Politecnico di Torino

Master's Degree Thesis

PLC-Based Water Quality Monitoring and Separation System

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Abstract

Water quality monitoring is a fundamental necessity for industrial processes, human health, and environmental sustainability. This thesis introduces the development of an automated water quality monitoring and separation system controlled by a PLC, which uses Potential of Hydrogen (pH) and Total Dissolved Solids (TDS) sensors to evaluate water quality and display real-time readings on a Human-Machine Interface (HMI). Based on the measured parameters (pH and TDS), the system displays indications on the HMI, helping the user manually select the appropriate drainage compartment.

There is often a noticeable gap between the way industrial automation is taught in classrooms and the practical skills that engineers need in real-world applications. This thesis presents the development of a comprehensive PLC-based control system designed to emulate a scalable industrial process within a laboratory environment.

The system utilizes a Siemens PLC S7-1200 1215C AC/DC/RLY for control, accompanied by an HMI (KTP700 Basic PN) for user interaction.

The system performs the following functions:

- Initiates water pumping into the storage tank upon operator command.
- Measures water quality parameters, such as pH and TDS, in real time with integrated sensors.
- Displays live feedback of measured values and status messages on the HMI.
- Generates event-based text indications with variable visibility to classify water quality.
- Enables manual selection of drainage, directing water either to Compartment A (clean water) or Compartment B (contaminated water).

Before transitioning to the actual hardware, the system was first tested in a virtual environment using Siemens PLCSIM, which helped identify control logic issues and uncover design problems early on. After a successful simulation, the project moved forward through the entire development cycle. The mechanical design of the tank and its supporting structure was modeled in SolidWorks and 3D printed using Cura Software, which is compatible with the AnyCube Printer. The complete assembly was then integrated with the electrical and control hardware. Control logic was implemented and refined in Totally Integrated Automation (TIA) Portal.

Calibration and uncertainty analysis played a crucial role in this work. The pH sensor was calibrated using two standard buffer solutions (pH 4.00 and pH 10.00) through a two-point linear calibration (gain and offset adjustment), bringing sensor values into approximation with the buffer values. The TDS sensor exhibited a baseline offset of +5.35 ppm in the

absence of dissolved solids, which was corrected by subtracting this offset from all subsequent readings.

The repeatability of the two sensors was also assessed by measuring the standard deviation of ten repeated readings in different solutions (pH 4, pH 10, tap water, salt water, and lemon water). Results showed that the uncertainty from the experimental measurements was minimal compared to other factors.

Further improvements could include integrating a Supervisory Control and Data Acquisition (SCADA) system, which would enable remote monitoring and an automated drainage system, eliminating the need for human intervention for real-time water quality analysis.

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Abbreviations List

1. **PLC** — Programmable Logic Controller
2. **HMI** — Human–Machine Interface
3. **SCADA** — Supervisory Control and Data Acquisition
4. **pH** — Potential of Hydrogen
5. **TDS** — Total Dissolved Solids
6. **PROFINET / PN** — PROFINET (Industrial Ethernet standard)
7. **TIA** — Totally Integrated Automation
8. **S7-1200 (CPU 1215C)** — Siemens SIMATIC S7-1200 PLC (CPU 1215C model)
9. **PLCSIM** — PLC Simulation (Siemens software)
10. **AI** — Analog Input
11. **DI** — Digital Input
12. **DO** — Digital Output
13. **NO** — Normally Open
14. **NC** — Normally Closed
15. **PID** — Proportional–Integral–Derivative (controller)
16. **PWM** — Pulse-Width Modulation
17. **ISFET** — Ion-Sensitive Field-Effect Transistor
18. **RO** — Reverse Osmosis
19. **PCB** — Printed Circuit Board
20. **USB** — Universal Serial Bus
21. **WHO** — World Health Organization
22. **EPA** — Environmental Protection Agency
23. **BIS** — Bureau of Indian Standards
24. DIM — Dimension (drawing/schematic shorthand)
25. DQ — Digital Output (Q-memory area in Siemens PLCs)
26. DR — Data Register / Drive (depends on context)
27. EMF — Electromotive Force (valid term, but check if you want it as an abbreviation)
28. ESD — Electrostatic Discharge
29. FBD — Function Block Diagram
30. GUI — Graphical User Interface
31. KTP — Key Touch Panel (Siemens HMI family, e.g., KTP700)
32. LED — Light Emitting Diode
33. ML — Machine Learning
34. PPE — Personal Protective Equipment
35. RTU — Remote Terminal Unit
36. SB — Signal Board (Siemens hardware)
37. SM — Signal Module (Siemens hardware)
38. UPS — Uninterruptible Power Supply
39. VDC — Volts Direct Current

1. Introduction

1.1 Background and Motivation

Water is an essential resource for human survival, industrial processes, and environmental health. Increasing concerns about water contamination from industrial waste, agricultural runoff, and improper disposal of chemicals have caused significant damage to our planet, highlighting the need for more effective monitoring and treatment solutions. Providing safe and clean water, considered suitable for use, is a luxury today; it is vital for maintaining industrial efficiency and promoting environmental sustainability.

There are other traditional methods for monitoring water quality, which usually involve manual periodic sampling and laboratory analysis. These methods are often slow, labor-intensive, and susceptible to human error. This can also affect real-time data monitoring because samples are collected and sent to the lab, making it difficult to respond quickly to contamination events. As a result, there has been a rise in automation and intelligent control systems in industries and water facilities, aiming to improve efficiency, accuracy, and reliability in water quality assessment.

For instance, a study highlighted that effective water quality monitoring is crucial for alerting authorities to pollution incidents, enabling prompt action to protect public health and ecosystems [1].

The integration of Programmable Logic Controllers (PLCs) has provided a robust and automated solution for real-time water analysis and separation. PLCs are mainly used in industrial automation because of their durability, reliability, precision, and their ability to synchronize multiple sensors and actuators into a single control system. Therefore, by leveraging PLC technology combined with various sensors such as pH and TDS, I have designed a scalable water quality monitoring system. This system evaluates, categorizes, and allows the user to manually separate water based on sensor readings, simply by pressing a button on the HMI. This automation improves the accuracy of data collection and enables immediate corrective actions when water quality falls outside acceptable standards [2].

1.2 Problem Statement

Water contamination is a critical issue that affects multiple sectors, including drinking water supply, agriculture, industrial processes, and environmental conservation, which includes aquatic life. Existing water quality monitoring systems often lack real-time automation and require manual sampling of water, which involves sending samples to laboratories. This process is time-consuming and creates delays in the workflow. This can lead to inconsistencies and inefficiencies in the water treatment process.

A significant challenge in traditional water quality assessment is the inability to take quick and immediate corrective action when water quality deviates from acceptable limits. The absence of an automated mechanism to detect contamination, trigger alerts, and take corrective measures further exacerbates the issue. To address this gap, an intelligent **PLC-based water monitoring and separation system** is needed, which can:

- Monitor water parameters such as pH and TDS in real time.
- Automatically categorize water as clean or contaminated based on predefined thresholds.
- Trigger alerts and initiate corrective actions when contamination is detected.
- Minimize human intervention and improve overall efficiency in water quality management.

1.3 Objective of the Study

The primary objective of this thesis is to design and implement a PLC-based water quality monitoring and separation system capable of analyzing, detecting, and segregating water based on sensor results, and classifying its purity.

The specific objectives of the thesis include:

- Design a fully automated water monitoring system using Siemens S7-1200 1215 AC/DC/RLY PLC for real-time analysis of water quality parameters.
- Integrate sensors for measuring pH levels and Total Dissolved Solids (TDS) with the PLC system.
- Develop a decision-making algorithm using Ladder Logic (LAD) programming that can classify water as either clean or contaminated based on measured values.
- Implementing a Human-Machine Interface (HMI) for real-time monitoring, data visualization, and manual control.
- To evaluate the performance of the system in terms of accuracy, efficiency, and response time compared to conventional manual testing methods.
- To propose future enhancements, including IoT integration, cloud-based data storage, and AI-driven analytics, for improved scalability and intelligence.

1.4 Scope of the Study

This Thesis focuses on the development, design, and testing of an automated water quality monitoring system utilizing PLC technology. The Scope of the study includes:

1. Hardware and Software Implementation
    - The system is built around a **Siemens S7-1200 PLC**, which serves as the central controller.
    - **pH and TDS sensors** are used for water quality assessment.

- **Solenoid valves and a pump** are integrated to regulate the water flow and separation process.
- A **start** to start the process and a **stop** button to halt all operations.
- **Siemens TIA Portal** V15.1 is used for PLC programming and system control.

2. Water quality parameters and decision criteria
   - **pH Sensor:** The pH level of water determines its acidity or alkalinity, which directly affects overall suitability for consumption. Water with a very low pH is considered acidic and can cause corrosion of pipes and metal fittings. In contrast, water with a high pH, which is regarded as alkaline, may lead to scale formation and an undesirable taste. According to the World Health Organization (WHO), the recommended pH range for safe drinking water is 6.5 to 8.5 [3]. Similarly, the U.S. Environmental Protection Agency (EPA) classifies this pH range as non-enforceable but ideal for maintaining water quality [4].
     Maintaining water within this acceptable pH range is crucial for preventing the leaching of toxic metals such as lead and copper from plumbing systems. In industrial applications, improper pH levels can also affect chemical reactions, wastewater treatment efficiency, and equipment lifespan [5].
   - **TDS Sensor:** Basically, TDS measures the concentration of dissolved solids in water, helping it classifies whether it is usable or not. This includes minerals, salts, metals, and other dissolved matter, which contribute to the overall quality of the water. According to WHO guidelines, water with a TDS concentration below 600 mg/L is considered excellent, while values between 600 and 1,000 mg/L are acceptable for drinking [6]. However, a TDS level exceeding 1,000 mg/L may indicate contamination or excessive mineral content, making the water unfit for human consumption [7].
     The Bureau of Indian Standards (BIS) sets the acceptable TDS limit at 500 mg/L, with a permissible limit of up to 2,000 mg/L in cases where different sources are unavailable [8]. Very High TDS levels can cause scaling in pipes and appliances, alter the taste of water, and lead to adverse health effects if specific contaminants such as arsenic, nitrates, or heavy metals are present.

1.5 Significance of the Thesis

This thesis is critical in many ways, particularly in the domains of industrial automation, human health, and the environment.

Key Contributions of the Thesis:

1. **Real-Time Water Quality Monitoring**
   - Semi-automates continuous measurement of pH and TDS.
   - Reduces delays in contamination detection compared to manual sampling.
   - Enables immediate corrective action, minimizing health risks.

2. **Increased Accuracy and Reliability**

    - Eliminates inconsistencies and human errors in water testing.
    - Utilizes high-precision sensors and PLC logic for consistent data collection.
    - Ensures repeatability and standardization of measurements.

3. **Cost-Effective and Scalable Solution**

    - Reduces manual labor costs in water quality assessment.
    - Minimizes maintenance costs by preventing scale buildup and corrosion in pipelines.
    - Adaptable for municipal water plants, industrial applications, and rural water systems.

4. **Automation and Process Optimization**

    - PLC-controlled automated separation of clean and contaminated water.
    - Integrates HMI for remote monitoring and user control.
    - Supports customizable PLC logic to meet different operational needs.

5. **Environmental and Public Health Impact**
    - Ensures compliance with the WHO and EPA water quality standards.
    - Reduces waterborne diseases by preventing the distribution of contaminated water.
    - Contributes to sustainable water resource management and pollution control.

2. Literature Review

This section of my thesis presents an in-depth review of existing literature related to water quality monitoring techniques, automation in industrial settings, and finally, the role of PLC in modern water systems. The review focuses on traditional and advanced monitoring techniques, the benefits of PLC-based automation, and a comparative analysis of different automation technologies.

2.1 Water Quality Monitoring Techniques

This is a traditional water quality monitoring method that involves analyzing physical, chemical, and biological parameters to determine its sustainability and suitability for human consumption or industrial use. These methods primarily rely on manual sampling and laboratory-based analysis; however, modern sensor-based automated systems have enhanced efficiency and accuracy.

2.1.1 Manual Sampling and Laboratory Analysis

Historically, water quality analysis was conducted through manual sampling, where water was collected and assessed in laboratories using chemical reagents and spectrophotometry techniques [12].

This method, while highly accurate, is:

- **Time-consuming** – Laboratory testing requires extensive sample preparation and analysis.
- **Labor-intensive** – Skilled personnel are required to conduct tests and interpret results.
- **Delayed in response** – Results are often obtained after several hours or days, limiting real-time action.
- **Limited in scalability** – Monitoring large-scale water networks is impractical using manual techniques.

Despite its limitations, manual sampling remains a reference method for validating sensor-based and automated systems [13].

2.1.2 Sensor-Based Real-Time Monitoring

The development and advancement of sensor technology have enabled the real-time monitoring of water quality parameters, such as pH, Total Dissolved Solids (TDS), and dissolved oxygen (DO). Sensor-based monitoring offers:

- Continuous data acquisition for real-time decision-making.
- High accuracy with minimal human intervention.
- Immediate response to contamination events through automated alerts.
- Scalability for large water distribution networks.

Recent studies indicate that automated water quality monitoring systems, such as the one I have proposed, PLC-based, can enhance real-time surveillance and provide predictive insights for effective contamination control.

2.1.3 Remote Sensing (SCADA Systems and IOT Integration)

The integration of remote sensing, including SCADA systems and Internet of Things (IoT) technology, has further enhanced water quality assessment. Remote sensing systems utilize:

- Wireless sensors to collect real-time water quality data.
- Cloud computing for remote access to data.
- Machine learning algorithms to predict contamination trends.

A study conducted on intelligent water quality monitoring using automation reported that these systems reduce operational costs and improve monitoring efficiency by 40% compared to conventional methods.

2.2 Sensor-Based Water Quality Monitoring

A sensor-based monitoring system has revolutionized the water management industry by enabling real-time detection, continuous measurement, and an automated response mechanism. Various studies have demonstrated that sensors play a crucial role in assessing pH, Total Dissolved Solids (TDS), and other key water quality parameters.

2.2.1 pH Monitoring Sensors

The pH of water is a fundamental indicator in determining its acidic or alkaline nature, which affects both potability and industrial usability. With pH levels typically ranging from 6.5 to 8.5 for most uses, any pH below 6.5 is considered acidic and corrosive, while any pH above 8.5 is considered alkaline and unsuitable for most purposes [14].

There are many types of pH sensors, some of which are as follows:

- **Glass Electrode Sensors:** The most common pH sensors use a glass electrode and reference electrode, measuring hydrogen ion activity in water. These sensors are widely used in water treatment plants, industrial effluent monitoring, and environmental studies.
- **Solid-State Sensors:** More durable and suitable for harsh environments, these sensors use ion-selective field-effect transistors (ISFETs) for pH detection, providing longer lifespan and better response time.
- **PLC Integration:** Modern pH sensors are directly interfaced with PLCs via analog input modules, allowing real-time pH adjustment and corrective actions through automated dosing systems.

2.2.2 Total Dissolved Solids (TDS) Monitoring Sensors

The Total Dissolved Solids (TDS) refers to the concentration of organic and inorganic substances dissolved in water, typically measured in milligrams per liter (mg/L) or parts per million (ppm).

There are many types of TDS sensors, some of which are as follows:

- **Conductivity Sensors**: TDS is commonly measured using electrical conductivity (EC) sensors, which correlate the conductivity of water to its dissolved solids concentration. These sensors are frequently used in municipal water treatment plants and industrial applications.
- **Optical Sensors**: Advanced TDS sensors utilize infrared absorption techniques to differentiate organic and inorganic dissolved solids, improving accuracy in wastewater treatment.
- **PLC-Based TDS Control**: In automated systems, TDS sensors provide continuous feedback to PLCs, enabling automated reverse osmosis (RO) system adjustments to regulate water purification processes.

2.3 PLC-Based Automation in Water Treatment

2.3.1 PLC in Industrial Automation

Programmable Logic Controllers (PLCs) are widely utilized in industrial automation due to their robustness, reliability, and real-time processing capabilities. PLCs are designed to control machinery, process inputs from sensors, and execute logics for industrial operations.

2.3.2 Role of PLC in Water Treatment Plant

In my water treatment thesis, PLCs are used to:

- Semi-automate monitoring and control of water quality parameters such as pH, TDS.
- Regulate pumps, valves, and filtration systems to ensure proper water treatment.
- Trigger text on HMI and corrective actions when contamination is detected.
- Improve efficiency by reducing manual intervention and operational costs.

A study on PLC-based automation in municipal water treatment plants found that automation reduced human error and improved process efficiency by 35%.[15]

2.3.3 PLC Programming for Water Quality Control

PLCs are programmed using Ladder Logic, Structured Text (ST), or Function Block Diagrams (FBD). The PLC (S7-1200 1215C AC/DC/RLY) is responsible for automating the entire process, ensuring efficient water quality assessment and controlled separation based on real-time sensor data.

Key functionalities integrated into the PLC program include:

- Acquisition and Processing of Sensor Data: The system continuously collects readings from the pH and TDS sensors, normalizing and scaling the values for real-time decision-making.
- Automated Water Separation and Control Logic: The PLC determines the quality of water and actuates solenoid valves and pumps accordingly, directing clean water to Compartment A and contaminated water to Compartment B.
- Integration with HMI for Monitoring and Control: The KTP700 Basic PN HMI provides a real-time user interface displaying sensor values, system status, and operational alerts. Operators can start or stop the process and monitor whether the water is safe for usage.

Research and practical implementation show that PLC-based automation in water treatment enhances response time, system reliability, and operational efficiency compared to traditional manual or SCADA-based control methods. The ability to make real-time decisions, coupled with sensor-based automation, ensures a more accurate, responsive, and energy-efficient water treatment process.

2.4 HMI-Based Control Systems for Water Quality Monitoring

Human-Machine Interfaces (HMIs) play a vital role in real-time monitoring, data visualization, and system control in automated water quality monitoring systems. HMIs serve as an interface between the User/Operator and Programmable Logic Controllers (PLCs), allowing for intuitive system interaction and efficient monitoring of water parameters [16].

2.4.1 Siemens WinCC in Water Quality Monitoring

Siemens WinCC (Windows Control Center) is a SCADA/HMI platform for industrial automation, particularly in water treatment and quality monitoring applications [17]. In this project, Siemens KTP700 Basic PN HMI was implemented to interact with the PLC, enabling direct visualization of real-time sensor data and control of system components.

- **Graphical Representation of Water Quality Data:** The HMI continuously displays real-time sensor readings for pH and TDS, providing operators with a clear overview of water conditions without requiring complex manual measurements. This ensures accurate and immediate assessment of water quality.
- **User-Controlled System Operations:** The system enables activation of solenoid valves and compartment pumps. This allows the operator to intervene in the process as necessary.
- **Dynamic Text-Based Indications:** The HMI provides real-time feedback through textual indicators rather than triggering alarms. Based on sensor data, the system determines whether the water is safe or unsafe, displaying appropriate status messages directly on the interface.
- **Process Optimization and Data Tracking:** While the current system does not incorporate automated logging, it provides operators with continuous monitoring, helping them assess trends in water quality over time and make necessary system adjustments.

Studies indicate that integrating Siemens WinCC with PLC-based water quality monitoring systems enhances operational efficiency by 30-40%, resulting in reduced system downtime and increased compliance with water quality standards [18]. The implementation of an HMI-based approach in this project enables streamlined interaction between operators. It facilitates effective real-time decision-making, ensuring reliable and efficient control of the water separation process.

2.5 Comparison of Different Automation Technologies

Various automation technologies are available for water treatment and monitoring, including SCADA systems, IoT-based solutions, and AI-driven intelligent monitoring systems.

Technology	Advantages	Limitations
SCADA Systems	Real-time control, centralized monitoring	High setup and maintenance costs
IoT-Based Systems	Remote monitoring, predictive analytics	Requires stable internet connectivity
PLC-Based Systems	High reliability, real-time control	Limited cloud integration
AI-Driven Smart Monitoring	Self-learning, predictive maintenance	High computational requirements

Studies indicate that a hybrid approach integrating PLCs with IoT and AI provides the optimal solution for modern water treatment applications.

2.5.1 Supervisory Control and Data Acquisition (SCADA) Systems

SCADA (Supervisory Control and Data Acquisition) is an industrial automation system that enables centralized monitoring and control of various processes in water treatment industries [19].

SCADA systems consist of:

- Remote Terminal Units (RTUs) and Programmable Logic Controllers (PLCs) that collect sensor data.
- A central SCADA server that processes and analyzes data in real time.
- A Human-Machine Interface (HMI) that displays water quality parameters and control options for operators.

Some of the Advantages of SCADA Over Traditional Methods are as follows

- Centralized control of multiple water treatment facilities.
- Automated alerts to detect contamination and take immediate action.
- Historical data storage for regulatory compliance and performance optimization.
- Remote access capability, allowing operators to monitor water treatment plants from different locations.

Some of the Limitations of SCADA are:

- High initial setup costs make it less feasible for small-scale applications.
- Cybersecurity risks, requiring strong network protection to prevent hacking or unauthorized access.

SCADA is most effective when integrated with PLC-based control systems, allowing precise real-time adjustments in water quality treatment.

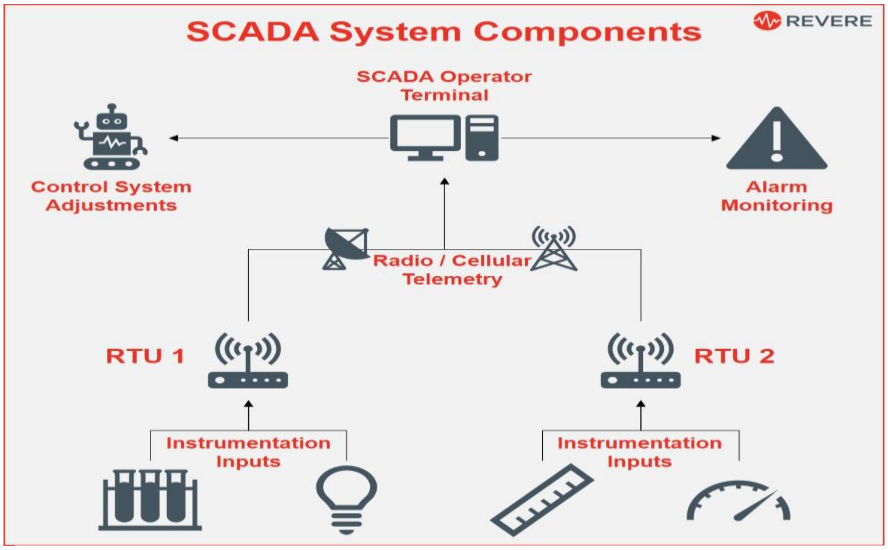

Figure 1. SCADA System

2.5.2 Internet of Things (IoT)-Based Water Quality Monitoring

The Internet of Things (IoT) is transforming water management by enabling wireless sensor networks, providing remote access to real-time data, and facilitating cloud-based analytics.

Functioning of IoT-Based Water Quality Monitoring

- Wireless smart sensors collect pH, TDS, and other water quality parameters.
- Data is transmitted via the internet to cloud-based servers.
- Operators access dashboards via mobile or web applications.
- AI-driven algorithms analyze patterns to predict contamination risks.

From many Advantages of IoT Over Traditional Methods, some of them are as follows:

- Real-time monitoring, reducing the need for frequent manual sampling.
- Predictive analytics, allowing early intervention before contamination occurs.
- Cost-effective for large-scale water networks, such as municipal water supplies.
- Mobile access, allowing operators to monitor water quality from anywhere.

Limitations of IoT-Based Systems are:

- Requires stable internet connectivity, which may be unreliable in remote areas.
- Potential data security risks, as cloud-based platforms may be vulnerable to cyberattacks.

IoT-based systems are ideal for smart cities and large-scale water distribution networks, where real-time monitoring and predictive analytics are essential [20].

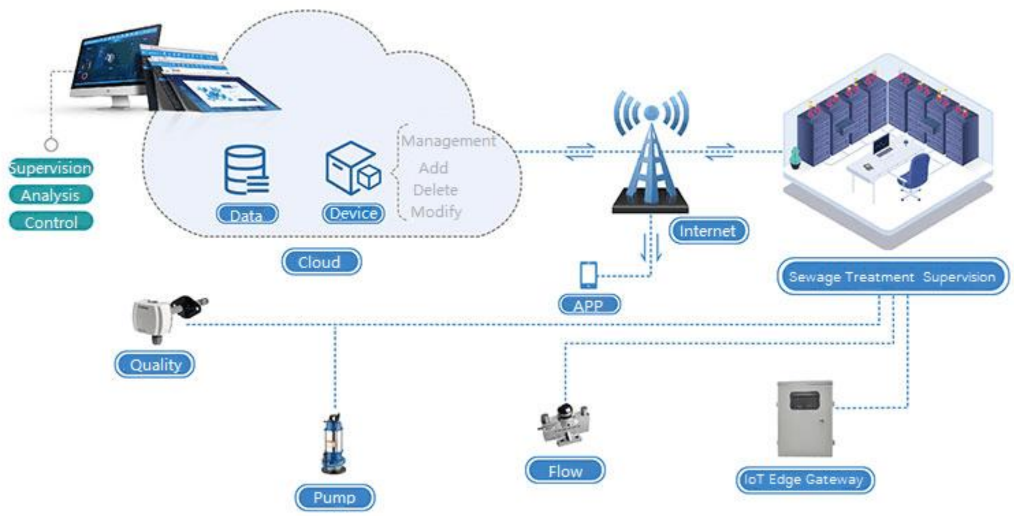

Figure 2. IOT Water Quality Monitoring System

2.5.3 AI-Driven Water Monitoring System

The world is rapidly changing and evolving, and so is the technology we use, AI is considered to be the revolutionary technology which will create a new pathway as to we visualize digital tech, it's like we have discovered fire for the first time, with the help of AI we can transform water quality monitoring and management by providing predictive analytics, anomaly detection, and process optimization. Unlike traditional systems that rely on predefined threshold-based decision-making, AI systems learn from historical data, make future predictions, and continuously improve their accuracy over time by making adjustments. It's as if the machine will be learning and making decisions on its own, without any human interaction [21].

Functionality of an AI Model based on Water Quality Monitoring:

The basic principle on which all AI is based is Machine Learning (ML) algorithms and learning models that analyze incoming data from sensors or actuators/relays to predict potential events and make decisions based on that.

This process can have multiple steps, which are as follows:

- **Data Collection** – AI-based system will gather real-time data from water quality sensors (pH, TDS, turbidity, conductivity, etc.).
- **Preprocessing & Feature Extraction** – Raw sensor data is cleaned, normalized, and structured for analysis.
- **Predictive Analytics** – AI models detect abnormal trends (e.g., sudden pH drops, rising TDS) and forecast potential failures and, in some cases, prevent them.
- **Automated Decision-Making** – AI makes corrective actions, such as adjusting filtration rates, chemical dosing, or activating alarms if they have been integrated with the system.
- **Continuous Learning & Model Optimization** – The system learns from past data to improve accuracy and reduce false alerts over time.

3. System Design Flow

In this chapter, a detailed description of the water quality monitoring system is provided, which is a semi-automated, PLC-based system that analyzes and monitors key water parameters, including pH and Total Dissolved Solids (TDS). It analyzes the collected data in real-time and classifies them according to the predefined logic, alerting the user to changes in water quality. I ensured that the parameters comply with international water safety standards (e.g., WHO, EPA, BIS).

We begin with a block diagram, followed by a design flow (Gantt Chart), hardware and software components, working principle, flow of operation, block diagrams, and Ladder Logic (LAD) implementation of the system. The Siemens S7-1200 CPU 1215C PLC serves as the central control unit, equipped with various sensors, actuators, and an HMI interface, facilitating automated decision-making and real-time monitoring.

3.1 PLC Thesis Gantt Chart

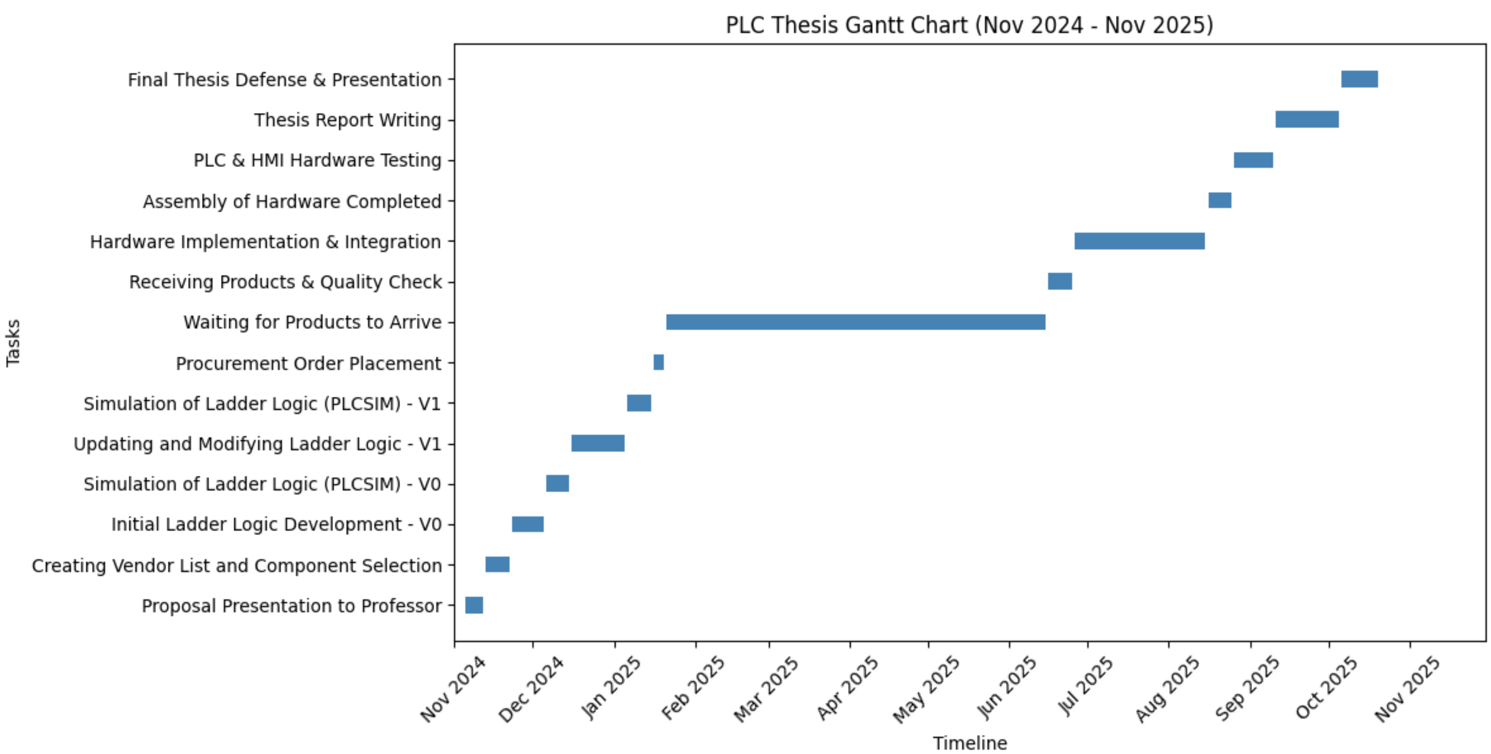

Figure 3.Gantt Chart

The Gantt chart shown in the image outlines the timeline and major tasks involved in completing the PLC-based Water Quality Monitoring and Separation System thesis. The project follows a structured and systematic approach, ensuring proper planning, execution, and finalization before the thesis defense.

Breakdown of Key Tasks

1. Proposal Presentation to Professor

The thesis work begins with conceptualizing and presenting initial proposals to the professor. Three proposals were considered, and finally, the Water Quality Monitoring and Separation System was selected.

Tasks included problem identification, reviewing prior works, and justifying the need for a PLC-based automation approach.

It was agreed to first implement the system at a lab scale, with the possibility of future industrial scaling.

2. Creating Vendor List and Component Selection

A vendor list was created to identify reliable suppliers for the required hardware.
Components selected:

- PLC (Siemens S7-1200 1215C AC/DC/RLY)
- Sensors (pH and TDS)
- Actuators (pumps, solenoid valves)
- HMI (Siemens KTP700 Basic PN)
- Electrical accessories (power supplies, wiring, connectors).

3. Initial Ladder Logic Development – V0

The first version of the PLC ladder logic program was developed in Siemens TIA Portal V19.
Basic functionalities included:

- Reading sensor inputs (pH, TDS).
- Controlling pumps and solenoid valves.
- Displaying real-time readings on HMI.

4. Simulation of Ladder Logic (PLCSIM) – V0

The initial ladder logic was tested and debugged in Siemens PLCSIM.
Verified correct handling of sensor signals and control logic for water separation.

5. Updating and Modifying Ladder Logic – V1

Improvements have been made to refine the logic and HMI interface.
Updates included:

- Sensor calibration (reducing noise).
- Optimized ladder logic for efficient control.
- Enhanced HMI with alarms, error messages, and real-time trends.

Due to firmware issues, logic was later adapted in TIA Portal V15.1 for compatibility with the HMI.

6. Simulation of Ladder Logic (PLCSIM) – V1

The improved ladder logic was validated through simulation.
Different water conditions were tested to ensure reliability and stability.

7. Procurement Order Placement

- Orders were placed for all required components after finalizing the vendor list.

8. Waiting for Products to Arrive

- A long waiting period followed as components were procured and shipped.

9. Receiving Products & Quality Check

- Upon arrival, all products underwent inspection and quality verification to ensure conformity with project requirements.

10. Hardware Implementation & Integration

Full hardware integration carried out:

- Mounting and wiring PLC, HMI, sensors, and actuators.
- Programming the HMI for real-time monitoring and control.
- Running initial functional tests.

11. Assembly of Hardware Completed

- Final setup of hardware assembly completed successfully, preparing for real-time testing.

12. PLC & HMI Hardware Testing

End-to-end testing was performed on the integrated system.
Verified:

- Correct sensor readings on HMI.
- Accurate control of pumps and valves.
- Synchronization between PLC and HMI.

13. Uncertainty Calculations

Following hardware testing, a detailed uncertainty analysis was conducted for the pH and TDS sensors to assess the reliability of measurements.

- Type A uncertainty was determined from repeated experimental trials (10 readings per solution) for tap water, salt water, and lemon water in the case of TDS, and buffer solutions (pH 4, pH 10) plus tap water for pH.
- Type B uncertainty was taken from the manufacturer's specifications
- Combined standard uncertainties were computed and expanded uncertainties reported (k=2, 95% confidence).
- Results highlighted that TDS uncertainty was dominated by manufacturer accuracy, while pH showed comparable contributions from both repeatability and calibration.

This analysis was crucial for understanding the risk of misclassification of water quality near decision thresholds and was documented as part of the thesis results.

14. Thesis Report Writing

A comprehensive report was written covering:

- System architecture and design.
- Ladder logic details and simulation results.
- Hardware integration and testing outcomes.
- Calibration and uncertainty analysis.
- Limitations, challenges, and future scope.

15. Abstract Submission

- The abstract of the thesis was submitted as per departmental deadlines.

16. Final Thesis Defense & Presentation

The project was formally defended before the evaluation committee. A prototype demonstration was carried out, highlighting water quality monitoring and separation.

Design choices, simulation outcomes, calibration/uncertainty results, and system scalability were explained to the panel.

Analysis of Gantt Chart

- The project follows a sequential and structured workflow.
- Early-stage planning (Proposal, Vendor Selection) ensures a smooth execution.
- Simulation and testing phases prevent errors before hardware integration.
- The timeline ensures the project is completed efficiently before the thesis defense.

3.2 Block Diagram and Design Flow

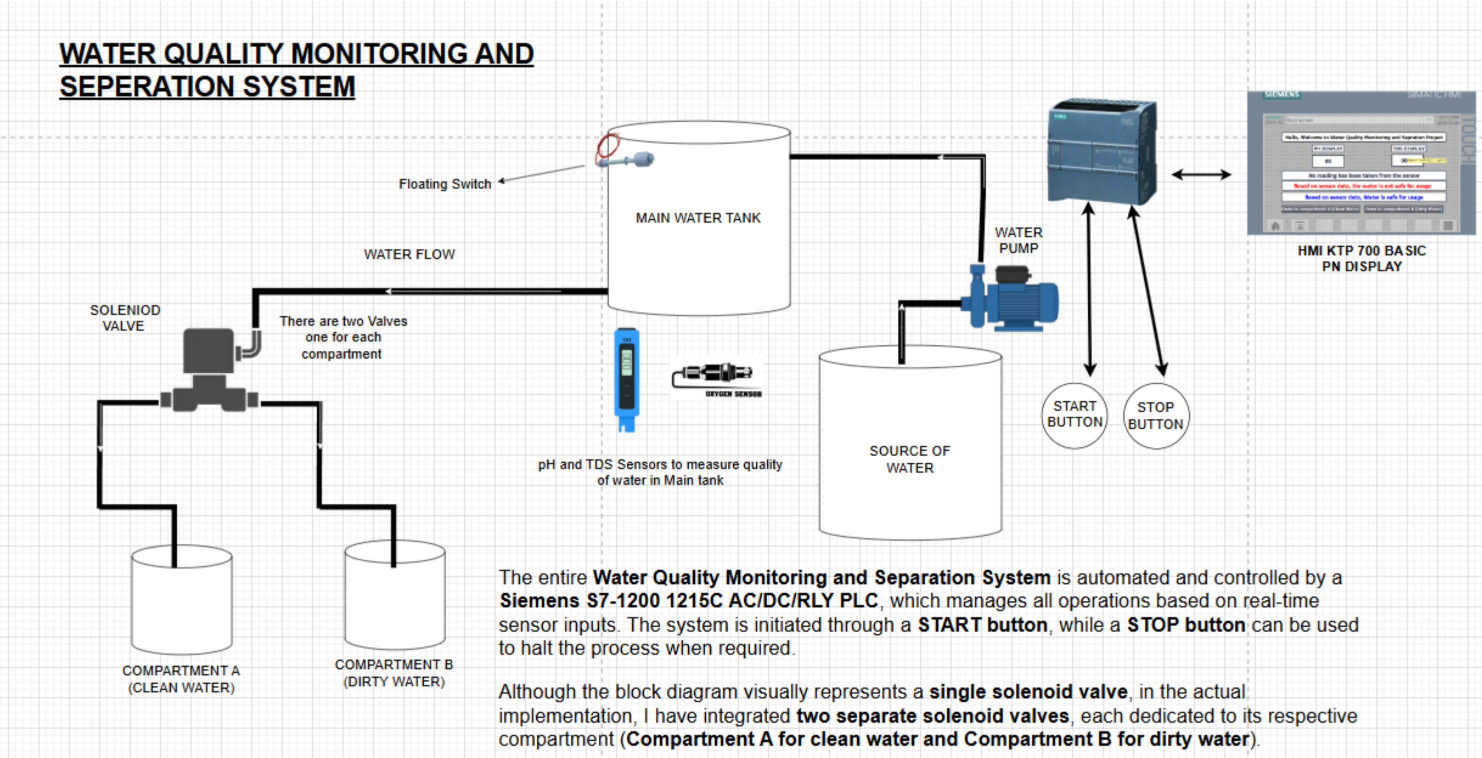

Figure 4. Block Diagram

Figure 4 visually represents the Water Quality Monitoring and Separation System, detailing its hardware components, connections, and working principle. The system is semi-automated, requiring the user to make decisions using the HMI and data analysis, and then control water quality assessment and separation with a Siemens S7-1200 PLC.

Key Components and Working

1. **PLC (Siemens S7-1200 1215C AC/DC/RLY)**

The Siemens S7-1200 PLC serves as the system's CPU, controlling the entire water quality monitoring and separation process. It receives input from sensors, processes the data, and activates pumps and solenoid valves accordingly, enabling the user to make an informed and data-driven decision, ensuring water is directed to the correct compartment.

How the PLC Works in the System:

- Receives real-time data from the pH and TDS sensors.
- Processes sensor values and checks if they fall within predefined limits.
- Determines water quality based on sensor thresholds.
- Activates solenoid valves and pumps to separate clean and dirty water based on what the user decides.
- Stops water flow when the tank reaches maximum capacity (using a float switch).
- Sends status updates to the HMI, allowing the user to monitor the process.

The PLC runs a Ladder Logic program inside the Totally Integrated Automation (TIA) Portal V15.1, ensuring an automated, reliable, and efficient operation.

2. HMI (Siemens KTP700 Basic PN Display)

The HMI (Human-Machine Interface) provides a graphical user interface (GUI) for monitoring and controlling the system.

Functions of the HMI in the System:

- Displays live water quality readings (pH, TDS).
- Indicates whether water is within acceptable quality levels or needs separation.
- Provides control buttons for manually starting and stopping the process.
- Allows users to select drainage compartments for water disposal.

The HMI communicates with the PLC via PROFINET, ensuring real-time updates and smooth system control.

3. Start & Stop Buttons

- Start Button: Initiates the monitoring and separation process by activating the main water pump and sensor readings.
- Stop Button: Immediately halts all operations, stopping pumps and closing valves to ensure safety.

4. Main Water Pump

- Transfers water from the source tank into the main water tank, where it undergoes quality assessment.
- Controlled by the PLC, ensuring that water only enters when needed and stops when the tank is full by float switch or manual stop button.

5. Float Switch

- Detect water levels in the main tank.
- Prevent overflow by signaling the PLC to stop the pumps when the tank reaches full capacity.
- Ensures safe operation and water level management.

6. Compartment A - Solenoid

- If the water is clean and the user selects Compartment A from the HMI, the PLC opens Solenoid Valve A.
- Water is directed into Compartment A (Clean Water Storage).

7. Compartment B - Solenoid

- If the water is contaminated, and the user selects Compartment B from the HMI, the PLC opens Solenoid Valve B.
- Water is directed into Compartment B (Dirty Water Storage).

3.3 System Schematic and Wiring

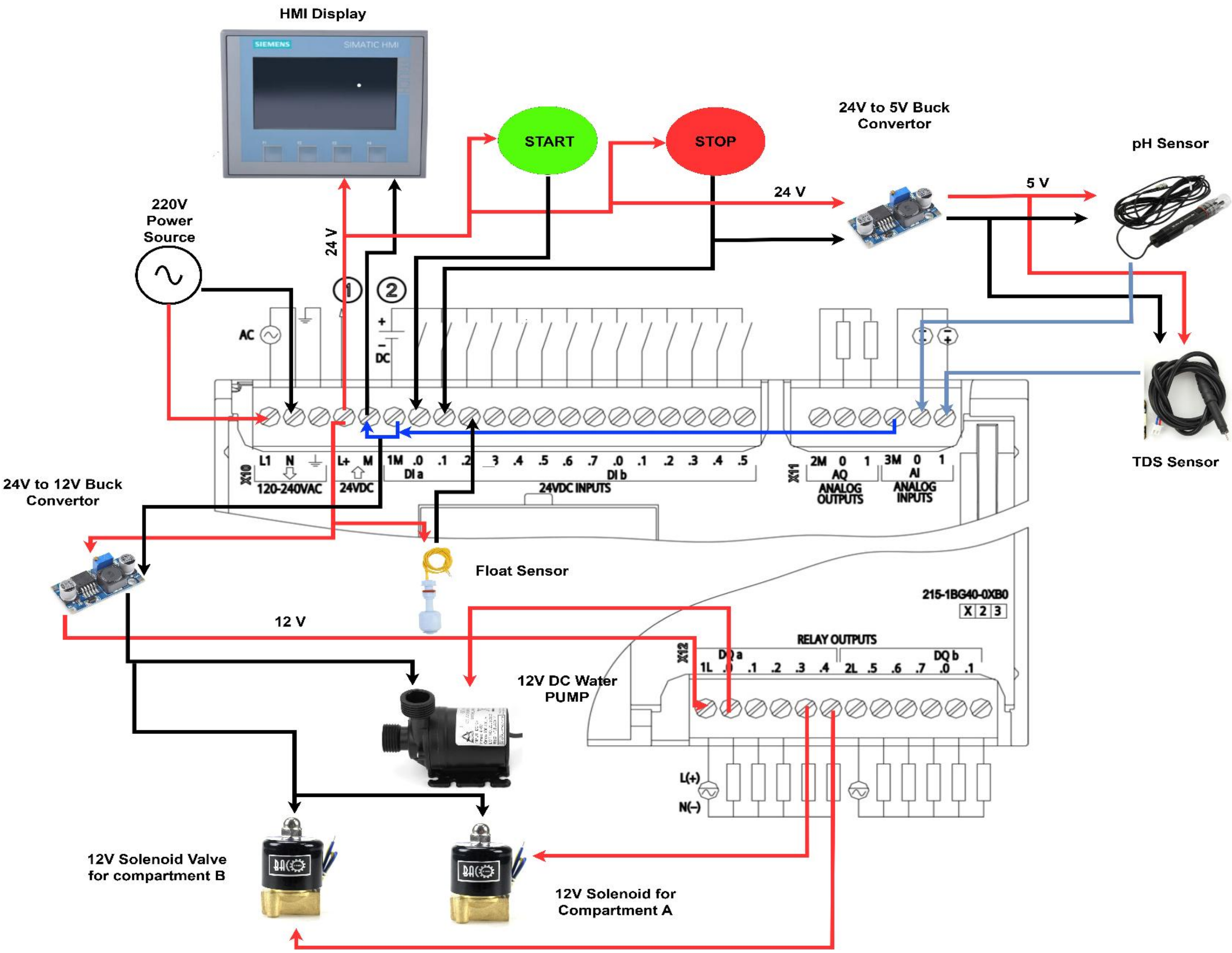

Figure 5. Schematic of the system

The complete wiring layout of the water quality monitoring and separation system is depicted in Figure 5. Initially, to power up the PLC, a 220V AC supply is used. The PLC then internally steps down this voltage to 24V DC. This line further supplies power to the different components used in the system, including the HMI (KTP700 Basic PN), ensuring stable operation.

Since the Water pump and Solenoids require 12V DC, and the sensors consume 5V DC, two buck converters are used to provide the voltages needed for the field devices. Using a single 24V source from the PLC itself and stepping down the voltage using buck converters reduces the system's complexity and keeps the design compact.

There are dedicated slots for digital inputs, labelled from %I0.0 to %I0.7 in section A, which the system uses. The start button in the system is connected to I0.0, followed by the stop button, which is connected to I0.2, and the float switch, which is connected to I0.2. Signals from these digital inputs form the basis of the PLC logic, ensuring the start/stop functionality of the DC water pump and the water level interlock.

TDS and pH sensors, both analog sensors, are powered by a 5V DC supply through a buck converter, which is itself powered by a 24V DC supply from the PLC. The signal wire from these sensors is connected to the PLC’s analog input channel. In the system logic, pH is mapped to %IW64 and TDS to %IW66, where raw voltages are scaled and corrected using calibration routines. For example, the TDS offset of +5.35 ppm is compensated in software, while pH readings are adjusted using a two-point linear calibration.

The relay output controls the 12V DC pump and solenoid valves of the system. The pump is wired to %Q0.0, while solenoid valves for compartments A and B are connected to %Q0.3 and %Q0.4, respectively. Relays provide isolation between the PLC and higher-current loads, ensuring safe switching.

The HMI is powered from 24 V and communicates with the PLC over Profinet. It displays real-time sensor data, with Intuitive text-based displays that guide the user on whether the water is contaminated or safe for use. Additionally, it features interactive buttons that allow the user to open the solenoid for drainage manually.

The schematic is a critical element of the project as it provides a clear link between hardware and control logic. It ensures that every sensor, actuator, and supply rail is correctly documented, simplifying troubleshooting, supporting reproducibility, and maintaining safety during operation.

4. System Hardware Components

The hardware components of the Water Quality Monitoring and Separation System are carefully selected to ensure accurate monitoring, reliable automation, and efficient water management. These components include sensors for water quality assessment, a PLC for automation control, an HMI for user interaction, actuators for water flow control, and essential wiring and power management elements. The integration of these components enables a fully automated, real-time monitoring system that ensures effective separation of clean and contaminated water.

A list of components is mentioned below:

1. **Control System**

- Siemens S7-1200 1215C AC/DC/RLY PLC – Main processing unit for automation
- Siemens KTP700 Basic PN HMI – User interface for monitoring and control
- ProfNet Cable – to ensure connection between devices

2. **Water Quality Sensors**

- pH Sensor (DFRobot Gravity SEN0161-V2) – Measures acidity/alkalinity of water
- TDS Sensor (DFRobot SEN0244) – Measures total dissolved solids (impurities)

3. **Actuators and Water Flow Control**

- Main Water Pump (HSeaMall Brushless Submersible Pump) – Transfers water from the source tank to the main water tank
- Solenoid Valve A (Qrity Water Purifier Valve) – Directs clean water to Compartment A
- Solenoid Valve B (Qrity Water Purifier Valve) – Directs contaminated water to Compartment B

4. **Safety and Control Components**

- Float Switch – Prevent overflow by detecting water levels in the tank
- Start Button – Initiates the monitoring and separation process
- Stop Button – Halts all system operations immediately

5. **Power Management**

- Buck Converter – Steps down voltage for various components
- Electrical Wiring – Ensures stable connections and power distribution

4.1 PLC – Siemens S7-1200 CPU 1215C AC/DC/RLY

A Programmable Logic Controller (PLC) is an industrial-grade device that is used to automate electromechanical processes. Unlike general-purpose computers, PLCs are designed to withstand the extreme harsh conditions of industrial environments, featuring real-time operation, modular expandability, and integration with field devices such as sensors, actuators, SCADA systems, and Human-Machine Interfaces (HMI).

For this project, the Siemens S7-1200 CPU 1215C AC/DC/RLY PLC has been selected due to its robust performance, ease of Integration with analog sensors, flexible communication capabilities, and compatibility with PROFINET networks.

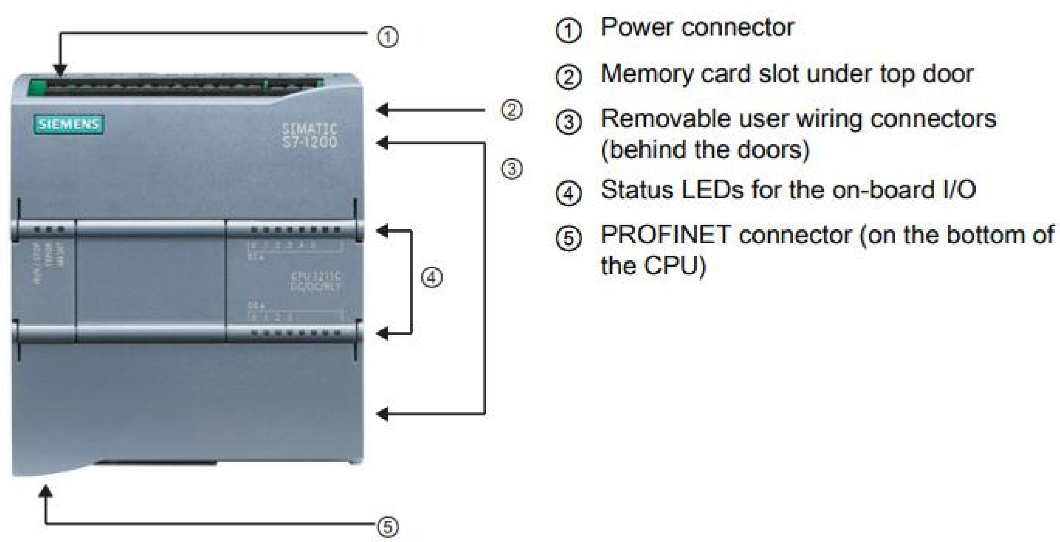

Figure 6. PLC S7-1200 1215C

The PLC S7-1200 is available in various variants, including 121C, 1212C, 1214C, and 1215C, which we have utilized. Each variant offers different processing capabilities, memory capabilities, and I/O configurations. The CPU 1215C is the most powerful model, which features 100 KB of working memory, 4 MB of load memory, and 10 KB of retentive memory. It supports 14 digital inputs, 10 digital outputs, two analog inputs, and two analog outputs, making it highly suitable for complex automation applications.

In terms of scaling, the CPU 1215C supports up to 8 signal modules (SM), three communication modules (CM), and additional signal boards (SB). It features two PROFINET Ethernet ports, enabling high-speed communication with HMIs, SCADA systems, and remote monitoring interfaces, making it ideal for real-time industrial applications.

The following image compares different PLC models of the S7-1200.

Feature		CPU 1211C	CPU 1212C	CPU 1214C	CPU 1215C
Physical size (mm)		90 x 100 x 75	90 x 100 x 75	110 x 100 x 75	130 x 100 x 75
User memory	Work	30 Kbytes	50 Kbytes	75 Kbytes	100 Kbytes
	Load	1 Mbyte	1 Mbyte	4 Mbytes	4 Mbytes
	Retentive	10 Kbytes	10 Kbytes	10 Kbytes	10 Kbytes
Local on-board I/O	Digital	6 inputs/4 outputs	8 inputs/6 outputs	14 inputs/10 outputs	14 inputs/10 outputs
	Analog	2 inputs	2 inputs	2 inputs	2 inputs / 2 outputs
Process image size	Inputs (I)	1024 bytes	1024 bytes	1024 bytes	1024 bytes
	Outputs (Q)	1024 bytes	1024 bytes	1024 bytes	1024 bytes
Bit memory (M)		4096 bytes	4096 bytes	8192 bytes	8192 bytes
Signal module (SM) expansion		None	2	8	8
Signal board (SB), Battery board (BB), or communication board (CB)		1	1	1	1
Communication module (CM) (left-side expansion)		3	3	3	3
High-speed counters	Total	3 built-in I/O, 5 with SB	4 built-in I/O, 6 with SB	6	6
	Single phase	3 at 100 kHz SB: 2 at 30 kHz	3 at 100 kHz 1 at 30 kHz SB: 2 at 30 kHz	3 at 100 kHz 3 at 30 kHz	3 at 100 kHz 3 at 30 kHz
	Quadrature phase	3 at 80 kHz SB: 2 at 20 kHz	3 at 80 kHz 1 at 20 kHz SB: 2 at 20 kHz	3 at 80 kHz 3 at 20 kHz	3 at 80 kHz 3 at 20 kHz
Pulse outputs[1]		4	4	4	4
Memory card		SIMATIC Memory card (optional)			
Real time clock retention time		20 days, typ. / 12 day min. at 40 degrees C (maintenance-free Super Capicator)			
PROFINET		1 Ethernet communication port			2 Ethernet communication ports
Real math execution speed		2.3 μs/instruction			
Boolean execution speed		0.08 μs/instruction			

[1] For CPU models with relay outputs, you must install a digital signal board (SB) to use the pulse outputs.

Figure 7. Comparing S7-1200 CPU Models

4.1.1 Technical Specification of S7-1200 CPU 1215C

The Siemens S7-1200 CPU 1215C AC/DC/RLY is a compact yet powerful PLC designed for industrial automation applications.

Feature	Specification
Model	Siemens S7-1200 CPU 1215C
Order Number	6ES7 215-1BG40-0XB0
Programming Software	Siemens TIA Portal
Processing Speed	0.08 µs per instruction
Operating Voltage	85 – 264V AC at 47 – 63 Hz
Memory	125 KB Work Memory, 4 MB Load Memory
Onboard I/O	14 Digital Inputs (24V DC), 10 Digital Outputs (Relay 2A), 2 Analog Inputs (0-10V DC), 2 Analog Outputs (0-20mA DC)
Communication Ports	2x PROFINET Ports
High-Speed Counters	6 Counters (3 at 100 kHz, three at 30 kHz)
Pulse Outputs	2 Pulse Outputs for PWM Control
PID Controller	Integrated PID Control for Closed-Loop Applications

The PLC continuously reads sensor data, processes values, and controls actuators (solenoid valves, pumps, and alarms) based on Ladder Logic (LAD) instructions.

The table below shows the different Memory types of PLC S7-1200

Memory Type	Size	Function
Work Memory	125 KB	Stores active program and data
Load Memory	4 MB	Stores program code and configuration
Retentive Memory	10 KB	Stores values that persist after a power loss
Bit Memory (M)	8 KB	Used for internal data processing
Process Image Input (I)	1 KB	Stores digital input states
Process Image Output (Q)	1 KB	Stores digital output states

This architecture ensures high-speed execution and reliable data retention, making the S7-1200 suitable for real-time industrial automation applications.

Data Types Supported by Siemens S7-1200 PLC

1. Boolean data types

They are used for binary data control signals, for example, (On/Off, True/False, 1/0)

Data Type	Size	Description
Bool	1 bit	Stores TRUE (1) or FALSE (0) values. Used for switches, sensors, actuators, and logic conditions.

2. Integer data types

This data type stores whole numbers, whether they are unsigned or signed

Data Type	Size	Range	Description
Byte	8 bits	0 to 255	Stores small unsigned numbers (1 byte).
Char	8 bits	0 to 255 (ASCII)	Stores characters (text values, ASCII codes).
Word	16 bits	0 to 65,535	Stores unsigned 16-bit values.
Int	16 bits	-32,768 to 32,767	Stores signed 16-bit values.
DWord	32 bits	0 to 4,294,967,295	Stores large unsigned numbers (32-bit).
DInt	32 bits	-2,147,483,648 to 2,147,483,647	Stores large signed numbers (32-bit).

3. Floating-point data types

These are used for point/decimal values, as well as real-time data, such as sensor readings.

Data Type	Size	Range	Description
Real	32 bits	$\pm 1.18 \times 10^{-38}$ to $\pm 3.4 \times 10^{38}$	Stores floating-point numbers (IEEE 754 format). Used for sensor values such as pH and TDS.

4. Strings and Character data types

These types of data are used for text, HMI messages, and data storage.

Data Type	Size	Description
Char	1 byte	Stores one ASCII character.
String	Variable	Stores text values (max 254 characters). Used in HMI displays and error messages.

5. **Complex Data Types (User-Defined Types - UDTs & Structures)**

This data type is used for custom grouping of variables

Data Type	Description
Array	Stores a group of values of the same data type. Example: An array of 10 integers (ARRAY [1.10] OF INT).
Struct (Structure)	Group multiple variables of different types into a single data block.
UDT (User-Defined Type)	A custom structure where users define their own variable layout.

These were the few Data types I mentioned in my report, which represent the vast majority of the data types that a PLC can support. However, I have focused on those related to my thesis, so I have mentioned them.

4.1.2 PLC in Water Quality Monitoring System

The Siemens S7-1200 PLC performs multiple critical functions in the Water Quality Monitoring and Separation System:

- **Sensor Data Acquisition** – Reads and processes pH and TDS values.
- **Decision Making & Logic Processing** – Compares sensor readings with predefined thresholds to determine water quality status.
- **Actuator Control** – Activates solenoid valves and pumps to separate clean and contaminated water.
- **HMI & Alarm Management** – Provides real-time monitoring and operator alerts.
- **Data Logging & Remote Monitoring** – Stores water quality data and allows web-based access for remote supervision.

This automation system ensures compliance with WHO safety standards, minimizes human intervention, and improves water quality management efficiency.

1. Sensor Data Acquisition

Sensor data acquisition is the first and most crucial step in the PLC process. The entire system relies on data acquired from pH and TDS sensors to analyze and assess water quality. These sensors are linear and provide analog outputs, which must be processed and converted into units by the PLC for decision-making and display of the actual value from the sensor.

Process Flow of the Sensors and PLC

- Sensors monitor water parameters and send signals to the PLC via Analog Inputs (AI).
- The PLC reads raw sensor values in the form of electrical signals (voltage or current).
- Using calibration formulas, the PLC converts raw data into meaningful water quality values.

Conversion Formulas for Sensor Data

Some of the general formulas to calculate data coming from sensors are mentioned below

I. pH Value Calculation

The pH sensor provides an **analog voltage output (Vout)**, which is converted into a **pH value** using the formula:

$$PH = \left(\frac{Vout - Vmin}{Vmax - Vmin}\right) \times (PHmax - PHmin)$$

Where:

- Vout = Sensor output voltage
- $Vmin, Vmax$ = Sensor voltage range
- $PHmin$ = 0, $PHmax$ = 14

II. TDS Value Calculation

The TDS sensor measures **electrical conductivity (EC)**, which is **converted into TDS (mg/L)** using:

$$TDS = \ EC(\mu S/cm) \times K$$

where K It is a calibration factor based on the water sample.

Role of the PLC in Data Processing

- Reads sensor values periodically (e.g., every 1 second).
- Filters noisy data using software-based signal filtering techniques.
- Stores processed sensor values in PLC memory for real-time processing.

2. Logical Analysis & Decision Processing

By using comparators and predefined threshold values, the PLC determines whether the water is safe for storage or should be discarded, displaying text on the HMI based on the result obtained from the sensors.

The Ladder Logic (LAD) program in Siemens TIA Portal follows these conditions:

Condition	Action
pH < 6.5 or pH > 8.5	Display water as not safe for use, else display safe for use
TDS > 500 ppm or TDS < 50 ppm	Display water as not safe for use, else display safe for use
All values are within safe limits.	Display on the HMI that the water is safe for use.

3. Actuator Control

Before and after processing the sensor data, the PLC activates or deactivates system actuators, such as solenoid valves and water pumps, based on the water quality conditions.

Controlled Actuators in our Thesis are:

Solenoid Valves

- Used to direct water flow into clean storage or waste compartments.
- The PLC sends a 12V DC signal to energize or de-energize the valves.

Water Pump

- Ensure continuous water movement through the system.
- PLC triggers pump activation/deactivation based on tank levels and sensor readings.

The Siemens S7-1200 CPU 1215C is a powerful, modular, and efficient PLC automation application. With its extensive communication capabilities (PROFINET, MODBUS, and Web Server), flexible I/O configurations, and robust memory structure, it serves as the ideal control unit for the Water Quality Monitoring and Separation System.

This PLC ensures precise sensor data processing, seamless actuator control, and real-time monitoring, making it a critical component of modern industrial automation solutions.

4.2 Human-Machine Interface (HMI) – Siemens KTP700 Basic PN

The HMI KTP700 Basic PN is a Siemens human-machine interface that is designed for compact and medium-scale industrial applications. It features a 7-inch high-resolution display that supports a broad color spectrum of up to 65,500 colors, ensuring clear and detailed visualization of processed data. The “PN” designation highlights its built-in PROFINET connectivity, which, together with an integrated PROFIBUS interface and USB port, guarantees robust and flexible communication within modern automation systems.

Optimized for cost efficiency, the panel is part of Siemens' Basic HMI series and is tailored for environments where space and resources are limited, yet high-quality operation is required. The configuration and operation processes are streamlined through the updated WinCC software within the TIA Portal, enabling faster setup and simplified maintenance. This makes the KTP700 Basic PN a reliable solution for applications demanding precise control and efficient user interaction in industrial settings.

SIMATIC HMI, KTP700 Basic DP, Basic Panel, Key/touch operation, 7" TFT display, 65536 colors, PROFIBUS interface, configurable as of WinCC Basic V13/ STEP 7 Basic V13, contains open-source software, which is provided free of charge see enclosed CD

Figure 8. HMI KTP700 Display

4.2.1 System Architecture: HMI-PLC Communication Flow

A Basic Panel equipped with a PROFINET interface is used for operator control and monitoring in industrial automation. It enables communication with programmable logic controllers (PLCs) such as Siemens SIMATIC S7 series, WinAC, SIMOTION, and LOGO. The connection is established through an Ethernet-based PROFINET/LAN, enabling real-time data exchange between the HMI and the PLC.

Components Required for Connection

To establish a PROFINET connection between the HMI and a controller, you need:

- PROFINET-compatible Basic Panel (e.g., KTP700 Basic)
- Industrial Ethernet Cable (Cat5e or higher)
- SIMATIC PLC (e.g., S7-1200)
- Power Supply (24V DC)
- TIA Portal Software (V15.1 in my case)

Connection Setup Procedure

Step 1: Connect the PROFINET Cable

- Power off all devices before making the connection.
- Use an RJ45 Industrial Ethernet cable to connect the PROFINET port of the HMI Panel to the Ethernet port of the PLC.
- If using a network switch, connect both the PLC and HMI to the switch.

Step 2: Configure the HMI in TIA Portal

- Open TIA Portal and create a new project.
- Add the HMI Basic Panel and PLC to the project.
- Assign a unique IP Address to both devices within the same subnet (e.g., HMI: 192.168.0.2, PLC: 192.168.0.1).
- Configure the PROFINET Communication Protocol for the HMI to communicate with the PLC.
- Assign Process Tags to link HMI elements with PLC data.

Step 3: Download and Test the Configuration

- Download the project to the HMI and PLC.
- Start the HMI Runtime and check if the controller connection is established.
- Verify real-time data exchange between HMI and PLC.

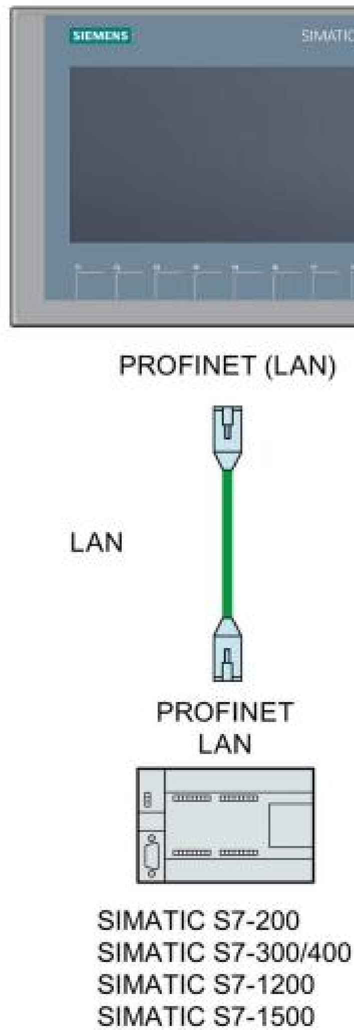

Figure 9. HMI to PLC Connection

4.2.2 HMI Device Operating Modes

HMI devices are designed to support various operational states, enhancing system flexibility and efficiency. These states—offline, online, and transfer modes—enable tailored interactions between the HMI unit and the controller to meet diverse operational requirements.

1. Offline Mode

- **Definition:** In this state, the HMI device operates independently of the controller, meaning that while local operations can continue, there is no data exchange with the controller.

- **Configuration:** This mode can be selected either via the configuration PC or directly on the HMI device using a designated operating element, which must be pre-configured by the system engineer.

2. Online Mode

- **Definition:** When the device is in online mode, active communication is established between the HMI and the controller. This facilitates real-time data exchange, allowing the system to operate according to its configured parameters.
- **Activation:** Similar to offline mode, online mode can be enabled on both the configuration PC and the HMI device through an appropriate operating element.

3. Transfer Mode

- **Definition:** Transfer mode is designed for the movement of projects or data between the configuration PC and the HMI device. This mode is also essential for backup and restore procedures.
- **Activation Methods:**
    1. **Startup Initiation:** The device can automatically enter transfer mode during startup when activated manually through the HMI device loader.
    2. **During Operation:** Alternatively, transfer mode may be initiated on the fly via a pre-configured operating element or automatically when a transfer is triggered from the configuration PC.

4.2.3 Technical Specifications of KTP700 Basic PN

The table below summarizes the technical specifications of the KTP700 Basic PN HMI:

Feature	Specification
Display	7-inch TFT, LED-backlit, 65,536 colors
Resolution	800 × 480 pixels
Touch Type	Analog-resistive touchscreen
Function Keys	8 function keys, onscreen numeric keyboard
Memory for User Data	10 MB Flash memory
Interfaces	1x PROFIBUS, 1x USB, 1x RS-485/RS-422
Power Supply	24V DC (19.2V - 28.8V range)
Current Consumption	230mA @ 24V DC
Protection Class (Front)	IP65 (dust and water-resistant)
Operating Temperature	0°C to 50°C (vertical)

The drawing below showcases the front view of the device, measuring 214mm in width and 158mm in height, featuring a display with a touch-sensitive surface and eight function keys beneath it.

The side view highlights the overall depth of 39mm, including a mounting flange of 6.2mm, ensuring secure panel installation. The rear view provides insights into the input/output ports, including an RJ45 Ethernet/PROFINET port, power connector, and other interfaces, with a 196mm mounting width.

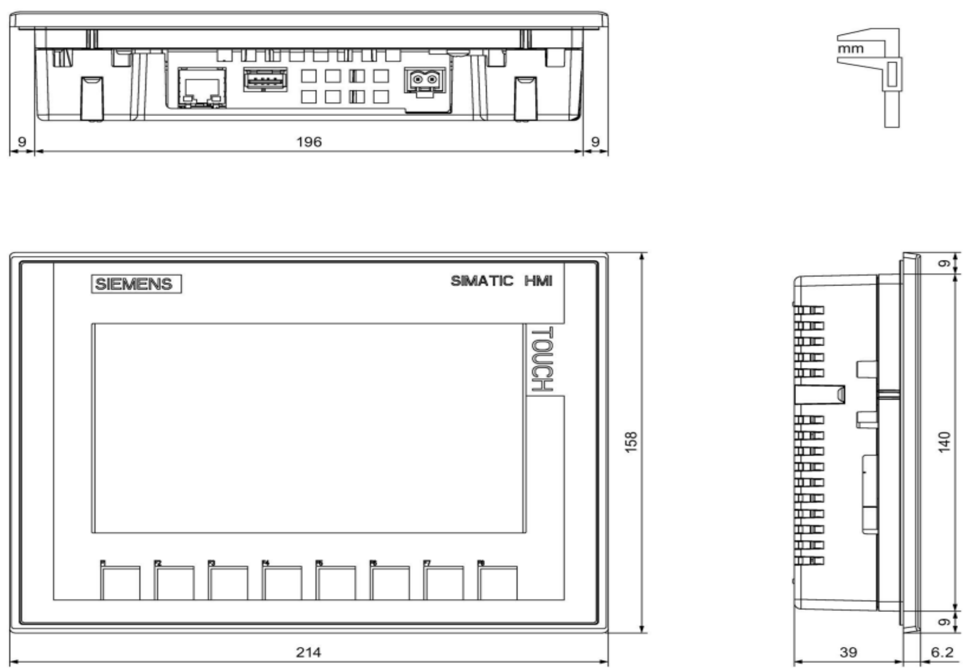

Figure 10. Dimensional drawing of HMI

4.2.4 Functionality of the HMI in the Water Quality Monitoring System

The HMI serves several key functions that facilitate communication between the user and the water monitoring system. Some of which are mentioned below

Real-Time Water Quality Monitoring – Based on data from sensors

The HMI continuously displays sensor readings, including:

- **pH levels** (0–14 range)
- **Total Dissolved Solids (TDS)** in ppm
- Data is being updated in real-time through communication with the PLC.

Interactive Status Display

HMI provides clear and interactive notifications to indicate the quality of water:

- Blue Color Message → "Water is safe for usage."
- Red Color Message → "Water is not safe for usage."
- Black Color Message → "No reading has been taken from the sensor."

The messages are automatically updated based on PLC logic as they are linked to PLC ladder logic tags.

Manual Control of Valves

Two interactive buttons allow the user to direct water to the appropriate compartments manually:

- Drain to Compartment A (Clean Water)
- Drain to Compartment B (Dirty Water)

This feature is helpful as the user can decide, based on the acquired data, whether the water is still usable or not; the user can then make a logical data-driven decision.

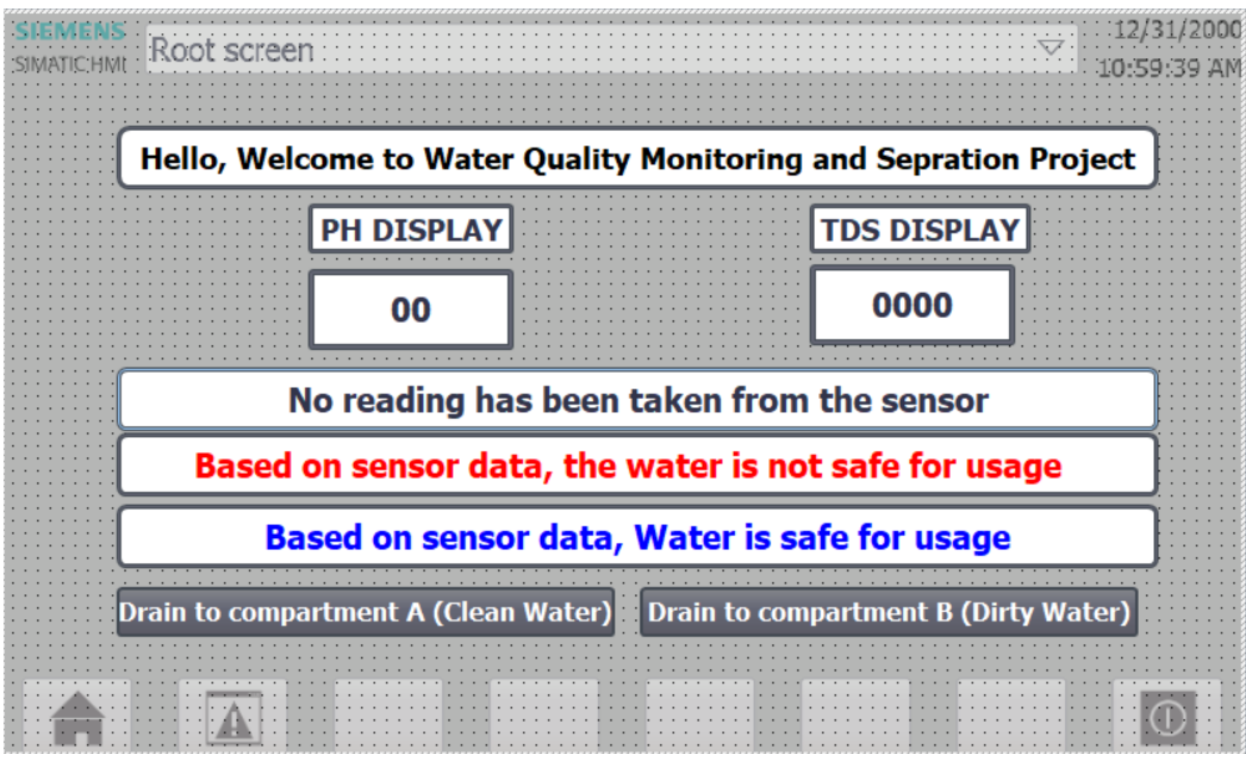

Figure 11. HMI Display for Water Quality Monitoring

Integration with WinCC in TIA Portal

The HMI is configured using WinCC in TIA Portal, which is an additional feature, hence making the HMI essential for my thesis, and enables:

- Custom screen designs for water monitoring.
- Tag assignments linked to PLC variables.
- Event-based screen updates for improved efficiency.

The Siemens KTP700 Basic PN HMI plays a crucial role in the PLC-based Water Quality Monitoring System. Its touchscreen interface provides real-time sensor data and manual control options, enabling users to monitor and ensure water quality.

The integration with Siemens S7-1200 PLC via PROFINET ensures seamless automation and precise monitoring, making the system efficient, reliable, and user-friendly.

4.3 Industrial Ethernet (PROFINET) Cable

The Siemens 6XV1870-3RH60 cable

It is a high-performance PROFINET Industrial Ethernet cable designed for reliable and high-speed data transmission in industrial settings. It is a preassembled crossover patch cable, optimized for connecting PLCs, HMIs, and network devices in automation systems. The cable supports Ethernet speeds of up to 10 Gbps and ensures robust shielding against electromagnetic interference (EMI), making it highly reliable in Industrial and plant environments.

IE TP XP Cord RJ45/RJ45, 4x2
Crossover patch cable, preferred length, preassembled with two RJ45 connectors (10/100/1000/10000MB)
Industrial Ethernet TP XP Cord RJ45/RJ45, CAT 6A, crossed TP cable 4x2, pre-assembled with 2 RJ45 plugs, length 6 m.

Figure 12. ProfNet Cable

4.3.1 Application in PLC, HMI, and Network Integration

Siemens PROFINET cable is used to establish high-speed, reliable connections between PLCs, HMIs, SCADA systems, and PCs in industrial automated systems.

1) PLC-HMI Communication

- Connects the Siemens S7-1200 PLC to the KTP700 HMI panel.
- Enables real-time monitoring of water quality parameters on the HMI.

2) PLC to Industrial Network (SCADA Monitoring)

- Provides Ethernet-based communication for SCADA and remote supervision.
- Ensures secure data exchange between controllers and higher-level networks.

3) HMI to PC / Engineering Workstation

- Facilitates HMI configuration and WinCC project updates via TIA Portal.
- Supports data logging and remote visualization.

4.3.2 Technical Specification

The ProfiNET Cable is designed for various networks, ensuring seamless real-time communication in industrial automation systems.

Below are some of the technical specifications for the **Siemens 6XV1870-3RH60 Profinet cable.**

Feature	Specification
Product Type	IE TP XP Cord RJ45/RJ45, 4x2
Cable Type	Industrial Ethernet TP XP, CAT 6A
Length	6 meters
Connectors	RJ45 (both ends)
Number of Conductors	8 (4 twisted pairs)
Shielding	Overlapped aluminum-clad foil with a tin-plated copper braided screen
Outer Diameter	6.2 mm ± 0.3 mm
Operating Voltage	80V RMS
Impedance	100 Ω (1 MHz to 600 MHz)

Transfer Impedance	10 mΩ/m at 10 MHz
Bending Radius (Single Bend)	Minimum 31 mm
Bending Radius (Multiple Bends)	Minimum 43.5 mm
Temperature Range	-25°C to +80°C (operation) / -40°C to +80°C (fixed installation)
Fire Resistance	IEC 60332-1-2, smoke density IEC 61034
Compliance & Certifications	ISO/IEC 11801-1, IEC 61035, RoHS-compliant
Ingress Protection (IP Rating)	IP20

4.3.3 Advantages of using Profinet

There are several advantages to using Profinet, in addition to other protocols such as Profibus and standard Ethernet cables. Some of them are mentioned below,

1. **High-Speed Data Transfer**
   - Supports up to 10 Gbps Ethernet communication.
   - Reduces latency in real-time industrial networks.
2. **Robust Shielding & Signal Integrity**
   - The foil and braided shielding will protect against EMI and crosstalk, ensuring stable communication.
   - Ensures error-free data transmission in electrically noisy environments.
3. **Superior Mechanical Durability**
   - It is Flame-resistant and oil-resistant, suitable for harsh industrial conditions.
   - Can withstand multiple bends and vibrations, which ensures long service life.
4. **Optimized for PROFINET Industrial Networks**
   - Designed for Seamless PLC-HMI-Controller communication.
   - Fully compatible with Siemens S7-1200 PLC and KTP700 HMI.

4.3.4 Profinet Integration in the Water Quality Monitoring System

In the PLC-based Water Quality Monitoring and Separation System, PROFINET cable facilitates:

1. **Seamless Communication between PLC & HMI**
   - Transmits pH and TDS readings to the HMI display.
   - Enables User interaction with system control parameters.
2. **Real-Time Water Quality Data Processing**
   - PLC receives sensor input data and processes control decisions.
   - Sends control signals to actuators in the PLC for valve and pump operation
3. **Remote Monitoring & SCADA Integration (A Future Improvement)**
   - The Siemens S7-1200 PLC can transmit process data to SCADA systems.
   - Supports network-based remote supervision of water quality trends

4.4 pH Sensor

pH Sensors are devices that utilize electrochemical principles to measure hydrogen ion concentration (H+) in a mixture, which is expressed as pH (potential of hydrogen). The pH scale ranges from 0 to 14, where zero is strongly acidic, 14 is strongly alkaline, and seven is neutral.

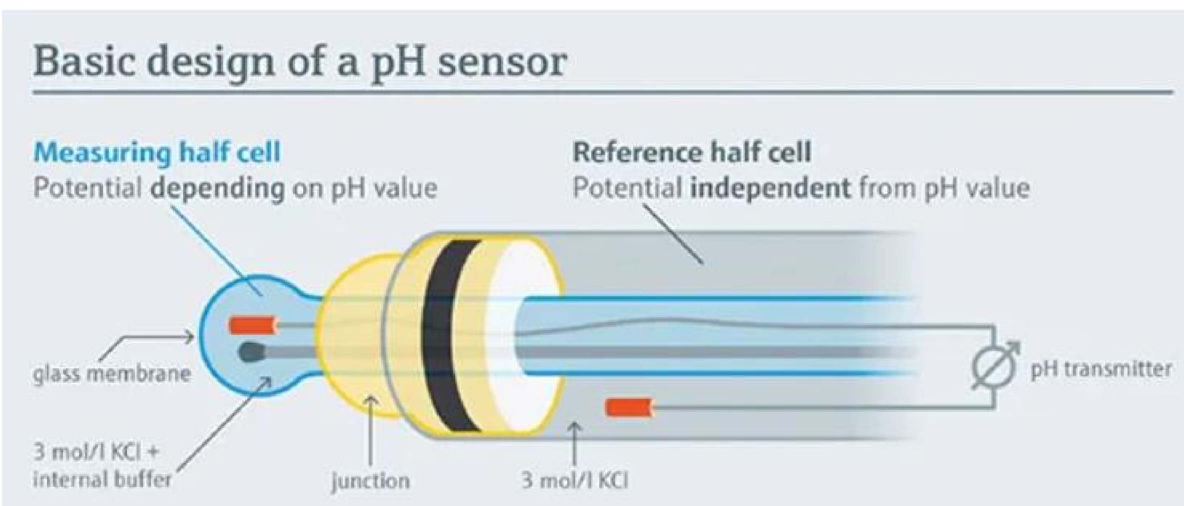

Figure 13. Basic Design of pH Sensor

4.4.1 General Principle and Key Components

A typical pH sensor works on a fundamental principle of electromotive force (EMF), which is generated by the difference in ion activity between the measured solution and a reference electrode.

Some of the Key Components of pH sensors are mentioned below,

Glass Electrode (Measuring Electrode)

- Contains a special hydrogen ion-sensitive glass membrane.
- Generates a voltage based on the hydrogen ion activity in the test solution.

Reference Electrode

- Maintains a constant potential (usually Ag/AgCl or calomel).
- Acts as a reference point for potential difference measurement.

Internal Buffer Solution

- Typically, a known pH (e.g., 7) helps in calibration and stability.

Junction (Diaphragm)

- Allows ionic contact between the internal reference solution and the test solution.

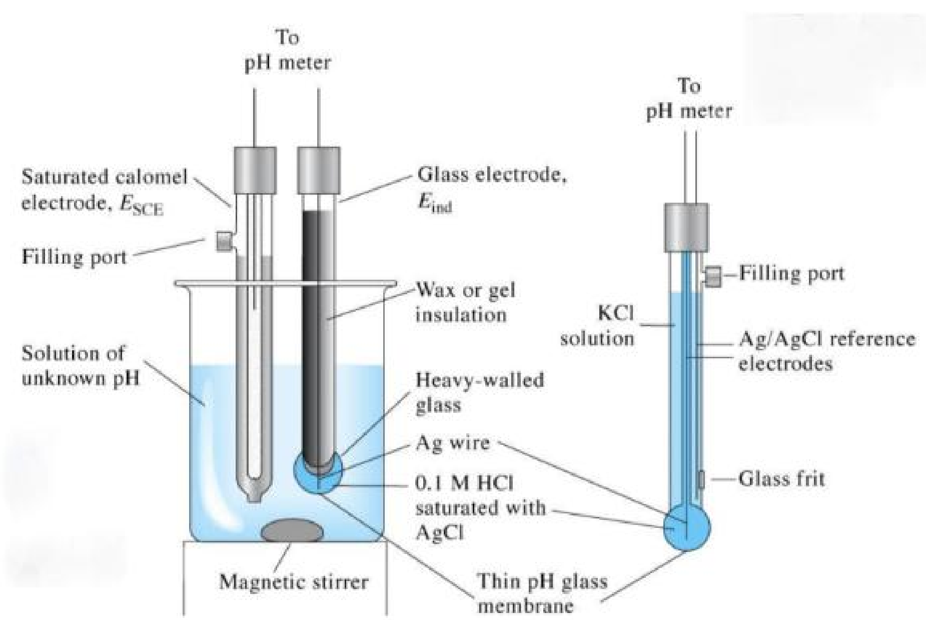

Figure 14. Key Components of pH sensor

The Nernst Equation is a governing principle by which pH sensors work, which relates the measured voltage (EMF) to the hydrogen ion concentration (pH):

$$\mathrm{E} = \mathrm{E}_0 + \frac{2.303 * \mathrm{R} * \mathrm{T}}{\mathrm{n} * \mathrm{F}} \log_{10}[\mathrm{H}^+]$$

Where:

- E = Electrode potential (mV)
- E_0 = Standard electrode potential
- R = Universal gas constant (8.314 J/mol·K)
- T = Temperature in Kelvin
- F = Faraday constant (96485 C/mol)
- n = Number of electrons transferred (1 for H^+)

4.4.2 Gravity Analog pH Sensor (SEN0169-V2)

The Gravity Analog pH Meter Pro Kit V2 (SEN0169-V2) by DFRobot is the sensor used in my thesis. It is a high-precision industrial-grade analog pH sensor, ideal for long-term water quality monitoring and environmental control. It is used for real-time pH measurement and water classification.

Calibration Method

The gravity analog pH supports two-point calibration using standard buffer solutions:

- pH 4.0 and pH 7.0 solutions are used.
- Calibration is performed via onboard potentiometers or via code (if interfaced with microcontrollers).
- This ensures high linearity and accuracy across the full 0–14 range.

Detailed Calculations are mentioned in the later section

Technical Specification

Parameter	Value
Measuring Range	0 – 14 pH
Uncertainty	±0.1 pH at 25°C
Response Time	< 1 minute
Output Voltage Range	0 – 3.0 V

Power Supply	3.3V to 5.5V DC
Signal Interface	Gravity pH2.0-3P connector
Probe Connector	BNC (twist-lock secure type)
Cable Length	1 meter
Operating Temperature	0°C to 60°C
Lifetime	Approx. 1 year (continuous use)

The sensor outputs an analog voltage (0 to 3.0V) corresponding to the pH value. To interface with a PLC:

- Analog Input: Ensure the PLC has an analog input module capable of reading 0-3V signals.

The manufacturer specifies the pH sensor uncertainty as ±0.1 pH at 25 °C, within an operating range of 0–60 °C. Since this value is only valid at 25 °C, deviations in temperature can increase measurement errors due to electrode sensitivity, changes in solution properties, and electronic drift. Thus, actual uncertainty may be higher when operating outside standard calibration conditions.

Functional Role of the pH Sensor in PLC

In the PLC-based Water Quality Monitoring and Separation System, the pH sensor is:

- Installed in the main water tank.
- Provides real-time analog voltage corresponding to pH level and is displayed on HMI.
- Interfaced to the Analog Input channel of the Siemens S7-1200 PLC.
- PLC logic compares the pH value against WHO standards (6.5 to 8.5).

1. If out of range: Water is classified as unsafe and should be diverted to the dirty compartment.
2. If within range, water is classified as safe and should be routed to a clean compartment

Figure 15. Gravity Analog pH Sensor

Advantages of SEN0169-V2 for Industrial Applications

- **Wide Compatibility**: Works with Arduino, Raspberry Pi, and industrial PLCs.
- **Long-Term Stability**: Designed for continuous monitoring.
- **Industrial-Grade Probe**: High accuracy and resilience.
- **Easy Calibration**: Two-point calibration ensures linearity.

4.4.3 Types of pH Sensors

1. Glass pH Electrodes

- Most common type.
- Made with special hydrogen ion-sensitive glass.
- High accuracy and stability.
- Fragile and unsuitable for rough environments.

2. ISFET (Ion-Sensitive Field-Effect Transistor) pH Sensors

- Solid-state sensors, no glass membrane.
- Durable and fast response.
- Suitable for field applications.

3. Optical pH Sensors

- Use pH-sensitive dyes that change optical properties.
- Ideal for biological samples or harsh environments.

4. Antimony Electrodes

- Metal-based, used in highly viscous or solid samples.
- Lower accuracy than glass electrodes.

4.5 Total Dissolved Solids (TDS) Sensor

TDS (total dissolved solids) represents the number of inorganic salts like sodium, calcium, magnesium, and organic matter in small amounts dissolved in water. The TDS value is a crucial indicator of water purity, typically measured in parts per million (ppm) or milligrams per liter (mg/L). High TDS levels can negatively impact the taste of water, cause scaling in pipes, or affect biological systems in aquaculture and agriculture.

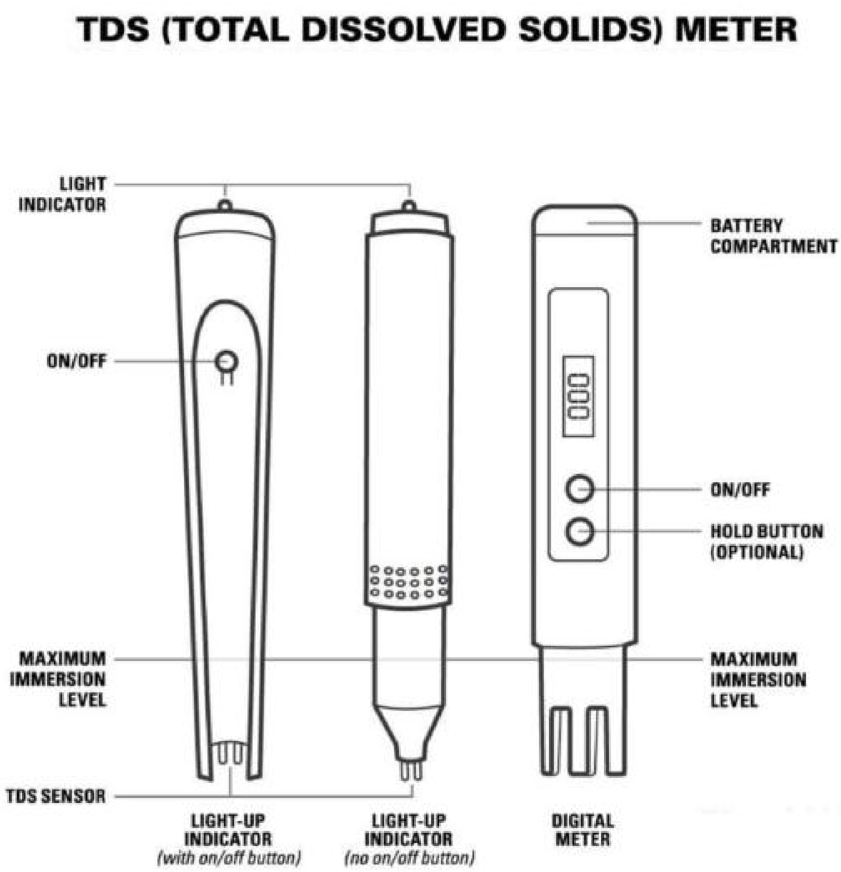

Figure 16. A general TDS Meter

4.5.1 General Principle and Key Components of TDS

The primary measuring principle of TDS meters is the measurement of electrical conductivity (EC) of a solution. Since, in principle, dissolved solids carry an electrical charge, the more the ions present, the greater the conductivity. The TDS value is evaluated by a conversion factor (K) to the EC.

$$TDS(ppm) = EC\left(\frac{\mu S}{cm}\right) x\ K$$

Where:

- K = Calibration factor (typically 0.5 – 0.7 depending on solution characteristics)
- EC is derived from the resistance between the electrodes in the probe.

This method is cost-effective, widely adopted, and sufficient for most water quality assessments.

The Key Components of the TDS Sensor are mentioned below,

Component	Function
Graphite Electrode Probe	Submersible sensor that measures the conductivity of the water (ion content)
Signal Conditioning Module	Converts raw electrical signal from the probe to a clean, filtered analog voltage
pH2.0-3P Interface Connector	Standard 3-pin Gravity interface for power, ground, and analog signal
Voltage Divider Circuit	Ensures safe signal scaling to 0–2.3V range for 3.3–5.5V systems
Onboard Filter Circuit	Reduces signal noise and fluctuation, improving output stability
Waterproof Shielded Cable	Protects signal integrity and allows safe immersion of the sensor probe
Calibration Potentiometer (internal)	Fine-tunes the signal for precise adjustment during calibration

Summary Work flow for the sensor

1. Submerge the probe into the water tank or sample.
2. Ions in the water allow current to flow between the probe's graphite electrodes.
3. This flow of current is used to calculate the electrical conductivity (EC).
4. The signal module converts the EC into a proportional voltage (0–2.3V).
5. The voltage is read by a PLC or microcontroller and scaled to a TDS value in ppm.
6. The TDS value is used to classify water as clean or contaminated in real time.

2.5.2 Gravity Analog TDS Sensor (SEN0244)

This TDS sensor by DFRobot is a gravity-series analog sensor, optimized for integration with Arduino, Raspberry Pi, and industrial PLCs. It is designed for real-time monitoring of TDS in water and provides an analog voltage output (0- 2.3V) proportional to the TDS concentration.

Calibration and Maintenance Method

1. Calibration

- Use a known TDS calibration solution (e.g., 342 ppm, 500 ppm)
- Compare the PLC output value with the known value and adjust if needed.

2. Maintenance

- Rinse probe with clean water after use
- Do not expose to >50°C
- Avoid biofouling – clean periodically with isopropyl alcohol

Technical Specification

Parameter	Specification
Sensor Type	Analog EC-based TDS sensor
Measurement Range	0 – 1000 ppm
Output Voltage	0.0 – 2.3 V (analog signal)
Input Voltage	3.3 – 5.5 V DC
Accuracy	±10% Full Scale
Probe Type	Waterproof epoxy-sealed twin-pin probe
Temperature Range	5 – 50 °C
Cable Length	~60 cm
Interface	Gravity Analog 3-pin (pH2.0-3P)
Response Time	< 1 second
Dimensions (PCB)	42 mm × 32 mm
Power Consumption	Low (<30 mA)

Functional Role of the TDS Sensor in the PLC

In my thesis, the TDS sensor is mounted in the main water tank to measure dissolved solids at the user's convenience.

Operational Flow:

1. The sensor provides an analog voltage signal to the PLC analog input
2. PLC logic converts voltage to TDS (ppm)
3. Based on WHO standards:
   - If TDS > 500 ppm → water is contaminated
   - If TDS is between 50 and 500 ppm → water is safe and can be used
4. PLC sends control signals to valves for separation as per user instructions
5. Real-time data and decisions are displayed on the HMI

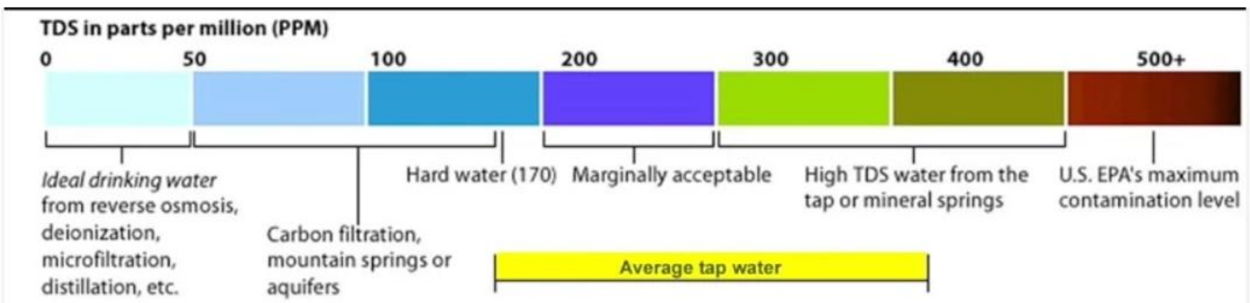

Figure 17 TDS Range.

Advantages of TDS (SEN-0244) for Industrial Applications

- **Real-time monitoring** with fast analog voltage response
- **Wide voltage compatibility** (3.3V–5.5V)
- **Waterproof, submersible probe** ideal for tanks, aquariums, and lab beakers
- **Low power draw**, perfect for embedded systems
- **Plug-and-play** with Gravity 3-pin connector and BNC probe

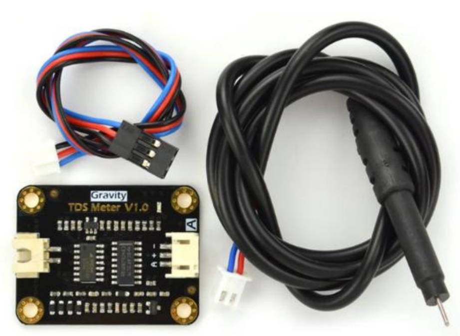

Figure 18. TDS SEN-0244

4.6 Auxiliary Devices

Float Sensor

Generally, Float Sensors, also known as liquid level switches, are electromechanical devices used to detect the presence or absence of liquid at a specific level. They are widely used in tanks, chemical storage systems, and oil filling stations. Their primary course of action is to trigger some kind of action control, such as turning solenoids, relays, pumps on/off, or even activating alarms, which will be based on the liquid level inside the tank.

Float switches are elementary, low-cost, and very reliable, making them ideal for both analog and digital automation systems.

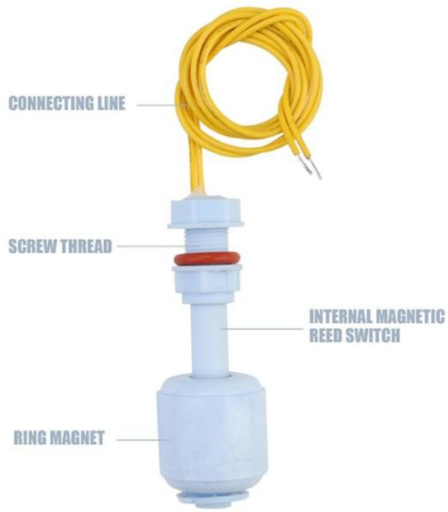

Figure 19. Float Sensor

Working Principle:

Most float switches have a reed switch mechanism combined with a magnet embedded in a floating ball.

- The reed switch is housed inside a sealed, non-magnetic pipe.
- A hollow float ball containing a permanent magnet ring moves vertically along the pipe with the liquid level.
- When the float rises and the magnet nears the reed switch, the magnetic field closes the switch contacts, generating an ON (closed circuit) signal.

- When the float drops, the magnet moves away, opening the reed switch and resulting in an OFF (open circuit) signal.

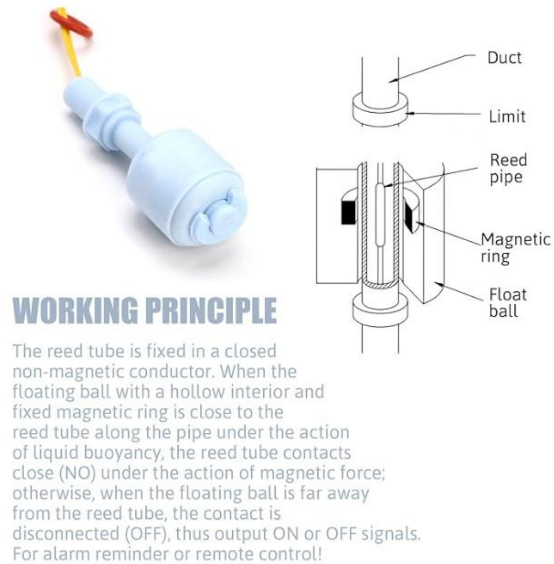

Figure 20. Working Principle of Float Sensor

Functionality in Water Monitoring System:

In my thesis, the float switch is mounted inside the main water tank. It is placed at the top of the tank

So, the following steps were taken, which define the functionality,

1. **Wiring**:
   - Connect one wire to the PLC digital input, and the other to GND.
2. **Logic Implementation**:
   - If input = HIGH → float is up → tank is full.
   - If input = LOW → float is down → tank is empty or below threshold.
3. **Control Reaction**:
   - When a low level is detected, the water pump remains on, filling the main tank.
   - When a high level is detected, the water pump is turned OFF.

Water Pump

A water pump, such as the one used in this thesis, is a DC-powered electromechanical device that pumps water from one location to another. These types of water pumps are prevalent in the automation industry, filtration systems, aquariums, and process control systems, where low voltage and high efficiency are required.

In my Water Quality Monitoring thesis, water pumps play a crucial role. They are controlled through relay modules, contactors, or directly via PLC output modules, which are vital for ensuring continuous flow, drainage, or transfer of water between tanks.

Figure 21. A DC Water Pump

Functionality in Water Monitoring System

My brushless water pump is used in the Water Quality Monitoring and Separation System to transfer water from the source tank into the primary treatment tank.

System Integration Flow is mentioned below:

- Controlled via a relay module or PLC digital output (12V interface using buck converter).
- Triggered when the START button is pressed and the water level is below the floating threshold.
- Stops automatically when:
  - The main tank water pump stops when the Float sensor indicates the tank is full.
  - Emergency STOP is pressed.
  - Compartments water pumps are stopped based on the low-level float sensor.

Solenoid Valve

An electromechanical valve, also known as a solenoid valve, controls the flow of liquids or gases in response to an electrical signal applied to it. These solenoid valves are widely used in fluid control systems, including water quality measurement systems, irrigation systems, and hydraulic setups.

At the heart of a solenoid valve is a coil (electromagnet) and a movable plunger. When electrical power is applied, a magnetic field is generated, actuating the plunger to allow or block fluid flow through the solenoid.

Figure 22. A Solenoid Valve

Functionality in the Water Monitoring System

This valve is used to direct classified water (clean/dirty) to the appropriate compartments after the PLC analyzes sensor data.

The logic implementation is as follows:

- When **clean water is detected** (safe pH, TDS):
    1. PLC energizes solenoid valve A
    2. Valve opens → water flows to Compartment A (Clean)
- When **contaminated water is detected**:

1. PLC energizes solenoid valve B
2. Valve opens → water flows to Compartment B (Dirty water)

Each valve is controlled independently using digital outputs from the Siemens S7-1200 PLC, typically via a 12V relay or transistor output module.

The Solenoid valve serves as a critical pathway for my PLC-controlled water quality monitoring and separation system. By acting on real-time data and logic from sensors and feedback processed from the PLC, it semi-automates the direction of the flow, ensuring that clean water and contaminated water are handled separately and efficiently. Its robust construction, simple wiring, and fast actuation make it an optimal choice for intelligent fluid management.

Push Button

A push button is generally a momentary or maintained contact switch used to open or close a circuit by pushing it. It is widely used in various industries, including automation systems and control panels.

The main features of a push button are,

- **Actuation Type:** Momentary (returns to normal position when released) or maintained.
- **Contact Type:** SPST (Single Pole Single Throw), SPDT, DPDT, etc.
- **Mounting:** Panel or surface mount, depending on application.
- **Feedback:** Can be non-illuminated or illuminated for status indication.

Figure 23. A NO Pushbutton

Functionality in the Water Quality System

In my PLC-based Water Quality Monitoring and Separation System, the pushbutton switch acts as a vital human-machine interface (HMI) element. Although I have a graphical HMI (KTP700 Basic), this physical button adds a layer of reliability and redundancy for manual operations.

1. System Start Command (START Button):
   When pressed, the pushbutton sends a HIGH signal to the PLC input, which triggers the initial sequence in your ladder logic. This includes:
   - Powering the main water pump.
2. System Stop Command (STOP Button):
   When pressed, it forces the PLC to:
   - Deactivate pump outputs,
   - Close solenoid valves,

3. Manual Override or Emergency Reset:
   If the system hangs or the HMI fails, operators can directly use the pushbutton to override the logic or initiate a safe shutdown. It acts as a failsafe interface.

The ABW110-BGR pushbutton switch is an industrial-grade, highly reliable, momentary contact device used to manually control operations within automation systems. Its integration into my system enables manual intervention, system startup/shutdown, and emergency control, while offering IP65 protection and robust compliance with certification standards. Ideal for harsh environments, it ensures high performance and safety in conjunction with PLC, HMI, and other field devices.

Buck Converter (Step-Down Voltage Regulator)

A step-down voltage regulator, also known as a Buck convertor, is a power electronics device that converts a higher input DC voltage into a lower, regulated DC Voltage, e.g., from 24V to 12V. It utilizes high-frequency switching elements, such as MOSFETs and inductors, to efficiently step down voltage with minimal heat loss.

Mostly linear voltage regulators dissipate excess energy as heat; in contrast, buck converters utilize pulse-width modulation (PWM) to rapidly alternate between on/off states.

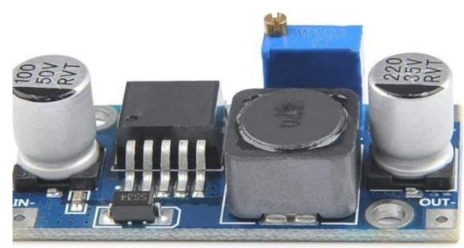

Figure 24. A Variable Buck Convertor

Components Requiring Voltage Regulation

Siemens S7-1200 PLC typically operates with 24V DC output signals. However, many devices in your system operate at 12V DC, thus requiring a voltage step-down using buck converters.

Hence, I have used a buck converter; the components requiring the buck converter are mentioned below,

Component	Rated Voltage	Buck converter needed	Description
Water Pump (QWORK)	12V DC	Yes	Needs 24V → 12V conversion
Solenoid Valves (BACOENG)	12V DC	Yes	Controlled via PLC output
pH Sensor (DFRobot)	5V DC	Yes	If powered from the PLC, a step-down is required from 24V to 5V
TDS Sensor	5V DC	Yes	Same as above

The above components can have alternative sources of power, but to maintain their integrity, I have decided to power them up from my PLC; hence, a buck converter was necessary.

4.10.1 Working Principle

The buck converter operates by alternately switching a transistor on and off, storing energy in an inductor, and filtering it through a capacitor. The duty cycle (ON time vs total time) determines the output voltage.

The basic buck converter formula is

$$V_{out} = D \times V_{in}$$

Where:

- Vout: Output voltage
- Vin: Input voltage
- D: Duty cycle (0 < D < 1)

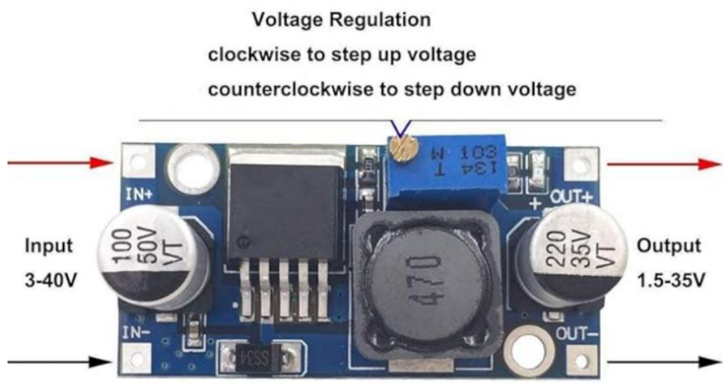

Figure 25. Working Principle

This allows for continuous and adjustable output voltages, suitable for sensitive components such as pumps, sensors, and solenoids.

Functionality in Water Quality System

The Buck converter used in this thesis is an ARCELI DC-DC Adjustable Step-Down Module, a compact and high-efficiency converter ideal for PLC and sensor-based systems.

Some of its technical Specifications are mentioned below,

Parameter	Specification
Input Voltage	3V to 40V DC
Output Voltage	1.5V to 35V DC (adjustable)
Max Output Current	3 A
Efficiency	>90% (typical)
Dimensions	45 mm × 23 mm × 14 mm
Output Indicator	Built-in LED for status
Adjustability	Trim the potentiometer to fine-tune the voltage.
Build	High-Q inductor, solid-state capacitors
Use Case	Ideal for converting 24V to 12V or 5V

The buck converter components are:

- 470µH Inductor for energy storage
- Variable resistor for adjusting output voltage
- 100µF Capacitors (50V rated) for filtering
- Schottky diode for fast switching recovery
- LED Indicator for power-on

The DC-DC Adjustable Buck Converter is a crucial component in my thesis, allowing safe and efficient interfacing between the 24V logic level of the PLC and low-voltage devices such as 12V pumps and solenoid valves. Its compact design, simple installation, and adjustable output make it a perfect fit for distributed automation systems requiring multi-voltage support.

5. Analysis of Ladder Logic, PLC Tags

This section outlines the ladder logic implementation; PLC tags have been interfaced with Siemens PLC S7-1200 1215C. It describes the internal program operation, Rung by Rung – A rung can be considered a network or a branch where the graphical logic has been orchestrated, and each network is treated as a discrete rung. This Logic controls water pumps, solenoid valves, performs value scaling, and reads sensor values, managing safe/unsafe water routing and display based on sensor readings.

5.1 Explanation of Ladder Logic

In this section, Ladder Logic will be explained in terms of its implementation in TIA Portal.

Network 1: Main Pump Operation

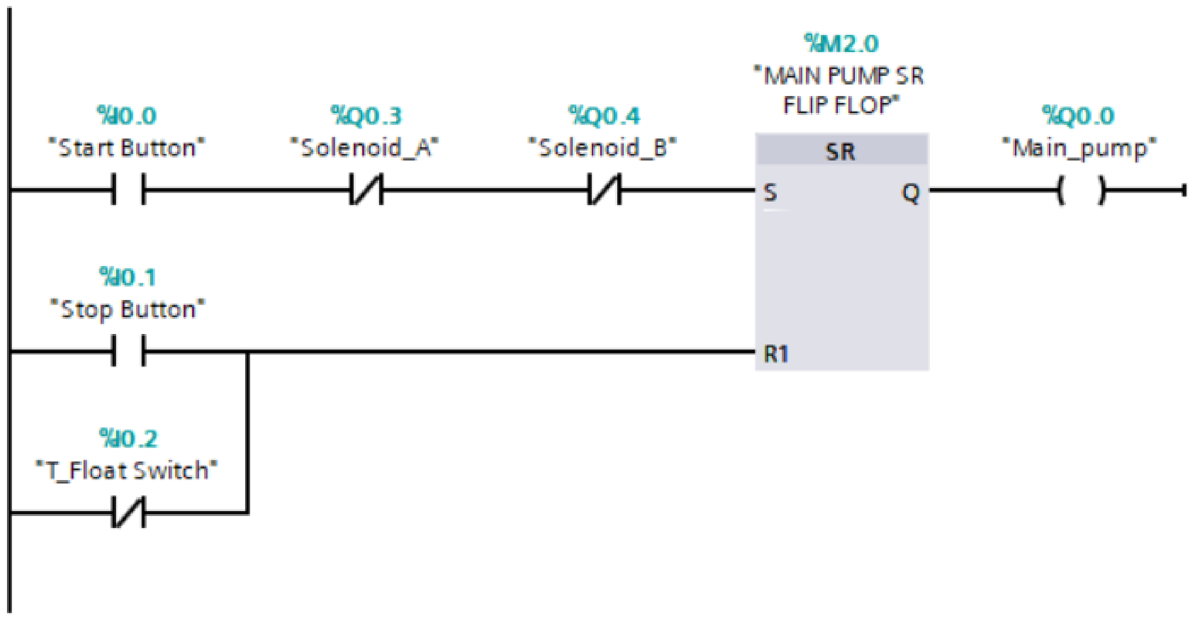

Figure 26. Main Pump Ladder Logic

This Network provides basic operation of the main pump; it implements the usage of an SR Flip-Flop to latch the main water pump even when the start button has been released. It Uses:

- **%I0.0** – Start button (NO contact)
- **%I0.1** – Stop button (NC contact)
- **%I0.2** – Float Switch (prevents overflow)
- **%Q0.3** and **%Q0.4** – Outputs to Solenoid A and B (when either solenoid is open, pumping is restricted)
- **%M2.0** – Memory bit (latched when system is running)
- **%Q0.0** – Main pump output

The NO contact on %I0.0 allows current flow only when pressed, initializing the Set operation on the flip-flop. The NC contact on %I0.1 is closed during regular operation and opens when the stop button is pressed, which activates the reset option. Furthermore, conditions such as a high-level float switch with a 0.2% I/O that is usually closed (NC) and a solenoid that is typically open (NO) also activate the reset, preventing the set point from being activated simultaneously. This interlock ensures the pump stops when it's not safe to operate.

Network 2: Obtaining pH Sensor Reading

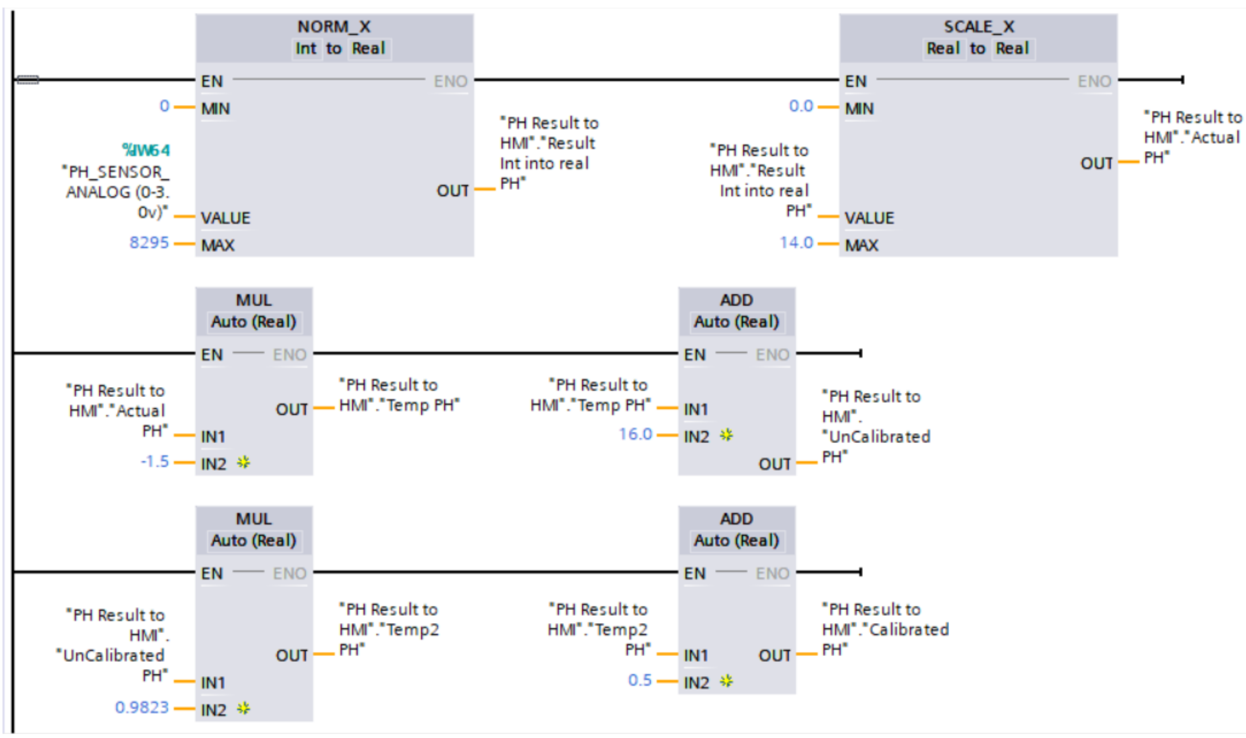

Figure 27. pH Sensor Reading

To extract meaningful measurements from analog sensors, such as the pH sensor used in my thesis, the voltages must be converted into engineering values (e.g., pH level). This function is done by implementing two standard function blocks, Norm_X and Scale_X.

Analog Input Module (AI) of the PLC receives a voltage (from 0–10 V) and internally represents this as an unsigned 16-bit integer value ranging from 0 to 27648 (13-bit effective resolution). The exact voltage range depends on the sensor, which may only output 0–2.3 V or 0–3.0 V, so custom scaling limits are applied. In our case, for pH, I have scaled from 0 to 8295.

So, the main logic I have used is:

- %IW64 – Raw analog input (from pH sensor)
- NORM_X – Normalizes the integer value from 0–27648 to 0.0–1.0 (0-8295 in my case)

- SCALE_X – Scales the normalized value to the actual pH range (0–14)
- Actual_PH – Final scaled output (REAL), displayed on HMI (Uncalibrated, Raw pH value)
- Calibrated_PH – The final value obtained after calibration and displayed on HMI

Norm_X functionality

The NORM_X block performs normalization, mapping a raw analog value to a standard range between 0.0 and 1.0.

The formula that converts this is:

$$Normalized\ Value = \frac{Input\ Value - \ Min_{raw}}{Max_{raw} - Min_{raw}}$$

- Input Value: Raw analog reading (e.g., %IW64 or %IW66)
- Min_{raw}: Minimum expected raw value (typically 0)
- Max_{raw}: Maximum expected raw value (sensor-specific, e.g., 8296)

This standardizes the sensor signal regardless of the voltage range or raw scaling applied.

Scale_X functionality

Once the Norm_X block has processed the data, it passes it onto the Scale_X block, which converts it to the required Real-world value by applying a linear transformation.

The formula that describes this block is as follows:

$$Scaled\ Value = Min_{Value} + (Normalized_{Value}\ \times (Max_{Value} - \ Min_{Value}))$$

Where:

- Min_{Value}: Minimum of the engineering range (e.g., 0 for pH)
- Max_{Value}: Maximum of the engineering range (e.g., 14 for pH)

This gives the final, Real-life value that can be displayed on the HMI or used in logical decisions within the PLC program.

Application to pH Sensor

The application for this process for my pH sensor is as follows,

- Sensor Voltage Range: 0–3.0 V
- PLC Raw Input Range: 0–8296
- Target Engineering Range: 0–14 pH

Process steps,

1. Raw analog input from the pH sensor is received at %IW64.
2. NORM_X normalizes the value:

$$Normalized_{PH} = \frac{Raw\ Input}{8296}$$

3. SCALE_X maps it to the actual pH value:

$$PH = Normalized_{PH}\ \times 14$$

4. This result is stored in the "Actual _pH" tag on the PLC, which is then displayed on the HMI.

Two-Point Linear Calibration

During calibration, it was observed that the sensor readings were inverted when tested with standard buffer solutions (e.g., pH 4 and pH 10). To correct this, a two-point linear calibration was applied. The resulting parameters were:

Gain = −1.5, Offset = 16

These values were implemented in the PLC logic after the scaling step, ensuring that the displayed pH values aligned with the actual buffer solution values.

This calibration step was crucial in addressing both the inversion error and the minor deviations between measured and actual values, ultimately improving the accuracy and reliability of the pH measurements shown on the HMI.

Network 3: Obtaining TDS Sensor Reading

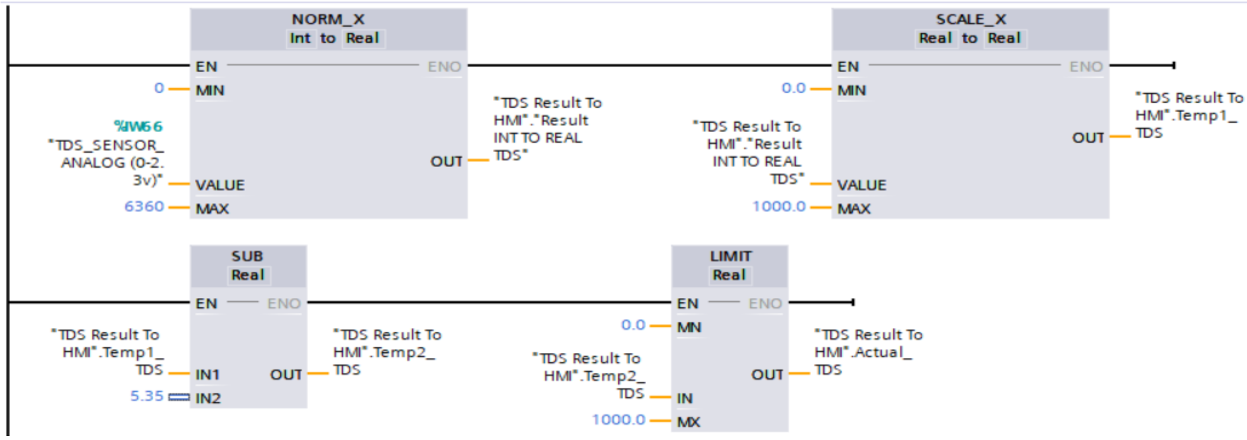

Figure 28. TDS Sensor Reading

This network rung is very identical in structure to Network 2 but handles the TDS sensor connected to %IW66 (Analog Input). The signal is normalized and scaled to produce Temp1_TDS, which is then further adjusted by an offset of 5.35 ppm.

So, the main logic I have used is:

- %IW66 – Raw analog input (from TDS sensor)
- NORM_X – Normalizes the integer value from 0–27648 to 0.0–1.0 (0-6360 in my case)
- SCALE_X – Scales the normalized value to the actual TDS range (0–1000)
- Actual_TDS – Final scaled output (REAL), displayed on HMI

So, essentially, the Norm_X and Scale_X blocks operate in a very similar manner to pH; they employ the same conversion formula. However, in the Norm_X block, since my input Analog voltage ranges from 0 to 2.3V, the range is customized to 0 to 6360, as each voltage represents a 2765 value.

Application to TDS Sensor

- Sensor Voltage Range: 0–2.3 V
- PLC Raw Input Range: 0–6360
- Target Engineering Range: 0–1000 ppm

Process steps,

1. Raw analog input from the TDS sensor is received at %IW66.
2. NORM_X normalizes the value:

$$Normalized_{TDS} = \frac{Raw\ Input}{6360}$$

3. SCALE_X maps it to the actual pH value:

$$TDS = Normalized_{TDS} \times 1000$$

4. This result is stored in the "Actual _TDS" tag on the PLC, which is then displayed on the HMI.

Network 4: pH Value Detection

Figure 29. pH Value Detection logic

This Logic basically checks if the scaled pH value (Calibrated_pH) is equal to or greater than 0.1. If so:

- Sets memory bit %M3.0 to TRUE

This logic ensures sensor disconnection or failure is detected promptly. Hence, essentially, acting is a safeguard to ensure our pH sensor is giving a proper reading.

Network 5: TDS Value Detection

Figure 30. TDS Value Detection Logic

As previously mentioned, this Logic basically checks if the scaled TDS value (Actual_TDS) is equal to or greater than 40. If so:

- Sets memory bit %M3.1 to TRUE

This logic ensures sensor disconnection or failure is detected promptly. Hence, essentially, acting is a safeguard to ensure our TDS sensor is giving a proper reading.

Network 6: Display Tag on HMI

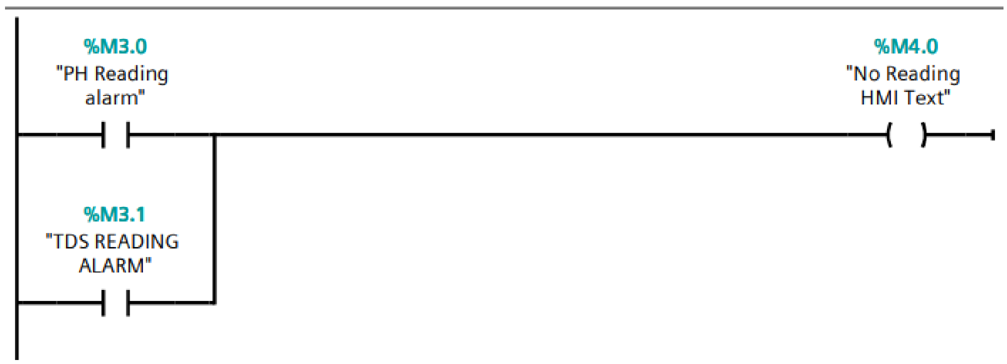

Figure 31. Sensor Reading Display Logic

In this network, it summarizes the networks 4 and 5 and then displays a dynamic display message on the HMI

- If either %M3.0 or %M3.1 is false, HMI displays a tag stating “No Reading Taken”.
- If even one of the tags is True, the message dynamically disappears.

This rung summarizes sensor error states into a single display condition.

Network 7: pH Sensor Comparator

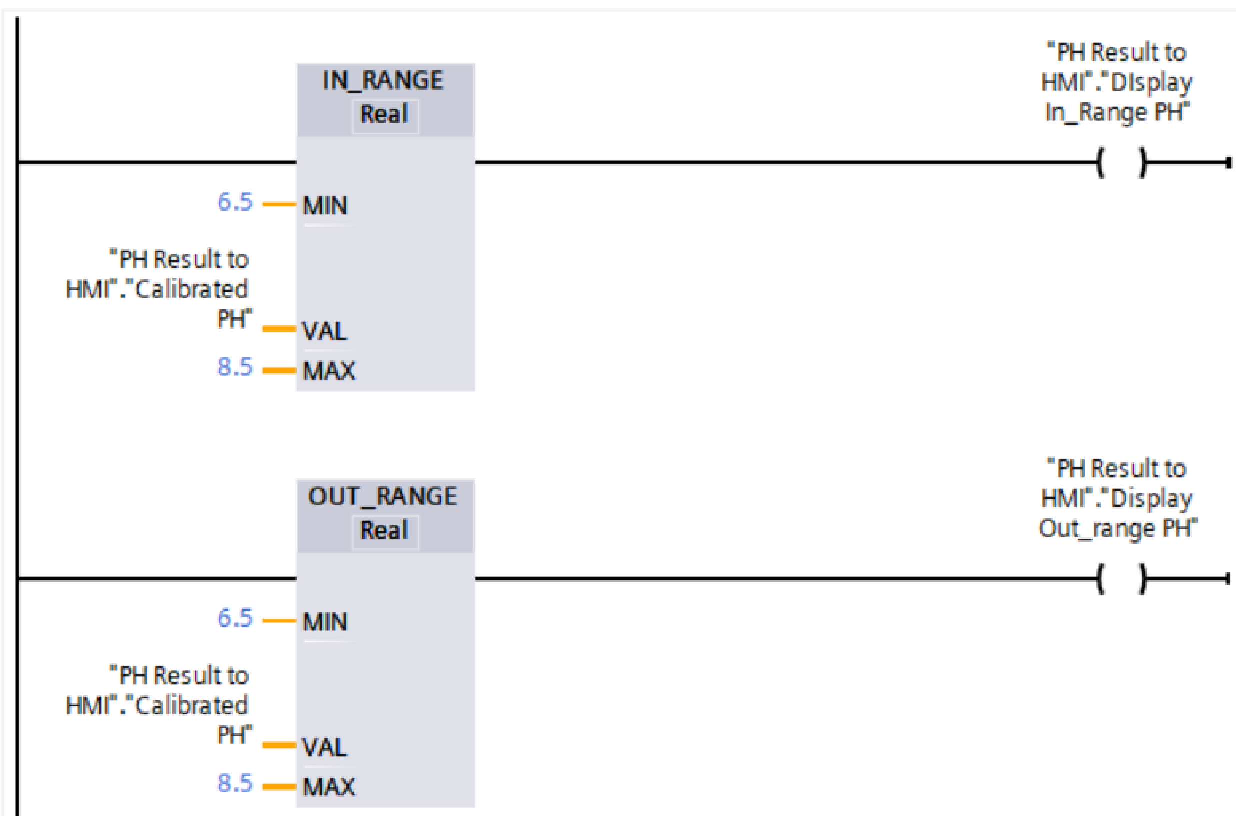

Figure 32. pH Comparison Logic

In a water quality system, parameters such as pH and TDS must be within acceptable limits and align with environmental and health standards. Therefore, networks 7 and 8 (following network) are responsible for comparing the measured values of pH and TDS against safe thresholds using IN_RANGE and OUT_RANGE logic blocks.

In this network, I have verified whether the measured pH value falls within the recommended safe limits for drinking water.

- WHO Guidelines state that the acceptable pH range for potable water is 6.5 to 8.5 [WHO, 2022; BIS 10500:2012].

It's Important because:

- **Acidic water** (pH < 6.5) may cause corrosion of pipes and release of metals like lead.
- **Alkaline water** (pH > 8.5) may affect taste and reduce disinfection efficiency.
- Semi-automated pH validation prevents unsafe water from being categorized as usable.

The Process is as follows,

1. The scaled analog input (from Network 2) representing actual pH is stored in Calibrated_pH.
2. This value is passed into two comparison blocks:

- IN_RANGE comparator:
    - Min: 6.5
    - Max: 8.5
    - Output: DISPLAY_INRANGE_pH
- OUT_RANGE comparator:
    - Also uses 6.5 and 8.5
    - Output: DISPLAY_OUT_OF_RANGE_pH

3. These bits are sent to the HMI to indicate safe or unsafe water.

Network 8: TDS Sensor Comparator

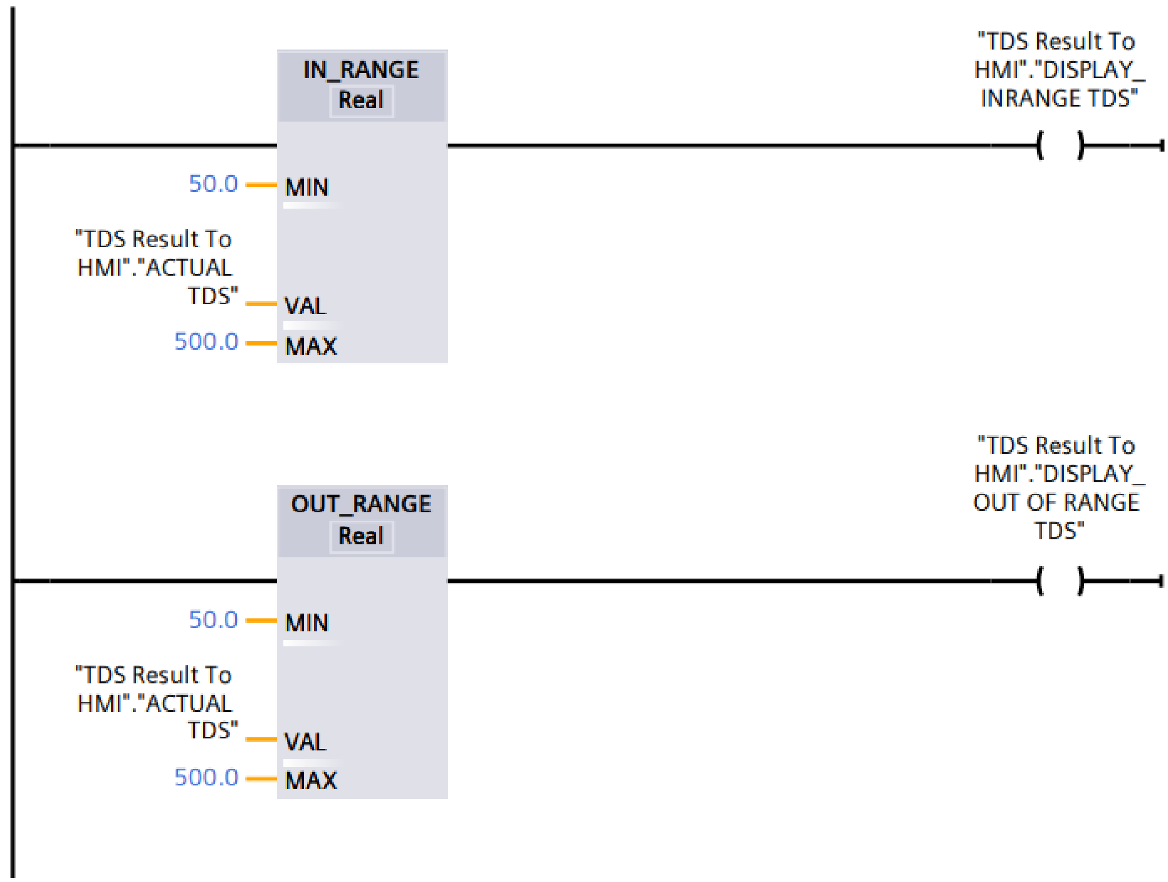

Figure 33. TDS Comparison Logic

This Logic is similar to network 7; The use of IN_RANGE and OUT_RANGE blocks streamlines safety logic in Siemens TIA Portal. These comparators provide clear, binary outputs that simplify HMI integration and conditional operations within the PLC.

- Each comparator outputs a Boolean (TRUE/FALSE), which is then stored in specific Data Block Boolean addresses (DBX).
- These flags are further used in Network 9 and 10 to trigger messages like "Water is Safe" or "Unsafe Water Detected" on the HMI screen.

The objective of this logic is to determine whether the TDS concentration in water falls within a desirable quality range.

- WHO and EPA suggest that water with TDS between 50–500 ppm is generally acceptable for taste and safety.

This water level is significant because,

- **Low TDS (<50 ppm):** May indicate aggressive water that can leach metals.
- **High TDS (>500 ppm):** Can affect taste, corrode plumbing, and signal pollution.
- Monitoring TDS ensures water is not only chemically safe but also palatable.

The process is as follows,

1. The scaled output from the TDS sensor is stored in Actual_TDS (%DB2.DBD4).
2. Two range-checking blocks are used:

- IN_RANGE comparator:
    - Min: 50.0
    - Max: 500.0
    - Output: DISPLAY_INRANGE_TDS
- OUT_RANGE comparator:
    - Min: 50.0
    - Max: 500.0
    - Output: DISPLAY_OUT_OF_RANGE_TDS

3. These bits are sent to the HMI to indicate safe or unsafe water.

Network 9: HMI Display – Clean water

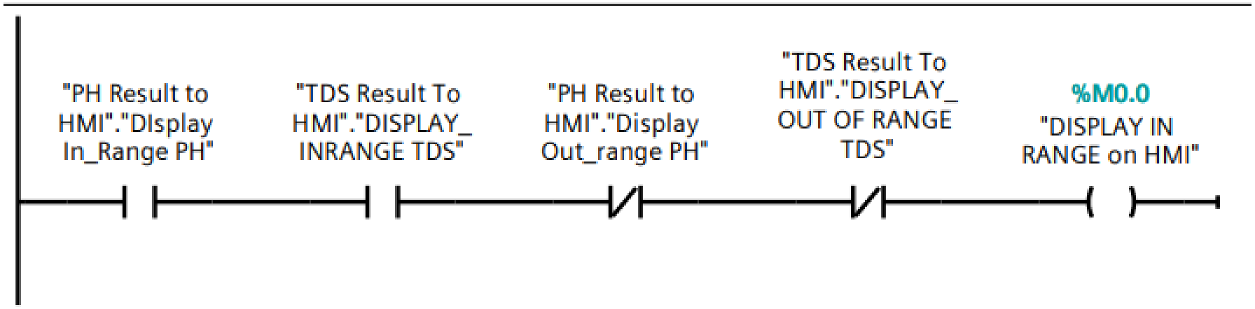

Figure 34. Clean water Display Logic

Network 9 and Network 10 are designed to check whether the water quality parameters fall within safe ranges for both pH and TDS, and subsequently display the appropriate status messages on the HMI. The logic behind these networks helps the operator make quick, informed decisions about the water's safety for use.

The primary purpose of this network 9 is to ensure that the water is safe for use when both pH and TDS values are within the safe ranges. According to a report and guideline from the WHO, drinking water should have a pH value range of between 6.5 and 8.5 and a TDS range of between 50 and 500 ppm. The PLC performs a series of checks to validate the conditions.

The system reads the pH and TDS values from the sensors; first, we need to ensure that they fall within an acceptable limit. When both pH and TDS are within their boundaries, the system triggers a memory bit (e.g., M0.0) to indicate that the water is safe to use. This memory bit is linked to the HMI display, which then shows a “Water is Safe to Use” message.

If both the pH and TDS are within the safe limits, the system confirms that the water quality is suitable for use, and the HMI provides this feedback to the operator. This interlocking process ensures that the system only displays a safe status when both conditions are met. Suppose either parameter is outside its specified range. In that case, the system will not display the “Water is safe to use” message, preventing any misunderstanding or improper use of water that may not meet quality standards.

Network 10: HMI Display – Display Water

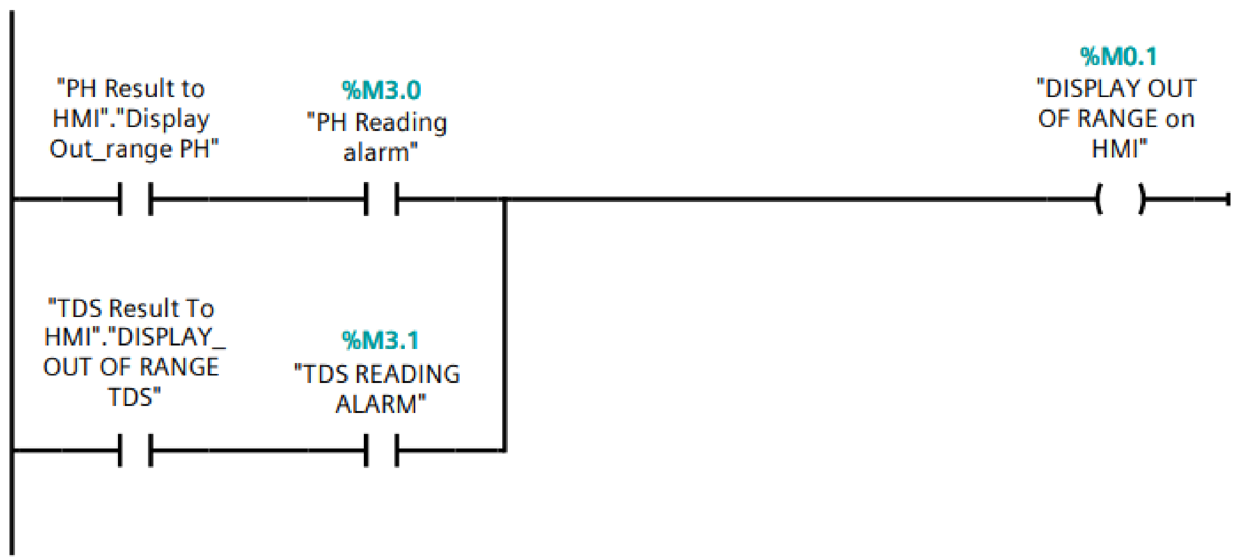

Figure 35. Dirty Water Display Logic

In this network, 10 performs the exact opposite function. It is responsible for indicating when either the pH or TDS level is out of range, making the water unsafe for use. In this logic, we implemented OR logic instead of AND logic in network 9. If either the pH value is outside the 6.5–8.5 range or the TDS value is outside the 50–500 ppm range, the PLC activates a separate memory bit (such as %M0.1), which triggers a “Water Not Safe to Use” message on the HMI.

By comparing the actual readings of the pH and TDS sensors with their safe and acceptable ranges, the PLC can effectively display an unsafe status if either or both of the parameters deviate from the permissible limits. This logic helps avoid any potential use of water that may be harmful or unsuitable for its intended purpose, such as consumption or processing.

Interlocking between Network 9 and Network 10

The interlocking of Networks 9 and 10 is a key aspect of the system's design. These two networks are complementary and work together to ensure that only one message—either "Water Safe" or "Water Unsafe"—is displayed at any given time.

When Rung 9 is active, it indicates that both TDS and pH are within safe ranges, and the message "Water is safe to use" is displayed. Even if one of the parameters is false, the entire logic becomes false. On the other hand, in Network 10, even if one of the logics is True, the entire reasoning is True; both logics must be false to render the whole logic false. Hence, in Network 9, we can say it is similar to AND logic, and in Network 10, we can say that it is identical to OR logic.

Network 11 and 12: Drainage into Compartments

Both networks 11 and 12 are constructed to control the drainage of water from compartment A (clean water) and compartment B (Dirty water). These two networks perform the critical function of pumps and solenoid valves when the user chooses from the button on the HMI.

The drainage process is tightly interlocked with a low-level float switch, which ensures that the water level in each compartment is not pumped once it reaches a certain point. These networks enable the operator to manage the drainage process by manually activating the appropriate controls on the HMI, allowing for the automated movement of water between the compartments.

Network 11: Drainage to compartment A

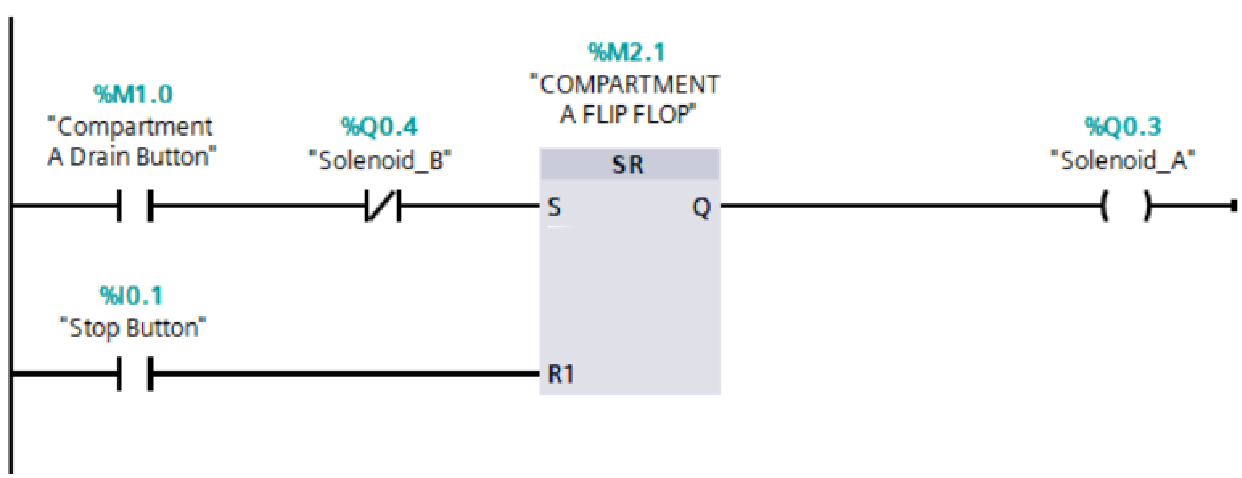

Figure 36. Drainage Logic for Compartment A

The primary function of this network 11 is to control the drainage of clean water from compartment A. This is particularly useful for a case scenario where we need to discharge clean, filtered water, either for storage or further processing.

The process is as follows,

1. **HMI Button Control:**
   - The drainage process for Compartment A is activated by pressing the "Drain to A" button on the HMI.
   - The HMI button corresponds to a memory bit (%M1.0), which serves as a trigger for the drainage operation.
2. **Interlocking Logic:**
   - The SR flip-flop acts as a latching state for the compartment A solenoid; this ensures that they remain true even when the button from the HMI is released.
   - Solenoid B here acts as an interlock, which means that if we are draining from solenoid A, the system will not let you drain from solenoid B until solenoid A is turned off. This ensures reliability and safety, and prevents contamination of the solution.
   - The process, once started, can only be stopped by either the stop button or by a timer-based process.
3. **Pump and Solenoid Activation**:
   - When %M1.0 is set, it activates:
     - Solenoid A (%Q0.3) to open the valve, allowing the water to flow out.

Network 12: Drainage to compartment B

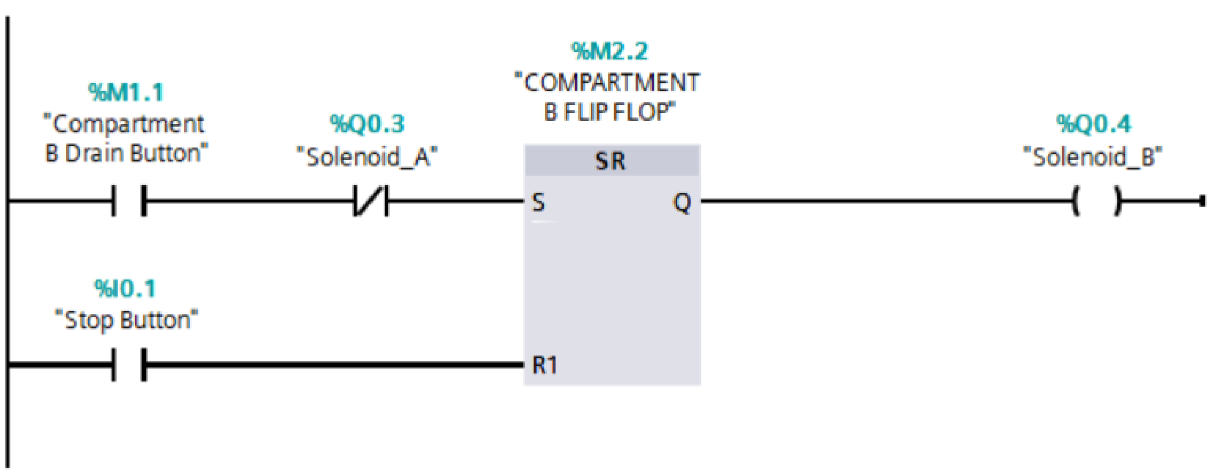

Figure 37. Drainage Logic for Compartment B

Network 12 is very similar in structure to network 11, and they go side by side. This work handles the drainage of dirty water to compartment B. This is activated through user manual interaction with the HMI, and the user decides whether the water is contaminated enough and is ready for disposal.

The process is as follows,

1. **HMI Button Control**:
   - Drainage of Compartment B is controlled by the "Drain to B" button on the HMI.
   - Just like in Network 11, pressing the "Drain to B" button sets the memory bit %M1.1 to TRUE, which triggers the drainage operation.
2. **Interlocking Logic**:
   - The %M1.1 memory bit is passed through an SR flip-flop to latch the state of the drainage process.
   - This ensures that solenoid B remains activated during the entire drainage process until the user stops the system.
   - Solenoid A here acts as an interlock, which means that if we are draining from solenoid B, the system will not let you drain from solenoid A; solenoid B is turned off. This ensures reliability and safety, preventing contamination of the solution.
3. **Pump and Solenoid Activation**:
   - When %M1.1 is set, it activates:
     - Solenoid B (%Q0.4) to open the valve and allow the water to flow out.
   - The drainage process continues until the low-level float switch in the main compartment detects that the water has been sufficiently drained or the operator stops it manually.

Analysis of PLC Tags

The table below breaks down each PLC tag, along with its operation in my ladder logic and HMI system for the Water Quality Monitoring and Separation System.

Tag Name	Address	Data Type	Description & Usage
Start_Button	%I0.0	Bool	Digital input from a pushbutton. Activates the main pump via the SR flip-flop (Network 1).
Stop_Button	%I0.1	Bool	Resets the SR flip-flop to stop the pump. Also used in emergency or float overflow.
T_Float_Switch	%I0.2	Bool	Top-level float switch. Used to stop the pump when the water reaches the maximum height.
B_Float_Switch	%I0.3	Bool	Bottom-level float. Use for draining control.
pH_SENSOR_ANALOG	%IW64	Word	Analog input from the pH sensor. Raw value (0–27648) normalized and scaled in Network 2.
TDS_SENSOR_ANALOG	%IW66	Word	Analog input from the TDS sensor. Converted into ppm using NORM_X + SCALE_X.
Actual_pH	DB / HMI Tag	Real	Final scaled real number from pH logic (0–14). Shown on the HMI display.
Actual_TDS	DB / HMI Tag	Real	Final scaled real value from TDS sensor (0–1000 ppm). Sent to HMI.
pH_Reading_Alarm	%M3.0	Bool	Set if the pH reading is < 0.4, indicating a faulty reading. Used in HMI "No Reading" message.
TDS_Reading_Alarm	%M3.1	Bool	Set if TDS reading < 40. Triggers no-reading alert (Network 5).
No_Reading_Message	%M4.0	Bool	Activated if either pH or TDS alarms are active. Toggles "No Reading" text on HMI.
IN_RANGE_DISPLAY	%M0.0	Bool	Activated if both pH and TDS are within a safe range. Used to display "Water is Safe."
OUT_OF_RANGE_DISPLAY	%M0.1	Bool	Activated if either pH or TDS is out of range. HMI shows "Water Not Safe."
Compartment_A_Drain_Button	%M1.0	Bool	Triggered from HMI. Open Solenoid A to drain the clean water.
Compartment_B_Drain_Button	%M1.1	Bool	Triggered from HMI. Start Pump B and open Solenoid B for the dirty water drain.
Main_Pump_Latch	%M2.0	Bool	Memory bit used to hold the pump ON state using SR flip-flop (Set/Reset logic).
Temp_PH	DB	Real	Stores a temporary value for the calibration of the pH value
Tag Name	**Address**	**Data Type**	**Description & Usage**
Solenoid_A_Latch	%M2.1	Bool	Latch to maintain activation of Solenoid A during Compartment A drain.
Solenoid_B_Latch	%M2.2	Bool	Latch to maintain activation of Solenoid B during Compartment B drain.
Main_Pump_Output	%Q0.0	Bool	Digital output to control a 12V pump via a buck converter and a relay.

Solenoid_A_Output	%Q0.3	Bool	Controls valve to Compartment A. Opens when clean water is routed.
Solenoid_B_Output	%Q0.4	Bool	Controls the valve to Compartment B, opening it to allow contaminated water to flow.
pH_Result_INT_to_REAL	Local Variable	Real	Intermediate real from NORM_X. Used to feed SCALE_X. Not shown on HMI.
TDS_Result_INT_to_REAL	Local Variable	Real	Intermediate real from NORM_X. Used to feed SCALE_X. Not shown on HMI.
UnCalibrated_PH	DB	Real	Stores the pH value after calibration, but it is not fine-tuned
Calibrated_PH	DB	Real	Stored, fine-tuned, and two-point calibrated pH value

6. Offset adjustment and Calibration of Sensors

TDS offset adjustment

During the initial testing of my TDS Sensor, it showed an offset of +5.35 ppm. This was when there was no reading being taken place to correct for this; an additive zero-offset correction was applied to all raw TDS readings:

$$TDS_{Calibrated} = TDS_{Measured} - 5.35$$

This offset correction removes the observed baseline bias before further analysis (uncertainty and comparison to actual/expected values).

pH Sensor Calibration

The pH Sensor initially showed inverted readings during initial pH base: When placed in a pH 10 buffer, it read ≈ 4 pH (Approx), and when placed in a pH 4 buffer, it read ≈ 8.25. A simple two-point linear calibration (gain + offset) was therefore used.

The calibration model is:

$$\mathrm{pH_{Calibrated}} = (\mathrm{Gain} * \ \mathrm{pH_{Measured}}) + \mathrm{offset}$$

Given the two-calibration pair (True1,Meas1) and (True2,Meas2), we calculate Gain and offset as follows:

$$Gain = \frac{True_2 - True_1}{Meas_2 - Meas_1}, \ Offset = True_1 - (\frac{True_2 - True_1}{Meas_2 - Meas_1} * \ Meas_1)$$

These two adjustments calibrated my pH Sensor readings and solved the problem of the inversion issue.

So, the inversion-correction formula is:

$$\mathrm{pH_{Calibrated}} = (-1.5 * \mathrm{pH_{Measured}}) + 16.25$$

7. Measurement Uncertainty of Sensors

In water quality monitoring systems, particularly those utilizing analog sensors such as pH and TDS, measurement precision and reliability are crucial for accurate results. The performance of such systems hinges not only on sensor quality but also on proper calibration, uncertainty analysis, and traceability to metrological standards. This chapter presents:

- Measurement uncertainty concepts (Type-A and Type-B methods)
- Calibration of Sensor in Ladder Logic
- Application to the hardware and logic of this project

7.2 TDS Sensor Uncertainty

The DFRobot Gravity Analog TDS Sensor (SEN0244) was tested using three water samples: tap water, salt water, and lemon water. Ten readings were recorded for each solution, as shown in the table below.

Reading No.	Tap Water (ppm)	Salt Water (ppm)	Lemon Water (ppm)
1	257.54	869.34	418.56
2	262.89	869.34	418.55
3	262.89	868.59	418.55
4	263.00	869.18	413.20
5	262.89	868.54	418.56
6	262.92	869.34	418.80
7	262.89	869.18	418.55
8	262.89	868.80	416.21
9	262.85	869.93	413.03
10	262.87	869.04	415.47

These experiments were performed in the lab under the same temperature and environmental conditions.

TDS Type A Uncertainty (Experimental Data)

In this section, all the formulas used are taken from annex section, and results are obtained using experimental data, which was performed in the lab

The Table below summarizes the result:

Solution	**Mean (ppm)**	**Sample Variance (S) (ppm)**	**Type A u_A (ppm)**
Tap water	262.363	1.695	± 0.536
Salt water	869.13	0.161	± 0.127
Lemon water	416.948	2.320	± 0.734

TDS Type B Uncertainty (Manufacturer Data)

According to the DFRobot datasheet, the TDS sensor accuracy is ±10% of full scale (0–1000 ppm). This corresponds to:

$$\alpha = \pm 100 \text{ ppm}, \ \mathrm{u_B} = \frac{100}{\sqrt{3}} \approx \pm 57.7 \text{ ppm}$$

Combined and Expanded Uncertainty

These were also formulated using the formula mentioned in the annex section.

Solution	u_A (ppm)	u_B (ppm)	u_C (ppm)
Tap water	0.536	57.735	57.738
Salt water	0.127	57.735	57.736
Lemon water	0.734	57.735	57.740

Observations

1. **Observation 1 – Type B Dominance:**
   The TDS sensor's manufacturer-specified uncertainty (±57.7 ppm) overwhelmingly dominates compared to the Type A experimental uncertainty. This clearly indicates that the sensor's measurement uncertainty is mainly governed by its intrinsic resolution and calibration accuracy, rather than short-term repeatability.
2. **Observation 2 – High Mean Stability:**
   The readings show minimal variation across 10 trials, confirming high repeatability and negligible noise under constant lab conditions.
3. **Observation 3 – Combined Uncertainty Influence:**
   Since $u_C \approx u_B$, the overall measurement confidence depends entirely on the sensor's design tolerance. Even though experimental spread is low, the measurement system's intrinsic uncertainty constrains the achievable confidence.

7.3 pH Sensor Uncertainty

As was done for TDS, pH sensor readings were measured in the same way. Still, the solutions that were used to measure the readings differ, for pH Solutions that were used are (Buffer pH 4, Buffer pH 10, and Tap water), 10 repeats per solution were taken. Experimental readings were recorded in the table below:

No.	Buffer pH 4	Buffer pH 10	Tap water (pH)
1	3.65	9.78	7.10
2	3.16	9.69	6.93
3	3.57	9.86	7.24
4	3.69	9.78	7.27
5	3.68	9.82	7.27
6	3.68	9.63	7.45
7	3.67	9.63	7.53
8	3.68	9.69	7.45
9	3.70	9.69	7.53
10	3.68	9.67	7.53

pH Type A Uncertainty (Experimental Data)

The table below summarizes the calculated Mean, standard deviation, and type A uncertainty of the pH Sensor, taken over 10 repeated readings in different solutions.

Solution	Mean (pH)	Sample Variance (S) (pH)	Type A u_A (pH)
Buffer pH 4	3.616	0.16433	0.052
Buffer pH 10	9.724	0.08031	0.025
Tap water	7.330	0.20467	0.065

The Type A uncertainty analysis shows that the pH sensor exhibits good repeatability across all test conditions. The lowest variability was observed in the pH 10 buffer ($\mathbf{u_A}$ ≈0.025 pH), while the pH 4 buffer and tap water showed slightly higher scatter ($\mathbf{u_A}$ ≈0.052 pH and $\mathbf{u_A}$ ≈0.065 pH, respectively). The higher variation in tap water is expected, as it lacks the stable ionic composition characteristic of buffer solutions. Overall, the results confirm that the sensor measurements are consistent, with random uncertainty remaining within a narrow range.

pH Type B Uncertainty (Manufacturer Data)

The Type-B contribution associated with the two-point calibration was calculated by propagating the uncertainty from the estimated gain and offset.

The following equations were used.

$$\mathrm{pH}_{Cal} = Gain * \mathrm{pH}_{Meas} + Offset$$

$$u^2(pH_{Cal}) = \left(\frac{\partial pH_{Cal}}{\partial Gain}\right)^2 * u^2(Gain) + \left(\frac{\partial pH_{Cal}}{\partial offset}\right)^2 * u^2(Offset)$$

Where we can say that,

$$\left(\frac{\partial pH_{Cal}}{\partial Gain}\right) = pH_{Meas} \;, \qquad \left(\frac{\partial pH_{Cal}}{\partial offset}\right) = 1$$

The gain formula is mentioned on page 84. Taking the readings True1, True2, Meas1, and Meas2, we will calculate u(G). Then, considering this, we will use it to calculate the type B uncertainty, as we have applied a calibration adjustment and cannot directly use the manufacturer's data.

The calibration used two standard buffers (4.00 and 10.00 pH) with measured mean responses:

- $Meas_1$ = 3.616 (for the pH 4 buffer)
- $Meas_2$ = 9.724 (for the pH 10 buffer)

Each mean was obtained from *n = 10* repeated measurements.

The standard uncertainties of the buffer values were taken from Apera Instruments Buffer Solutions:

- $u(True_1)$ = 0.015 pH (pH 4 buffer)
- $u(True_2)$ = 0.030 pH (pH 10 buffer)

Using the calibration equations:

- $G = (True_2 - True_1) \div (Meas_2 - Meas_1)$
- $OFF = True_1 - (G \times Meas_1)$

Figure 38.Apera Buffer Solutions (pH 4 and pH 10)

The calibration parameters were determined, and their standard uncertainties were obtained by first-order propagation of uncertainty. The results are:

- u(G) = 0.0108
- u(OFF) = 0.0660 pH

then propagation of u(G) and u(OFF) was taken into account to evaluate the standard uncertainty of pH_{Cal}, for which the formula is as follows

$$u_B(pH_{Cal}) = \sqrt{(pH^2_{meas})\big(u(G)\big)^2 + (u(OFF))^2}$$

So, depending on the equation the Uncertainty will vary according to pH_{Meas}.

Combined Uncertainty

These were also formulated using the formula mentioned in the annex section below and pH_{Cal} formula above.

Solution	u_A (pH)	u_B (pH)	u_C (pH)
Buffer pH 4	0.05197	0.07670	0.093
Buffer pH 10	0.02540	0.12406	0.126
Tap water	0.06472	0.10309	0.122

Observations

1. Sensor Calibration Necessity

The pH sensor did not align with manufacturer specifications during initial testing, A two-point linear calibration using buffer solutions (pH 4 and pH 10) was therefore essential to correct both the slope and offset, ensuring accurate pH measurement.

2. **Calibration-Based Uncertainty**
Uncertainty in the calibrated readings arises from the estimated Gain and Offset parameters, obtained through the propagation of their partial derivatives. These calibration-derived Type B uncertainties were more representative of real sensor performance than manufacturer data, confirming that calibration significantly influences total measurement uncertainty.

3. Measurement Reliability

Post-calibration results exhibited good repeatability and acceptable overall uncertainty for laboratory use. However, the dependence on calibration parameters and environmental factors such as temperature indicates that regular recalibration is required to maintain measurement reliability over time.

8. Impact of measurement uncertainty on decision making based on pH and TDS readings

Water quality monitoring and separation systems, along with thresholds for pH and TDS, are established to determine whether the water is safe for further use or requires treatment. The acceptable ranges were defined as pH 6.5 – 8.5 and TDS 50-500 ppm; these values were derived from international guidelines (World Health Organization (WHO), Environmental Protection Agency (EPA), and Canadian standards). These ranges were adopted and implemented in the PLC ladder logic to guide water separation into either a clean (Compartment A) or contaminated (Compartment B) drain tank.

The decision-making in the system heavily relies on the values and performance of the sensors used. Since this work focuses on developing a budget-friendly, scalable, and proof-of-concept system, low-cost sensors were chosen: the pH sensor (~€60) and the TDS sensor (~€11), both from DFRobot. While these sensors make the system affordable and accessible, their low cost comes at the expense of higher measurement uncertainty compared to Industry-grade equipment. This introduces additional risks in terms of repeatability, traceability, and long-term reliability.

8.1 Acceptable Ranges

pH Range

- The World Health Organization (WHO) recommends that the pH of drinking water should typically lie between 6.5 and 8.5 (WHO Guidelines for Drinking-water Quality, 2022).
- The U.S. EPA secondary standards also adopt 6.5–8.5 as the acceptable range for public water supplies.
- This range was therefore adopted in the PLC logic.

TDS Range

- The EPA and Health Canada provide a secondary guideline value of ≤500 ppm for TDS, based on aesthetic quality (taste, scaling).
- The WHO considers water below 1000 ppm generally acceptable to consumers, but 500 ppm is widely used as a practical cutoff.
- A lower limit of 50 ppm was also applied here to avoid very low mineral content water, which can have a flat taste and low buffering capacity.

8.2 Measurement Uncertainty and Sensor Limitations

Cost–Uncertainty Tradeoff

The selected pH and TDS sensors are low-cost, with their affordability (total cost < € 80) making the platform budget-friendly and replicable for scalable purposes. However, this low cost directly correlates with higher measurement uncertainty:

- pH Sensor: Required Initial Calibration as it didn't align with expected results.
- TDS Sensor: ±10% FS accuracy (±100 ppm), with a baseline offset of +5.35 ppm observed during testing.

A higher-grade probe for pH and TDS (several hundred euros each) could significantly reduce uncertainty, but this would increase the project cost and would be more suitable in an industrial-scale setup.

Repeatability (Type A)

- Despite the low cost, the sensors showed good repeatability during 10 repeated measurements (pH: ±0.025–0.065; TDS: ±1–2 ppm except in salt water).
- This indicates that the main limitation is not repeatability, but expanded accuracy and calibration stability.

Impact of Measurement Uncertainty on Decision-Making

In conformity assessment, decisions on whether a measured value is acceptable depend not only on the measurement itself but also on its uncertainty. This is especially important when the measurement is close to specification limits. If uncertainty is overlooked, there is a risk of false acceptance (accepting a non-compliant value). According to ISO/IEC 17025 and related metrological guidelines, this decision-making process must explicitly account for measurement uncertainty. If a calibrated measurement is exactly equal to a specification limit and the measurement uncertainty is Gaussian, then half of the probability mass lies beyond that limit. That means a 50% chance that the *true* value is non-conforming, clearly unacceptable for incase of Water Quality.

pH Conformity and Uncertainty

The acceptable specification range for drinking water pH is 6.5–8.5, as per the World Health Organization (WHO) guidelines. Figure 38 illustrates Gaussian distributions centered at the lower limit (6.5) and the upper limit (8.5). The measurement uncertainty by the following equation,

$$pH_{meas} = \frac{pH_{Cal} - OFFset}{Gain}$$

This above equation yielded 6.33 for 6.5 pH and 5.00 for 8.5 pH. Using this above equation and the equation mentioned on page 88, substituting these into the uncertainty model gives,

$$u_B(6.5) = 0.095\text{pH}, \qquad u_B(8.5) = 0.085\text{pH}$$

portions of the Gaussian tails extend outside the acceptable region.

- The left-hand distribution shows that if the actual value lies at 6.5, there is still a probability that measurements fall below this threshold, leading to false acceptance.
- The right-hand distribution indicates that if the actual value is at 8.5, some measurements may fall above the limit, resulting in false acceptance.

To reduce the risk of false acceptance, the acceptance region is narrowed by applying modified limits at 6.54 and 8.46. This means that only measurements well inside the specification are considered conforming, ensuring greater confidence that accepted water is truly within range.

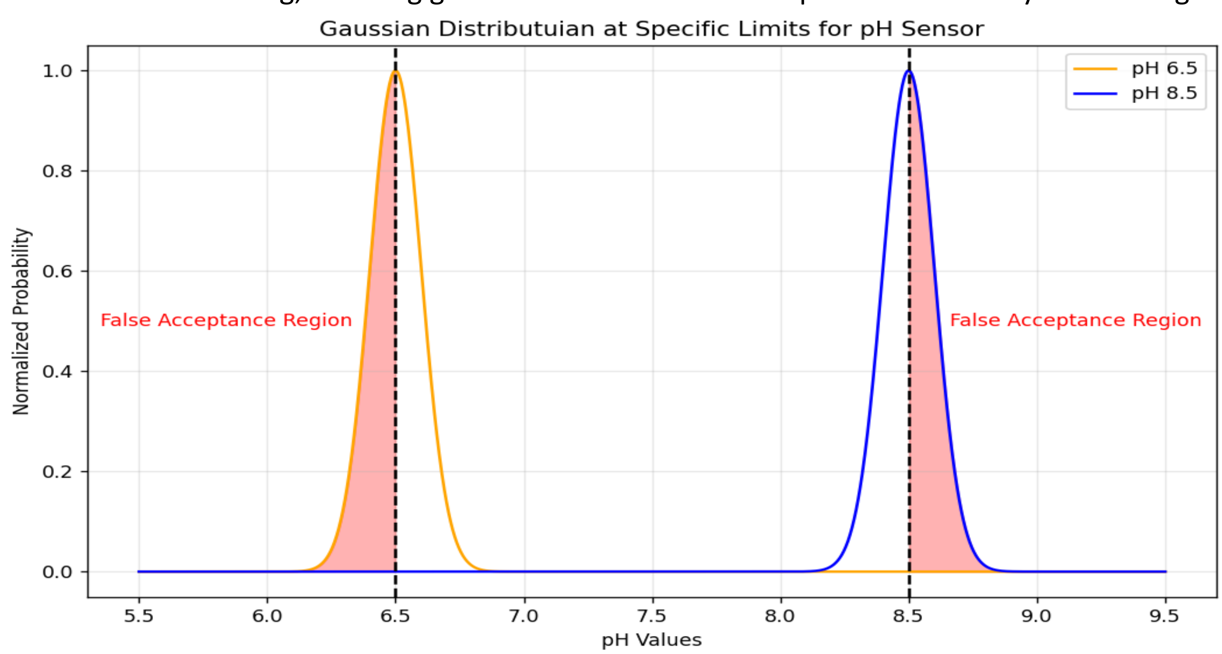

Figure 39. Gaussian Distribution of pH sensor

TDS Conformity and Uncertainty

For TDS, the acceptable specification range is 50–500 ppm. Due to the higher uncertainty of the low-cost sensor, approximately (±60 ppm), the Gaussian distributions centered at 50 ppm and 500 ppm are much broader than those of the pH sensor.

- At the lower limit (50 ppm), measurements may extend into the non-conforming region below 50 ppm, generating false acceptance.
- At the upper limit (500 ppm), uncertainty tails overlap significantly into the >500 ppm region, risking false acceptance.

To mitigate this, the decision boundaries are modified by applying acceptance limits of 110–440 ppm. This conservative approach minimizes the probability of false acceptance, ensuring that only measurements comfortably within the central region of the specification are accepted.

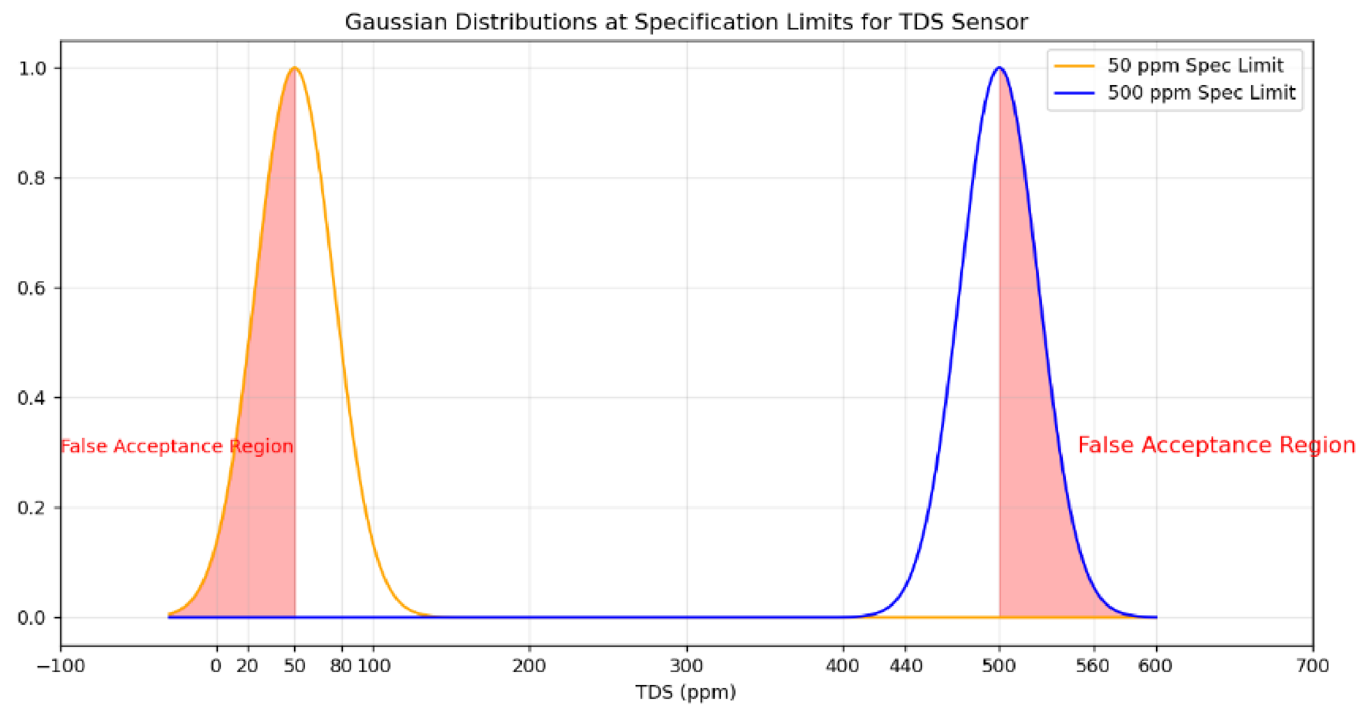

Figure 40.Gaussian Distribution of TDS Sensor

The Role and Importance of Guard Bands

While shifting acceptance limits inward (from 6.5–8.5 to 6.60–8.41 for pH, and from 50–500 ppm to 110–440 ppm for TDS) reduces the risk of false acceptance, uncertainty tails always extend beyond the specification limits. This means that even after narrowing the acceptance region, a residual probability of false acceptance persists.

Here, the concept of the guard band becomes essential. A guard band is a buffer region between the actual specification limit and the modified acceptance limit. By rejecting results that fall within the guard band, the decision process adopts a conservative approach:

- The guard band reduces the chance of accepting non-conforming water.
- It explicitly balances the trade-off between *false acceptance* and *false rejection*.
- It ensures that decisions are consistent with international conformity assessment standards.

In practice, the guard band is determined by the expanded measurement uncertainty. This creates an acceptance zone narrower than the specification zone, improving the reliability of conformity decisions even when using low-cost sensors with relatively high uncertainty.

9. Conclusion

Summary of work

This thesis developed, implemented, and evaluated a PLC-based water quality monitoring and separation system that integrates pH and TDS sensors with a Siemens S7-1200 PLC and a KTP700 HMI. The project encompassed the entire lifecycle, from concept and simulation (using PLCSIM) to physical assembly (mechanical design in SolidWorks and 3D printing of components), and deployment of control logic in TIA Portal. The system performs real-time sensing, displays results and status on the HMI, implements interlocks for safe actuator control, and lets an operator route water to the appropriate compartment based on measured values.

Calibration and measurement evaluation

Sensor calibration and verification were an integral part of the work. The pH probe was calibrated using a two-point correction method with standard buffers (pH 4 and pH 10), and a linear gain and offset model was used to correct residual bias. The TDS probe was zero-checked and corrected for a measured baseline offset before use. The project documents the calibration procedures used to produce traceable, scaled engineering values for the PLC logic.

Quantitative uncertainty findings (experimental)

Using ten repeated readings per sample and the manufacturer's specifications (converted to standard uncertainty), the uncertainty analysis produced the following representative results:

- pH (combined standard uncertainty):
  • Buffer pH 4: $u_c \approx 0.0777$ pH.
  • Buffer pH 10: $u_c \approx 0.0631$ pH.
  • Tap water: $u_c \approx 0.0867$ pH.

- TDS (combined standard uncertainty, ppm):
  • Tap water: $u_c \approx 57.74$ ppm.
  • Salt water: $u_c \approx 59.37$ ppm.
  • Lemon water: $u_c \approx 57.74$ ppm.

These values were obtained by combining Type-A (statistical repeatability from the 10 measurements) and Type-B (TDS ±10% F.S.) and Calibrated Uncertainty for pH contributions. The detailed methodology and the measurement-processing logic used to derive engineering values in the PLC are described in the report.

Interpretation and key findings.

- Dominant uncertainty sources: For TDS, the combined uncertainty is dominated by the manufacturer’s Type-B specification (±10% F.S.), so repeatability (Type-A).

- Cost–performance tradeoff: The system uses budget sensors (pH ≈ €60, TDS ≈ €11); this makes the platform highly affordable and suitable for teaching and proof-of-concept purposes, but it also increases measurement uncertainty compared to industrial-grade probes. The thesis documents these trade-offs and explains why frequent calibration and conservative decision logic are required for reliable operation.
- Operational thresholds & logic: The PLC logic compares measured values against the chosen thresholds (pH 6.5–8.5; TDS 50–500 ppm) to classify water quality and present guidance on the HMI; these thresholds are consistent with the standards and guidelines referenced in the report.

Limitations.

- The low-cost sensors impose considerable Type-B uncertainty (especially TDS), which limits the confidence interval around classification thresholds (i.e., a wide "gray zone" near the decision boundaries).
- Sensor drift, fouling, and temperature dependence require routine recalibration and maintenance for reliable long-term operation.
- Current separation is manual (operator selects drainage on HMI); automated drainage and closed-loop control were identified as future improvements.

Practical recommendations (for next steps/deployment):

- Implement hysteresis / dead-bands in PLC logic around decision thresholds to prevent oscillation and reduce misclassification near boundaries.
- Schedule and document periodic calibration (pH buffers and TDS reference solutions) and include automated "no-reading" alarms as implemented in the project to catch sensor failure.
- For production or safety-critical use, consider higher-grade sensors (laboratory-certified probes) to reduce Type-B uncertainty; keep the low-cost sensors for teaching, prototyping, and low-risk applications.
- Integrate data logging / SCADA and remote monitoring to enable trend analysis, remote alerts, and easier validation against laboratory measurements (already noted as a future enhancement in the thesis).

Final statement.

The project successfully demonstrates a cost-effective, PLC-driven framework for real-time water quality monitoring and operator-guided separation. It achieves the thesis objectives—hardware/software integration, HMI visualization, calibration procedures, and uncertainty analysis—while exposing the practical trade-offs between affordability and measurement accuracy. With modest upgrades (sensor-grade, automated actions, and robust calibration routines), the platform can be matured from a reliable educational proof-of-concept into a field-ready system suitable for pilot deployments.

Annex

Measurement Uncertainty:

Measurement uncertainty is the level of doubt we associate with a measurement result. It doesn't mean the measurement is wrong, but instead acknowledges that many factors can influence how close our measured value is to the actual value.

Classification of Uncertainty is as follows:

Uncertainty Type	Description	Source
Type A	Statistical evaluation of repeated measurements	Experimental repeatability
Type B	Based on prior knowledge (datasheets, manuals, calibration certs)	Manufacturer specs, environment, resolution

Type A Uncertainty

Type A uncertainty is evaluated by applying statistical methods to repeated observations under the same conditions. If (N) independent repeated measurements are performed, with measured values X1, X2,… Xn, then the following steps are applied (In my Experiments, I have measured 10 Readings):

1. Mean of Measurements:

$$\bar{x} = \frac{1}{n}\sum_{k=1}^{n} x_n$$

2. Experimental Standard Deviation:

Standard deviation (s) is evaluated as the positive square root of the sample variance:

$$s(x) = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(x_{k-}\bar{x})^2}$$

The r.v. of S(x) (experimental standard deviation of the sample) represents the dispersion of the single observations around the empirical average.

3. Standard uncertainty of the mean (Type A):

$$u_{A}=\frac{s(x)}{\sqrt{n}}$$

This represents the random (repeatability) component of the uncertainty. In this work, Type A uncertainty was calculated separately for each solution (tap water, salt solution, pH 4 buffer, pH 10, Lime water) using 10 repeated readings per case. This allows evaluating how sensor repeatability varies depending on the measurement conditions.

Type B Uncertainty

Type B uncertainty is evaluated by means other than repeated measurements. It accounts for systematic contributions and is usually derived from:

- Manufacturer specifications (accuracy limits, resolution, stability),
- Calibration certificates of instruments,
- Published data or previous experimental results.

If the manufacturer specifies an accuracy limit of ±a, and assuming a rectangular (uniform) distribution of possible values, the corresponding standard uncertainty is:

$$u_B = \frac{a}{\sqrt{3}}$$

The above formula indicates that after taking the accuracy limit given by the manufacturer, we will use the formula to obtain the uncertainty type B

Combined and Expanded Uncertainty

The combined standard uncertainty is calculated by combining Type A and Type B using the following equation,

$$u_c = \sqrt{(u_A)^2 + (u_B)^2}$$

Finally, the Expanded Uncertainty U, corresponding to a 95% confidence level, is obtained by applying a coverage factor k = 2

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