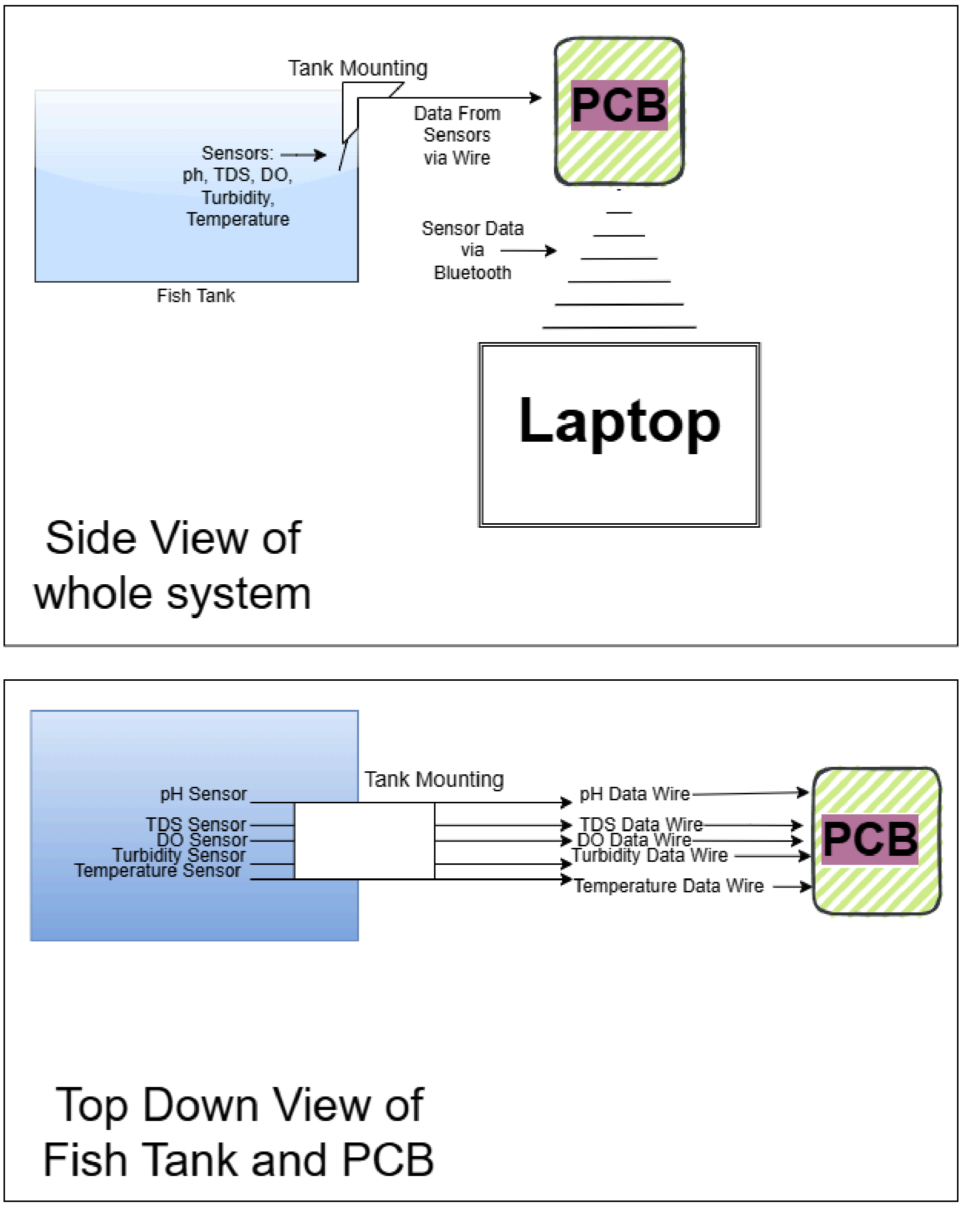


Figure 1: Visual Overview of the Water Quality System

1.4 High-level requirements list

- Sensor Accuracy: The system must measure pH, turbidity, temperature, total dissolved solids (TDS), and dissolved oxygen (DO) with an accuracy of within 5% of calibrated lab equipment to ensure reliable water quality assessment.

- Real-Time Data Transmission: The system must transmit sensor data to the cloud every 30 minutes with a packet loss of less than 5%, ensuring continuous and reliable monitoring.

- Sustained Operation: The system must be able to operate for at least 24 hours on battery power while collecting and transmitting data, making it suitable for off-grid and remote deployments.

2 Design

2.1 Block Diagram

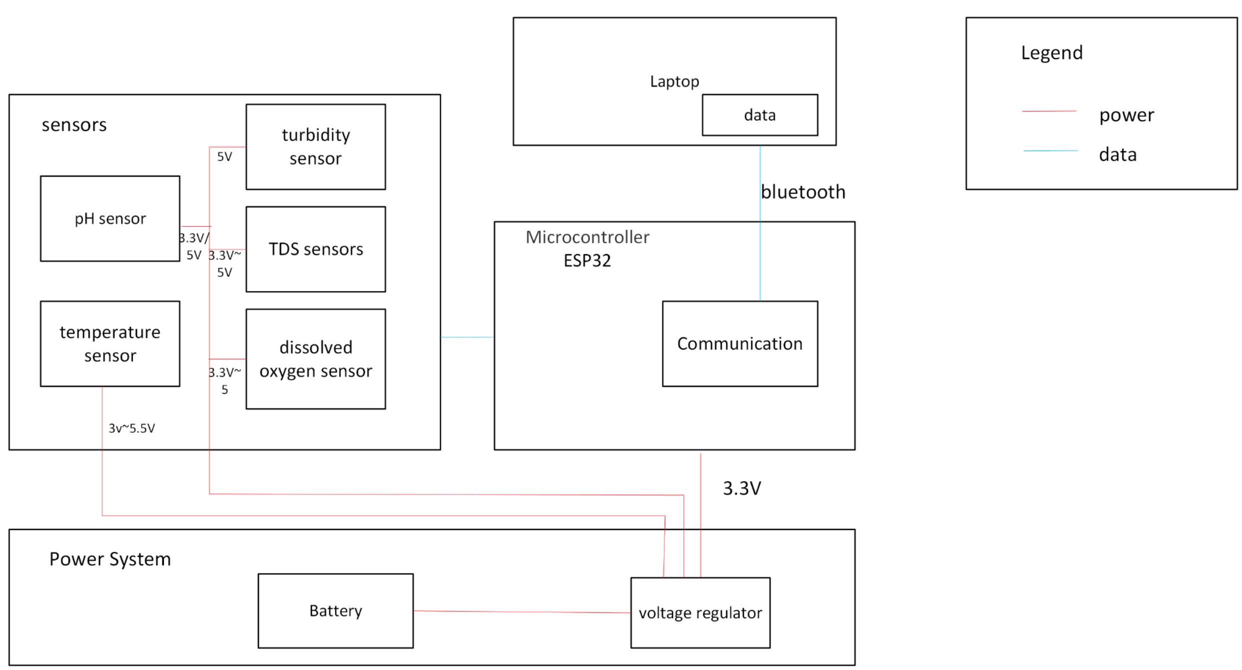
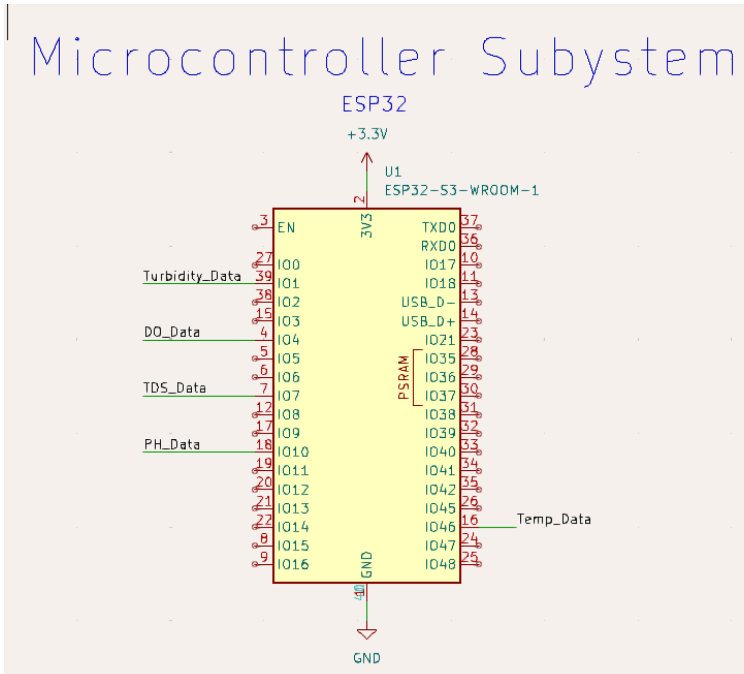


Figure 2: Block Diagram

2.2 Subsystem Overview

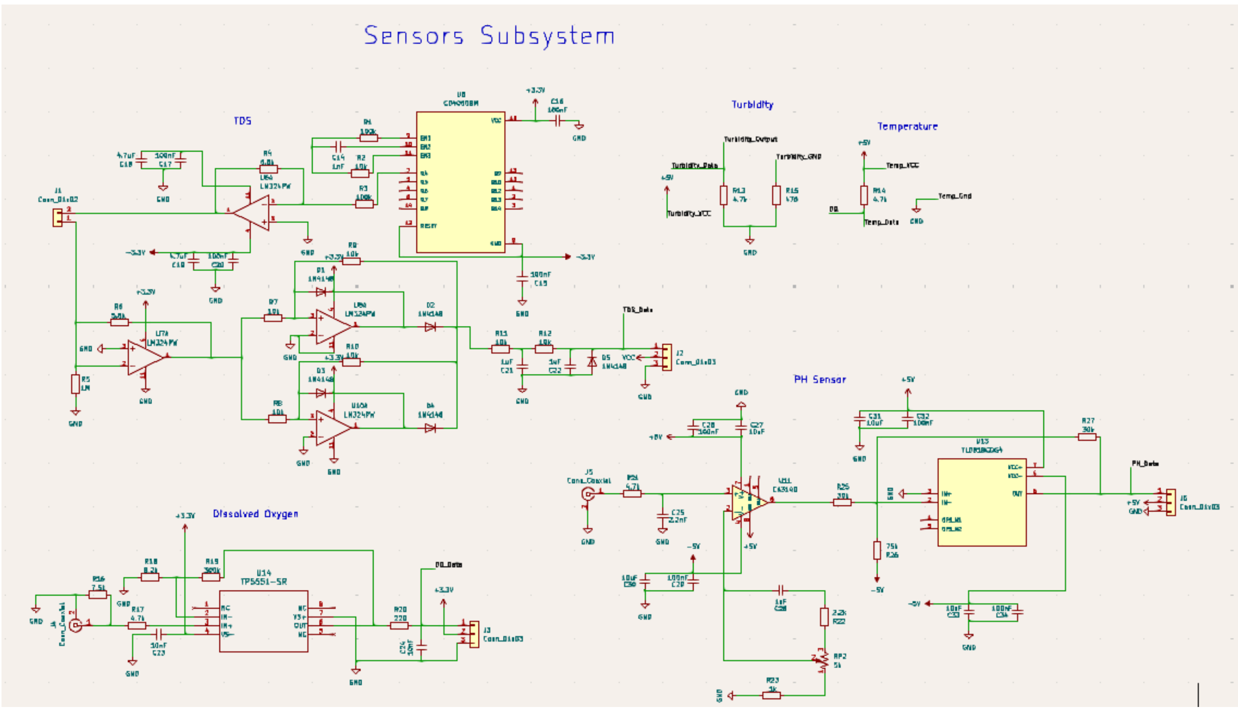


2.2.1 Microcontroller:

ESP32 (QFN package, pre-soldered by lab or ordered from E-Shop). The ESP32 microcontroller is the central processing unit in the water quality monitoring system, responsible for acquiring, processing, and transmitting data from the sensors. As the core of the system, it plays a crucial role in meeting the high-level requirements, particularly the need for real-time data transmission and reliable performance. The ESP32 interfaces with the sensor array, power subsystem, and communication subsystem to ensure that all components operate efficiently. It collects analog and digital signals from the pH, turbidity, temperature, and TDS sensors, converting them into digital values using its ADC. It also optimizes power usage for the battery, ensuring efficient operation with the power subsystem. [3] For communication, the ESP32 supports Bluetooth for data transmission. Bluetooth allows for short-range communication, ideal for local monitoring or connecting to mobile devices or a centralized hub. The ESP32 transmits sensor data to the mobile app or cloud dashboard via Bluetooth, ensuring continuous monitoring. This capability is essential for meeting the real-time data transmission requirement, where data must be sent to the cloud dashboard with less than 5% packet loss.

Requirements	Verification
The ESP32 must operate within a voltage range of 3V-5V	Use a Digital Multimeter (DMM) to measure the voltage supplied to the ESP32 VCC pin.
The ESP32 must correctly acquire and process data from all sensors with an accuracy of at least 95%.	1. Connect the ESP32 to a calibrated reference sensor (e.g., known pH buffer solution, precise temperature source). 2. Log sensor values from the ESP32 and compare against the reference. 3. Compute the error percentage and verify that accuracy is ≥ 95%. 4. Repeat the test at least 10 times for consistency.
The ESP32 must be able to handle at least five sensor inputs simultaneously without data loss.	1. Connect five different sensors (e.g., pH, turbidity, temperature, TDS, dissolved oxygen) to the ESP32. 2. Simultaneously request data from all sensors. 3. Log the readings over a continuous 10-minute period. 4. Check that there are no dropped readings or data corruption in the logs.
The ESP32 must transmit data every 30 minutes with less than 5% packet loss.	1. Configure the ESP32 to send sensor data to a cloud service every 30 minutes. 2. Monitor transmission logs for 24 hours (48 transmissions). 3. Count the number of successfully received packets and calculate the packet loss percentage. 4. Verify that packet loss ≤ 5% over the test period.
The ESP32 must be able to estimate data trends for future time points based on previous sensor readings.	1. Implement a simple moving average or predictive model in firmware. 2. Collect sensor readings over a 24-hour period. 3.

	Compare estimated vs actual values at future time points. 4. Verify that the prediction error is within an acceptable range (e.g., ±10%).



2.2.2 Sensor Array

The Sensor Array Subsystem is responsible for collecting real-time water quality data by measuring key parameters such as pH, turbidity, temperature, dissolved oxygen, and total dissolved solids (TDS). The Sensor Array Subsystem plays a key role in the overall design by providing the data input necessary for real-time monitoring. The sensors convert physical and chemical water parameters into analog or digital signals, which are then processed by the ESP32 microcontroller. These data points contribute directly to the system's ability to meet high-level requirements, including accurate water quality measurement and real-time data transmission for effective monitoring and early detection of contamination risks. pH Sensor: 5016-SRV-PH-ND, Turbidity Sensor: TSD-10 Liquid Temp Sensor: DS18B20 TDS Sensor: SEN0244 Dissolved oxygen sensor: DO-BAT. The sensor array provides analog and digital outputs to the ESP32 microcontroller for data acquisition and processing. The microcontroller collects these data points, applies calibration algorithms, and transmits the processed information to the cloud dashboard for remote monitoring. The sensors are powered by the voltage regulator, which provides stable voltage levels to ensure the sensors operate within their specified ranges. Each sensor requires 3V, 3.3V or 5V, depending on the model, and the voltage regulator ensures that these voltages are stable even under varying load conditions.

Requirements	Verification
The sensor array must provide accurate readings for pH, turbidity, temperature, TDS, and dissolved oxygen (DO) within ±5% of calibrated lab equipment.	1. Place the sensor in a known reference solution (e.g., pH buffer, turbidity standard). 2. Measure the sensor output using the microcontroller (ESP32) and compare the readings with calibrated lab equipment. 3. Record the measurement and verify it falls within ±5% of the reference value for each sensor.
The pH sensor must output a voltage that corresponds to pH values between 0 and 14	1. Prepare buffer solutions with pH values of 4, 7, and 10. 2. Use a DMM to measure the voltage output of the pH sensor and verify it falls within the expected range for each buffer solution. 3. Record the voltage and check the linearity between pH values and voltage output.
The turbidity sensor must measure water turbidity between 0 and 1000 NTU (Nephelometric Turbidity Units) with accuracy within ±5%.	1. Use a standard turbidity solution (e.g., 400 NTU). 2. Connect the turbidity sensor to the ESP32 and measure the turbidity. 3. Compare the sensor's output with the standard turbidity

	value and confirm that it is within ±5%. 4. Record results and check for consistency across multiple measurements.
The temperature sensor must measure water temperature with an accuracy of ±0.5°C over the range of 0°C to 50°C.	1. Place the temperature sensor (DS18B20) in water at known temperatures (e.g., 0°C, 25°C, 50°C). 2. Use a calibrated thermometer to verify the sensor's output. 3. Ensure that the sensor readings are within ±0.5°C of the calibrated temperature.
The TDS sensor must measure Total Dissolved Solids (TDS) in the range of 0 to 1000 ppm with accuracy within ±5%.	1. Prepare a standard TDS solution (e.g., 500 ppm). 2. Use the TDS sensor to measure the solution's TDS and compare it to the known reference value. 3. Ensure the readings fall within ±5% of the reference TDS. 4. Record the results and verify accuracy at multiple TDS concentrations.
The dissolved oxygen (DO) sensor must measure dissolved oxygen concentration in the range of 0 to 20 mg/L with accuracy of ±2%.	1. Place the DO sensor in a saturated oxygen solution (e.g., water exposed to air). 2. Measure the DO concentration and compare it with the expected value from the manufacturer's specifications. 3. Ensure the sensor output is within ±2% of the expected value. 4. Record the DO readings and verify consistency with known concentrations.
The sensor array must operate without significant interference or cross-talk between sensors.	1. Test the system by activating multiple sensors simultaneously. 2. Measure the output from each sensor and verify that each sensor provides a stable and independent reading

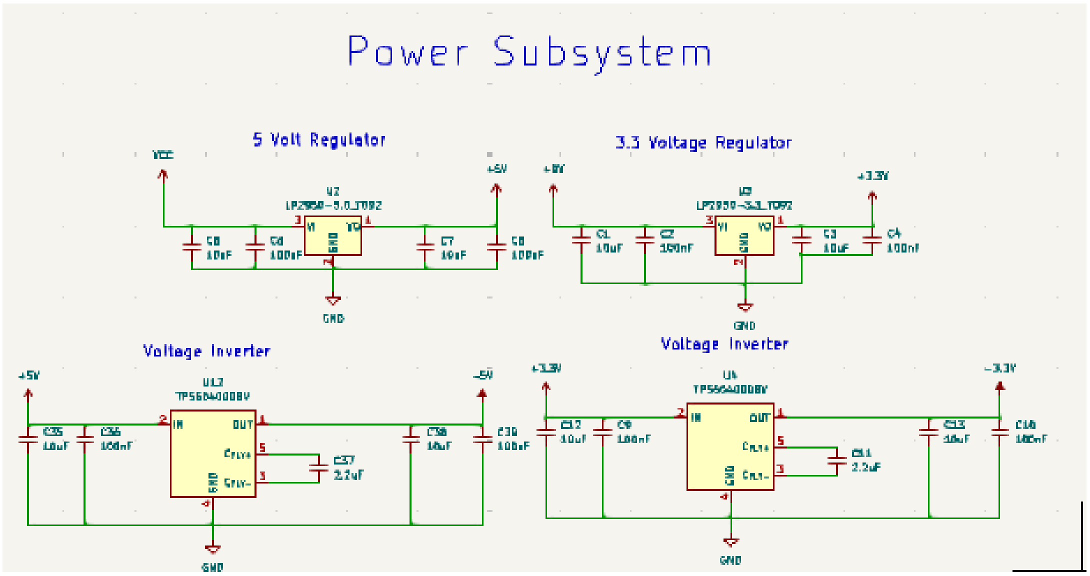
	without significant deviations or interference from the others. 3. Record results and confirm that sensor outputs remain unaffected by simultaneous operation.

2.2.3 Communication:

The Communication Subsystem enables data transmission, remote access, and cloud integration for the water quality monitoring system. This ensures real-time monitoring and data storage for further analysis. The Communication Subsystem connects the sensor array to the cloud-based platform, allowing users to remotely monitor and analyze water quality data. This subsystem supports real-time transmission of data collected from the sensors, ensuring that water quality conditions are always up to date and available for assessment. By transmitting data to a cloud server, the system provides the flexibility for remote access, enhancing the scalability and portability of the monitoring system. It also facilitates easy integration with mobile apps and other monitoring tools for end-users. ESP32 Built-in Bluetooth. UART Header for Programming (Through-hole pins). IoT Connectivity: ESP32/ESP8266 for Wi-Fi or LoRa module for long-range communication. Cloud Integration: Data sent to AWS IoT/ThingSpeak for storage and analysis. The ESP32 microcontroller serves as the interface point between the sensor array and the communication subsystem. It collects sensor data, processes it, and sends it to the cloud platform. The Bluetooth communication is handled by the ESP32’s internal module, allowing the system to transmit data wirelessly to the mobile device or central hub. The sensor array provides the raw data that is processed by the ESP32 and transmitted through the communication subsystem. The data collected by the sensors is sent as digital packets to the cloud or Bluetooth-enabled device for analysis.

Requirements	Verification
The ESP32 must establish a Bluetooth connection with the laptop application within 5 seconds of scanning.	1. Enable Bluetooth discovery mode on the ESP32. 2. Open the laptop application and scan for available Bluetooth devices. 3. Measure the time taken from scan initiation to successful connection. 4. Verify that the connection is established within ≤ 5 seconds.
The ESP32 must support UART communication for debugging and external programming.	1. Connect the ESP32 to a PC via USB-to-serial adapter. 2. Open a serial terminal (e.g., PuTTY, Arduino Serial Monitor) and send test commands. 3. Check if ESP32 properly transmits and receives messages over UART. 4. Use ESP32's UART to flash firmware and verify successful programming.
The ESP32 must store data locally in case of network failure and retry transmission.	1. Simulate Wi-Fi/Bluetooth disconnection while ESP32 attempts to send data. 2. Verify that data is stored in ESP32's SPIFFS, SD card, or EEPROM. 3. Restore network connectivity and confirm that stored data is successfully transmitted to the cloud. 4. Validate that no data is lost in the process.

2.2.4 Power System



The Power Subsystem ensures a stable and reliable energy supply for the water quality monitoring system, supporting battery-powered operation: external to PCB, connected via through-hole terminal block, Wide traces for high-current paths. The power subsystem is critical for maintaining system stability and longevity. It must provide a regulated power supply to all subsystems while ensuring that energy consumption is optimized for long-term operation. Since the system is designed for continuous water quality monitoring, the power subsystem must meet the high-level requirement of enabling the system to operate for at least 24 hours on a fully charged battery. Voltage Regulator (Through-hole for easy soldering). The ESP32 requires a stable 3.3V power supply to function correctly. The power subsystem provides regulated 3.3V output to prevent voltage fluctuations that could cause system instability. The pH, turbidity, TDS, temperature, and DO sensors require 3V, 3.3V or 5V to function. The power subsystem ensures that each sensor receives the appropriate voltage. The voltage regulator distributes power efficiently to avoid voltage drops that could affect sensor accuracy. Bluetooth communication requires bursts of power during data transmission. The power subsystem ensures that the system can handle power spikes when the ESP32 is actively transmitting data while maintaining efficiency during idle periods.

Requirements	Verification
The voltage regulator must supply at least 500mA continuously at 3V, 3.3V, and 5V to power the entire system.	1. Use a digital multimeter (DMM) or electronic load to measure the current drawn by the system at each voltage level (3V, 3.3V, 5V). 2. Apply a constant load of 500mA to each output (3V, 3.3V, 5V) and verify that the voltage stays within the specified range (±0.1V). 3. Record the results and check for any significant drop in voltage or instability during the test.
The system must operate for at least 24 hours on a fully charged battery.	1. Fully charge the battery and ensure it is connected to the system. 2. Run the system with all components operating (sensors, ESP32, communication) for normal operation. 3. Monitor the system and battery voltage every hour using a DMM to ensure it continues running for at least 24 hours without dropping below 3.3V. 4. Record the battery voltage periodically and confirm that the system functions for at least 24 hours under normal conditions.
The power system must handle a sudden short circuit without damaging components.	1. Intentionally short the output terminals of the voltage regulator for 5 seconds. 2. Confirm that the regulator enters protection mode (if applicable) and resumes normal operation after the short is removed. 3. Check for overheating or permanent damage to components. 4. Measure the temperature and current to ensure protection features are

	working as intended.

2.3 Tolerance Analysis

One of the most critical aspects of our water quality monitoring system is the accuracy and stability of sensor readings, particularly for pH, turbidity, and dissolved oxygen (DO) sensors. Ensuring these sensors operate within an acceptable error margin (≤5%) is crucial for reliable water quality assessment.

For the pH sensor 5016-SRV-PH-ND, factors such as temperature variations, ADC resolution, and electrical noise could introduce errors in pH measurements, impacting overall system reliability. The sensor will output a voltage from 3.00V to 0.265V. [8] We use Equation 1 below to convert voltage to pH value:

$$pH = (-5.6548 \times voltage) + 15.509 \tag{1}$$

This process can be done in the ESP32 microcontroller. When reading analog voltage from the sensor, the microcontroller will apply this equation to determine the pH value accurately. The ESP32 features a 12-bit ADC, meaning it can represent values from 0 to 4095. [3] Given a 3.00V to 0.265V working range for pH sensor, the smallest detectable voltage change is:

$$\frac{(3V - 0.265V)}{4096} \approx 0.000668V \tag{2}$$

Then, using equatio

$$\Delta pH = -5.6548 \times 0.000668 = 0.003778 \tag{3}$$

Equation 3 suggests that the ESP32 can resolve pH changes as small as 0.0045, ensuring sufficient precision within the 5% accuracy requirement. In addition, temperature can also have an effect on the accuracy of pH measurements. The pH sensor's output varies with temperature.

To mitigate this, we will integrate a temperature compensation algorithm using the temperature sensor. Furthermore, external noise may introduce errors. To reduce electrical noise, we can average over multiple samples to smooth fluctuations, and we can apply low-pass filtering to remove high-frequency noise. Regular calibration using standard pH buffers (pH 4, 7, and 10) [8] will ensure the system maintains accuracy within the 5% error tolerance.

3 Cost & Schedule

3.1 Bill of Materials

3.1.1 Sensors

Description	Part #	Reference Sheet	Purchase Link	Cost
pH Sensor	KIB-87	pH Sensor	pH Sensor	$17.99
Total Dissolved Solids Sensor	ef74534f-275e-4c61-8060-b8eec5ca4011	Total Dissolved Solids Sensor	Total Dissolved Solids Sensor	$4.26
Total Dissolved Oxygen Sensor	DO-BTA	Total Dissolved Oxygen Sensor	Total Dissolved Oxygen Sensor	$24.99
Turbidity Sensor	TSD-10	Turbidity Sensor	Turbidity Sensor	$8.96
Temperature Sensor	DS18B20 LM35DZ	Temperature Sensor	Temperature Sensor	$9.95
Total Cost				**$66.15**

3.1.2 Resistors and Capacitors

Description	Manufacturer	Quantity	Unit Price	Cost
10k Ohms resistor	Stackpole Electronics Inc	7	$0.10	$0.70

4.7k Ohms resistor	Stackpole Electronics Inc	4	$0.10	$0.40
6.8k Ohms resistor	Stackpole Electronics Inc	1	$0.10	$0.10
100k Ohms resistor	Stackpole Electronics Inc	2	$0.10	$0.10
5.6k Ohms resistor	Stackpole Electronics Inc	1	$0.10	$0.10
7.5k Ohms resistor	Stackpole Electronics Inc	1	$0.10	$0.10
8.2k Ohms resistor	Stackpole Electronics Inc	1	$0.10	$0.10
300k Ohms resistor	Stackpole Electronics Inc	1	$0.10	$0.10
30k Ohms resistor	Stackpole Electronics Inc	1	$0.10	$0.10
75k Ohms resistor	Stackpole Electronics Inc	1	$0.10	$0.10
470 Ohms resistor	Stackpole Electronics Inc	1	$0.10	$0.10
220 Ohms resistor	Stackpole Electronics Inc	1	$0.88	$0.88
1M Ohms resistor	Stackpole Electronics Inc	1	$2.67	$2.67
4.7 uF capacitor	Cal-Chip Electronics, Inc.	2	$0.0045	$0.0090
100 nF capacitor	Cal-Chip Electronics, Inc.	16	$0.0010	$0.0160
1 nF capacitor	Cal-Chip Electronics, Inc.	1	$0.0015	$0.0015
10 uF capacitor	Cal-Chip Electronics, Inc.	14	$0.0090	$0.1260
2.2 uF capacitor	Cal-Chip Electronics, Inc.	2	$0.0040	$0.0080
10 nF capacitor	Cal-Chip	2	$0.0013	$0.0026

	Electronics, Inc.			
1 uF capacitor	Cal-Chip Electronics, Inc	2	$0.0020	$0.0040
2.2 nF capacitor	Cal-Chip Electronics, Inc.	1	$0.0021	$0.0021
Total Cost				**$5.72**

3.1.3 Other

Description	Part #	Quantity	Cost per Unit
Diode	1N4148	5	$0.1
Microcontroller	ESP32	1	$5.92
Potentiometer	3296W-1-502	1	$2.90
BNC Connector	031-5540	2	$6.30
XH connector	xh2.54-2p	1	$0.95
3 Position Female Dupont	S7036-ND	5	0.266
Clock Generator	CD4060	1	0.564
Op-Amp	CD3140E	1	$3.70
Op-Amp	TP5551-SR	1	$3
Op-Amp	LM324	4	$0.01
Op-Amp	TL081CDR	1	$0.067
Charge Pump Inverter	TPS60400DBVR	2	$1
Linear Voltage Regulator	LP2950CZ	2	$1.50
Total Cost			**$36.571**

3.1.4 Cost Analysis

The total cost above for all the components is $81.287. For the labor cost, we can expect $45/hr*2.5*40=$4500. The total labor cost for all team members is $4500*3=$13500. The total cost for this project is $13581.287.

3.2 Schedule

Week	Jackie	Haokai	Harrison
3/3	Design Document Component Ordering	Design Document Completing PCB Design	Design Document Component Ordering
3/10	Breadboard Refining PCB Design	Breadboard Refining PCB Design	Breadboard Component Ordering
3/17	Spring Break	Spring Break	Spring Break
3/24	Soldering Refining PCB	Software Setup PCB Debugging	Soldering Software Setup
3/31	Coding ESP32 Data in from TDS sensor Interface setup for data	Coding ESP32 Data in from TDS sensor Interface setup for data	Coding ESP32 Data in from TDS sensor Interface setup for data
4/7	Coding ESP32 Data in from temperature and PH sensor Add future data estimates to graph	PCB debugging Coding ESP32 Data in from Dissolved Oxygen Add future data estimates to graph	Coding ESP32 Data in from Dissolved Oxygen and Turbidity Add future data estimates to graph
4/14	Debugging/refining	Debugging/refining	Debugging/refining

	design/final presentation preparation/team contract	design/final presentation preparation/team contract	design/final presentation preparation/team contract
4/21	Mock Demo	Mock Demo	Mock Demo
4/28	Final Demo	Final Demo	Final Demo
5/5	Final Presentation	Final Presentation	Final Presentation

4 Ethics and Safety

4.1 Ethics

Our IoT-based water quality monitoring system prioritizes ethical responsibility and safety to ensure secure, reliable, and environmentally conscious operation. We will mainly follow IEEE Code of Ethics adopted by the IEEE Board of Directors through June 2020 [6]. Guided by the IEEE Code of Ethics, we prioritize the following principles:

1. **Transparency and Accountability [6]**
   We uphold transparency by openly sharing the water quality system's methodologies, capabilities, and limitations with users. This ensures informed decision-making and fosters trust. Any potential biases in the system's performance will be addressed through rigorous testing with diverse water samples, ensuring equitable and reliable outcomes across different environments.
2. **Data Privacy and Security [6]**
   Protecting user data is an important part of our ethical framework. All water quality data collected will be securely stored and transmitted using encryption and other robust cybersecurity measures to prevent unauthorized access. We will adhere to data protection regulations and ensure that users retain control over their information.

3. **Fairness and Inclusivity [6]**
   The system is designed to be accessible and beneficial to all users, regardless of technical expertise or geographic location.
4. **Responsible Innovation [6]**
   We recognize the potential societal and environmental impacts of technological advancements. Our water quality system will be developed and deployed with careful consideration of its long-term effects, ensuring that it does not inadvertently harm communities or ecosystems. We will actively seek feedback from stakeholders to improve the system and address emerging ethical concerns.
5. **Professional Integrity [6]**
   As developers and engineers, we commit to maintaining the highest standards of honesty, integrity, and professionalism. We will avoid conflicts of interest, provide accurate and unbiased information, and ensure that our work is free from misrepresentation or misuse.

4.2 Safety

Data privacy and security are key concerns, so all collected water quality data will be securely stored and transmitted to prevent unauthorized access. The system's transparency is maintained by clearly stating its limitations and providing open access to methodologies, ensuring users understand its capabilities and accuracy constraints. To prevent bias, the system will be validated with diverse water samples to ensure reliable performance across different environments. Electrical safety is addressed through proper insulation, waterproofing, and the use of low-voltage components, reducing risks of short circuits or electric shock. Additionally, the materials used in our sensors will be non-toxic and safe for aquatic environments, preventing contamination. Our design minimizes environmental impact by using modular, repairable components and providing clear disposal instructions for batteries and electronic waste. System reliability is critical, so measures such as alert mechanisms for sensor malfunctions and guidelines for proper maintenance will be implemented to prevent false readings that could lead to incorrect decisions. Finally, the system will be designed for ease of use, ensuring that installation does not require technical expertise while mitigating risks associated with misuse or extreme environmental conditions. By addressing these ethical and safety concerns, our project aims to provide a responsible, user-friendly, and effective solution for real-time water quality monitoring.

5 References

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