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Deploying Automated Shut-Off Technology and Water Filtration Systems to reduce water loss caused bybdamaged pipelines in Rwanda

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Abstract

Water loss and water quality deterioration remain major challenges for water utilities, particularly where pipeline leakages, damaged infrastructure, and delayed fault response contribute to Non-Revenue Water (NRW) and contamination risks. This study designed, developed, and evaluated an Internet of Things (IoT)-based automated shut-off and water filtration system for WASAC Remera Branch, Rwanda. A Design-Based Research (DBR) approach combined with experimental testing was adopted. Data were collected through observation, interviews with WASAC technical personnel, system measurements, and experimental testing. The developed prototype integrated an ESP32 microcontroller, flow and pressure sensors, leak detection sensors, automated control components, communication technologies, a water filtration unit, and a web-based monitoring platform. Rule-based algorithms were applied to sensor readings to identify abnormal pipeline conditions and automatically initiate appropriate response actions. Findings from functional testing demonstrated that the system successfully detected leakage conditions, monitored pipeline parameters, generated alerts, recorded system events, and initiated automated shut-off actions when abnormal conditions were detected. The integration of automated monitoring, rapid leak response, and water filtration provided a practical mechanism for minimizing the consequences of pipeline failures while supporting water quality management. The study concluded that integrating IoT-based monitoring, automated shut-off technology, and water filtration provides a promising approach to improving smart water distribution management. It recommends that WASAC conduct further field testing in selected high-risk distribution zones before considering wider implementation.

Keywords: Automated Shut-Off System, Water Filtration System, Internet of Things (IoT), Water Loss, Pipeline Leakage, Water Quality, Smart Water Management.

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1. Introduction

Water loss and deterioration of water quality remain major challenges in water distribution systems worldwide. Non-Revenue Water (NRW), arising from pipeline leakages, bursts, infrastructure failures, and operational inefficiencies, reduces the sustainability and efficiency of water utilities. Damaged pipelines may also allow contaminants to enter distribution networks, creating additional risks to water quality. Globally, aging infrastructure, delayed leakage detection, and dependence on manual monitoring continue to contribute to water wastage, particularly in developing countries where real-time monitoring technologies remain limited (International Water Association [IWA], 2022; World Bank, 2021).

Recent developments in the Internet of Things (IoT), embedded systems, automation, and water treatment technologies provide opportunities for addressing these challenges. IoT-enabled sensors can continuously monitor flow and pressure conditions, while automated shut-off mechanisms can rapidly isolate damaged pipeline sections when abnormal conditions are detected. Water filtration technologies can further support the removal of impurities and contaminants. Integrating these technologies therefore provides a potential approach for reducing water loss, protecting water quality, and improving the operational efficiency of water distribution systems (Singh & Turaga, 2020; Akhter & Ahmed, 2020).

In Rwanda, the Water and Sanitation Corporation (WASAC) has made progress in expanding water access and improving water infrastructure; however, pipeline leakages, water losses, and water quality management remain important operational concerns. **At WASAC Remera Branch,** damaged pipelines and delayed fault response can contribute to unnecessary water wastage, increased operational costs, and potential contamination. Existing monitoring and control practices largely depend on manual intervention, which limits rapid fault detection and response (WASAC, 2024).

The problem addressed by this study was therefore the limited capacity of the existing water distribution system to provide real-time detection and automated response to damaged pipelines. Manual identification and isolation of pipeline failures can delay corrective actions, increase water loss, interrupt water services, and expose the distribution system to water quality risks. An integrated solution combining real-time monitoring, automated pipeline isolation, and water filtration was therefore required to improve water distribution management at WASAC Remera Branch.

Accordingly, this study aimed to design and deploy an IoT-based automated shut-off technology integrated with a water filtration system to reduce water loss and improve water quality caused by damaged pipelines at WASAC Remera Branch. Specifically, the study sought to:

i. Analyze the major causes of water loss and water contamination in WASAC Remera Branch pipeline networks.
ii. Design an IoT-based automated shut-off system for detecting and isolating damaged pipelines.
iii. Develop and integrate a water filtration system for improving water quality within the distribution network.
iv. Implement and test the proposed automated shut-off and water filtration prototype.
v. Evaluate the effectiveness of the proposed system in reducing water loss, improving water quality, and enhancing operational efficiency.
vi.

2. LITERATURE REVIEW

This section reviews the key concepts, theoretical foundations, and empirical studies related to IoT-based automated shut-off systems and water filtration. It also presents the conceptual framework and identifies the research gap addressed by the study.

2.1 Conceptual Review

2.1.1 Automated Shut-Off Systems

Automated shut-off systems use sensors, controllers, communication modules, and actuators to detect abnormal pipeline conditions and automatically regulate water flow. These systems support rapid isolation of damaged pipeline sections, thereby reducing water loss, operational costs, and dependence on manual intervention (Ahmed & Hassan, 2023; Patel et al., 2024).

2.1.2 Water Filtration Systems

Water filtration systems remove physical, chemical, and biological contaminants using technologies such as sediment filters, activated carbon, and membrane filtration. Their integration with automated monitoring systems can improve water quality, particularly where damaged pipelines create contamination risks (Zhang & Li, 2023; Johnson et al., 2024).

2.1.3 Internet of Things (IoT) and Smart Water Management

IoT enables interconnected sensors and devices to collect, transmit, and process real-time information. Within water distribution systems, IoT supports continuous monitoring of flow, pressure, and pipeline conditions, allowing faster detection and response to faults (Khan et al., 2023; Singh & Verma, 2024).

2.1.4 Water Loss, Pipeline Leakage and Water Quality

Water loss results from leakages, pipeline bursts, meter inaccuracies, unauthorized consumption, and operational inefficiencies. Pipeline damage can also allow contaminants to enter distribution networks, affecting water quality and increasing operational costs. Real-time leak detection, automated isolation, and filtration therefore provide complementary approaches for reducing NRW and protecting water quality (World Water Council, 2023; Ncube & Moyo, 2024; WHO, 2023).

2.2 Theoretical Review

The study was informed by **Systems Theory, Diffusion of Innovation Theory, Technology Acceptance Model (TAM), and Control Systems Theory**. Systems Theory explains how sensors, controllers, communication modules, valves, and filtration components operate as an integrated system. Diffusion of Innovation Theory and TAM explain the adoption and acceptance of technological innovations, while Control Systems Theory explains how sensor feedback can trigger automated corrective actions when abnormal pipeline conditions are detected.

2.3 Empirical Review

Empirical studies indicate that aging infrastructure, corrosion, excessive pressure, inadequate maintenance, and delayed fault detection contribute to water loss and contamination (Ncube & Moyo, 2024; Garcia et al., 2023; Patel et al., 2023). Other studies demonstrate that IoT-enabled flow and pressure monitoring improves leak detection and response time, while filtration technologies improve water quality (Zhang & Li, 2023; Johnson et al., 2024; Chen & Wang, 2024). However, many existing solutions address monitoring, automated control, or filtration separately rather than integrating them within one system.

2.4 Conceptual Framework

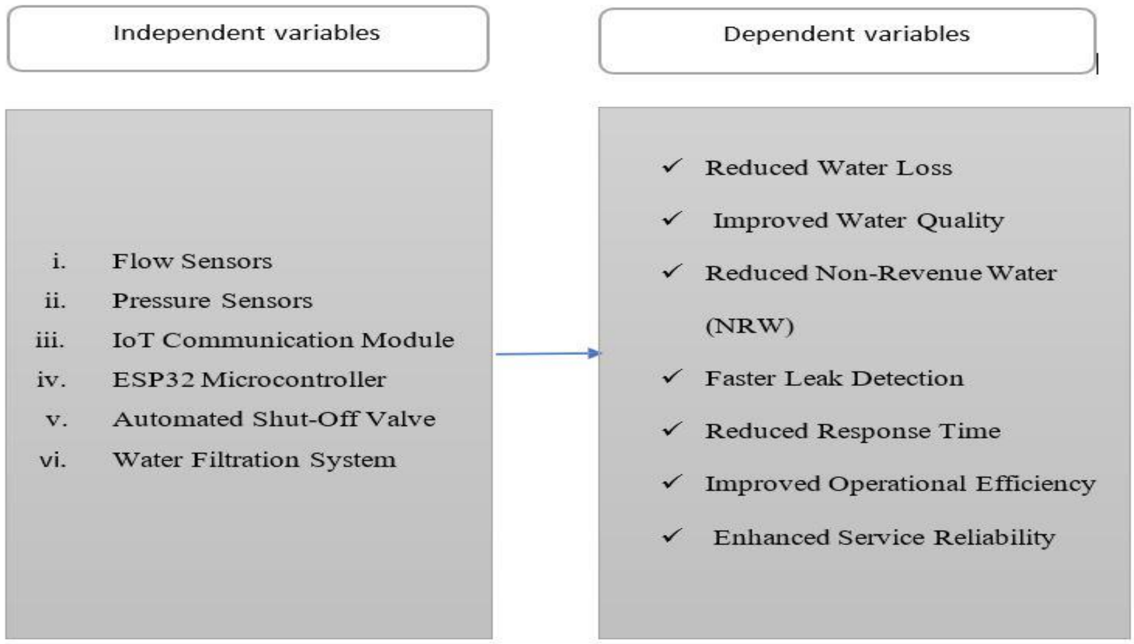


Figure 2: Proposed Conceptual Framework

2.5 Research Gap

Existing studies have demonstrated the effectiveness of IoT monitoring, leak detection, automated control, and water filtration; however, these technologies are commonly investigated independently. Limited research has integrated real-time pipeline monitoring, automated leak isolation, and water filtration within a single system, particularly within Rwanda's public water utility environment. This study addressed this gap by developing and evaluating an integrated IoT-based automated shut-off and water filtration system for WASAC Remera Branch.

3. Methodology

3.1 Research Design

The study adopted a Design-Based Research (DBR) approach combined with an experimental research design. DBR guided the identification of the water distribution problem, development of the IoT-based solution, and refinement of the prototype through testing. Experimental testing was conducted using simulated leakage conditions to assess the system's ability to detect pipeline failures and automatically activate shut-off actions.

3.2 Sampling

Purposive sampling was used to select approximately 20–30 WASAC engineers, technicians, and operational staff with relevant experience in water distribution and pipeline management. Selected pipeline sections and simulated leakage scenarios were also used for prototype evaluation.

3.3 Data Collection

Both qualitative and quantitative data were collected through observation, interviews, and experimental testing. An interview guide and observation checklist were used alongside flow and pressure sensors and system-generated logs. The system recorded flow rates, pressure measurements, leakage events, valve activation, and response times.

3.4 System Development and Implementation

The prototype integrated flow and pressure sensors, an ESP32 microcontroller, Wi-Fi/GSM communication, an automated shut-off valve, a filtration unit, and a web-based monitoring dashboard. The ESP32 processed sensor readings using predefined rules and automatically closed the valve when abnormal flow or pressure conditions indicated leakage. The system also transmitted alerts, updated the dashboard, and stored leakage events.

The Agile development methodology guided requirements identification, system design, development, integration, and testing. Arduino IDE was used for ESP32 programming, while PHP/Laravel, MySQL, HTML, CSS, JavaScript, and Bootstrap supported development of the monitoring platform.

3.5 Data Analysis

Qualitative interview data were analyzed using thematic analysis, while quantitative prototype data were analyzed using descriptive statistics, including frequencies, percentages, averages, and response times. System performance was evaluated using indicators such as leak detection accuracy, response time, valve activation success rate, and system reliability.

3.6 Ethical Considerations

Permission was obtained from relevant authorities, participation was voluntary, and respondents were informed about the study. Confidentiality, privacy, transparency, and research integrity were maintained throughout data collection, analysis, and reporting.

4. Findings and Discussion

4.1 Analysis of the Existing Water Distribution System

The findings showed that the existing water distribution system at WASAC Remera Branch largely depended on manual monitoring, routine inspections, customer reports, and manual operation of isolation valves. Consequently, pipeline leakages could remain undetected until considerable water loss had occurred, contributing to increased Non-Revenue Water (NRW), maintenance costs, service interruptions, and potential water contamination. These limitations demonstrated the need for real-time monitoring and automated fault response.

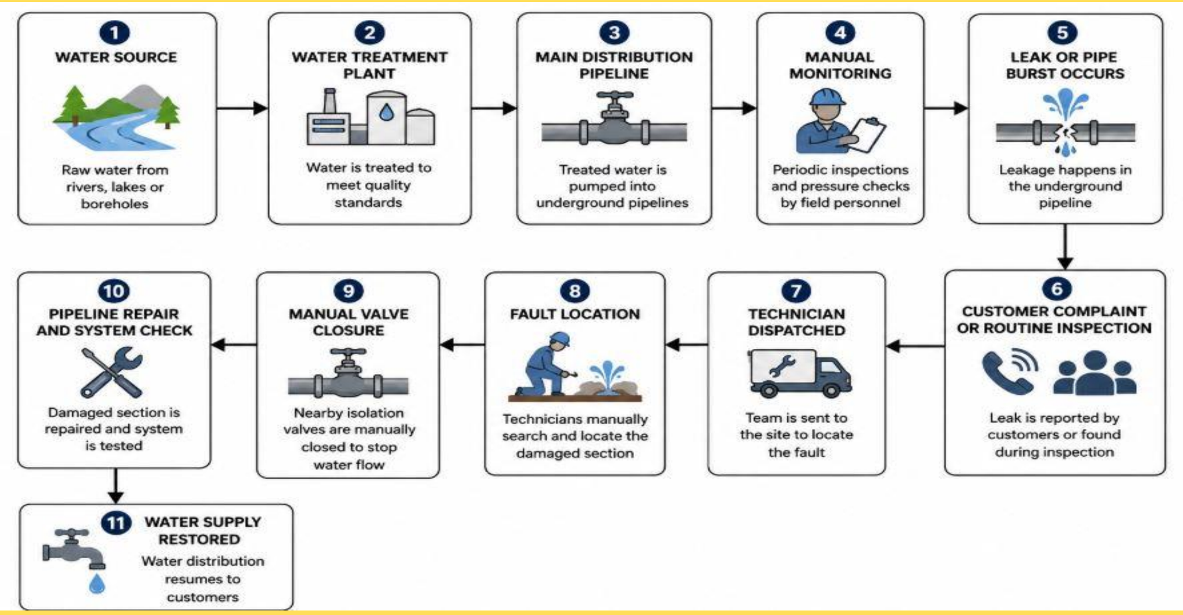


Figure2: Existing Water Distribution System Workflow

4.2 Development of the Proposed IoT-Based System

The developed system integrated flow, pressure, humidity, and leak sensors with an ESP32 microcontroller, automated shut-off valve, communication technologies, and a multi-stage filtration unit. Sensor information was processed in real time, enabling the system to detect abnormal conditions and automatically isolate damaged pipeline sections. The filtration unit incorporated sediment filtration, activated carbon, and ion exchange resin to support water quality improvement.

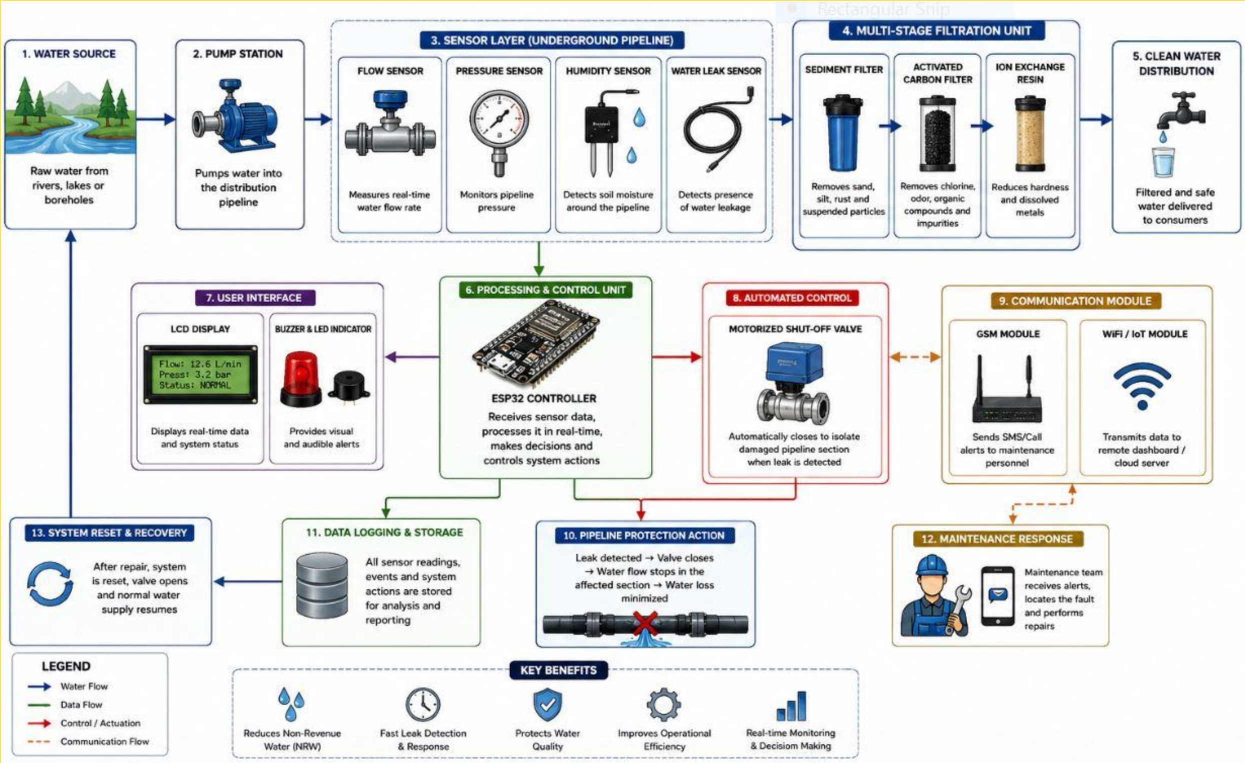


Figure3: Overall System Architecture of the Proposed Smart Underground Water Filtration System

4.3 Prototype Implementation

The prototype successfully integrated the physical pipeline, sensing devices, ESP32 controller, filtration unit, motorized valve, monitoring display, and communication components. This implementation demonstrated the practical integration of real-time monitoring, automated leak detection, shut-off control, and water filtration within a single system.

Figure4: Final Developed Prototype

4.4 Leak Detection and Automated Shut-Off Results

Functional testing showed that the flow, pressure, humidity, and water leak sensors operated successfully. When leakage was detected, the ESP32 processed the abnormal condition and automatically activated the motorized shut-off valve. The system also generated alerts and provided monitoring information, demonstrating its ability to respond automatically to pipeline failures.

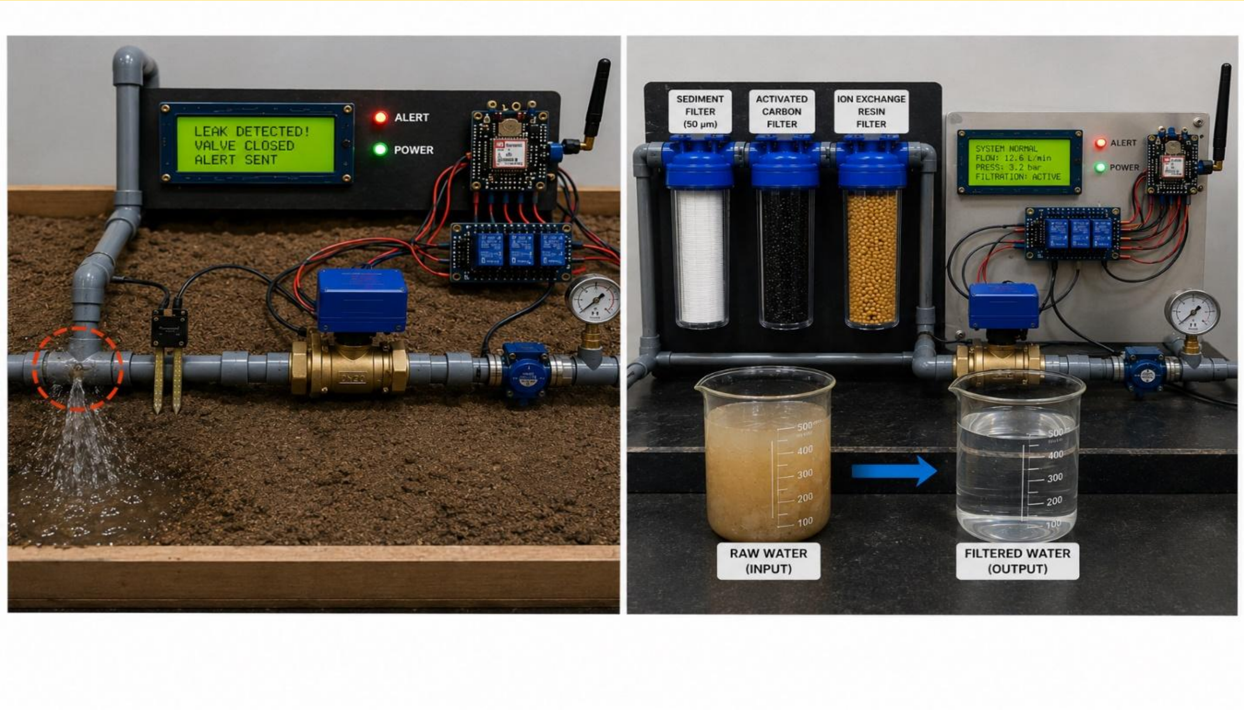
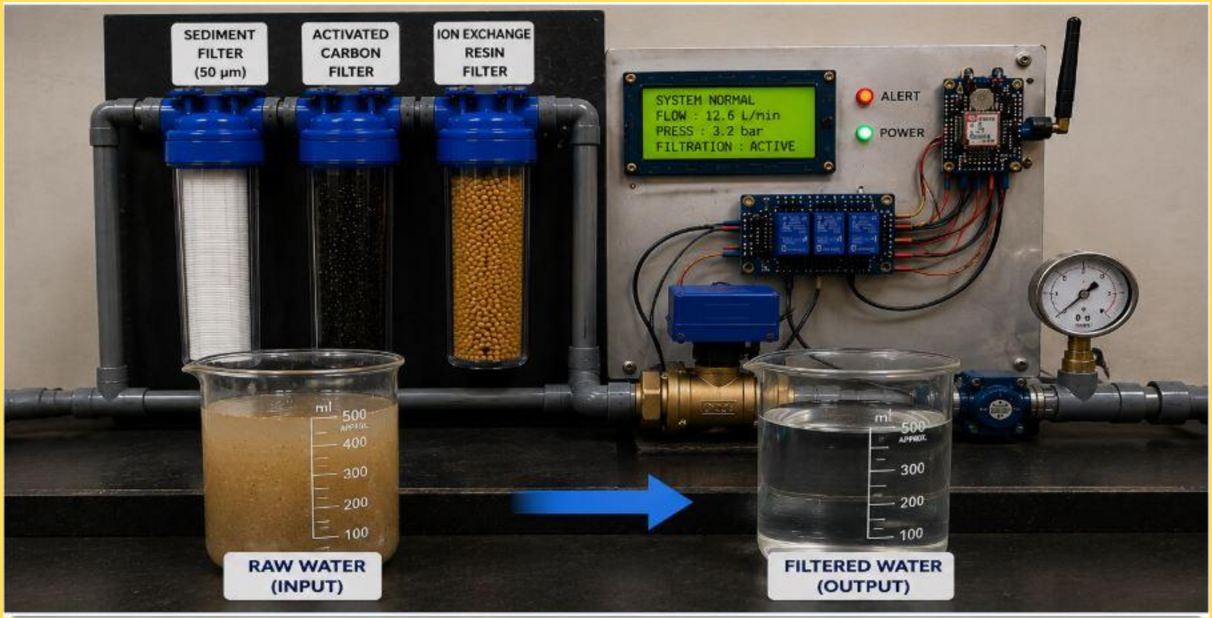


Figure5: Leak Detection and Automated Shut-Off during System Testing]

The performance tests further confirmed that normal water flow did not trigger unnecessary shut-off, while abnormal flow and pressure conditions generated leakage alerts and activated the automated valve. Leakage events were successfully stored in the system logs, and normal monitoring resumed after the system returned to normal conditions. These findings demonstrate the functional feasibility of automated leak detection and response for reducing prolonged water loss.

4.5 Water Filtration Results

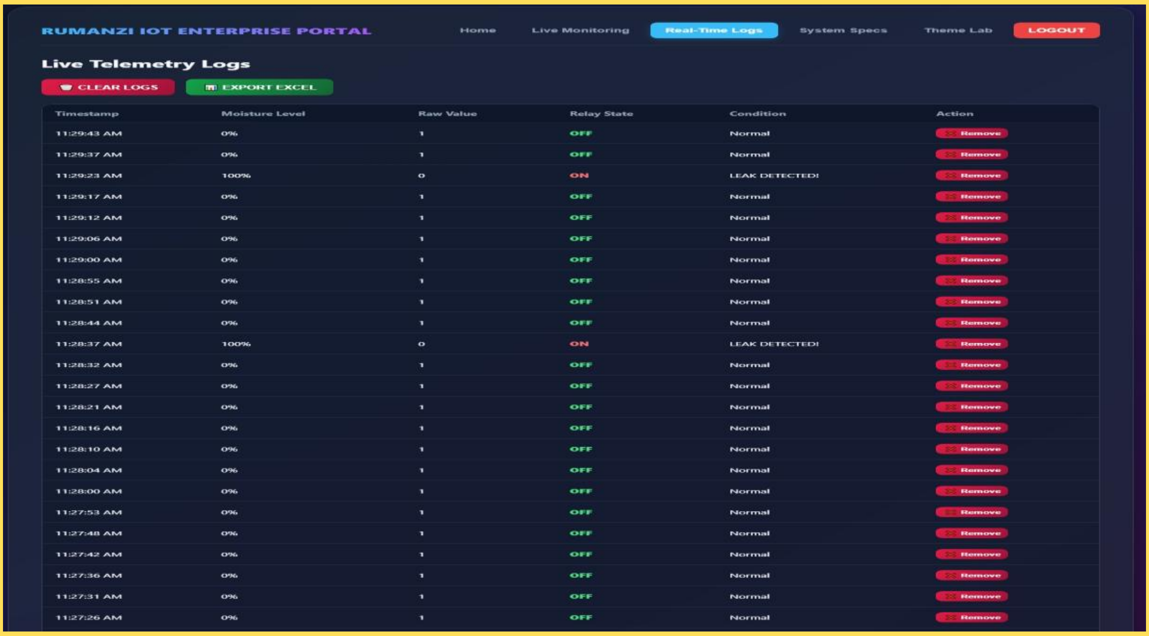
The filtration unit operated successfully during prototype testing. Water passed through sediment filtration, activated carbon, and ion exchange resin, and the resulting output showed improved clarity and reduced visible impurities compared with untreated water. The findings demonstrate that filtration could be incorporated alongside automated leak management to support water quality improvement.



Fire:6: Filtered Water Output after System Operation]

4.6 Real-Time Monitoring and System Evaluation

The developed web-based interfaces supported real-time monitoring, leakage detection, system logging, and automated shut-off status. During testing, leakage conditions were recorded together with sensor values and relay status, while system logs maintained historical information for monitoring and analysis.



Timestamp	Moisture Level	Raw Value	Relay State	Condition	Action
11:29:43 AM	0%	1	OFF	Normal	Remove
11:29:37 AM	0%	1	OFF	Normal	Remove
11:29:23 AM	100%	0	ON	LEAK DETECTED!	Remove
11:29:17 AM	0%	1	OFF	Normal	Remove
11:29:12 AM	0%	1	OFF	Normal	Remove
11:29:06 AM	0%	1	OFF	Normal	Remove
11:29:00 AM	0%	1	OFF	Normal	Remove
11:28:55 AM	0%	1	OFF	Normal	Remove
11:28:51 AM	0%	1	OFF	Normal	Remove
11:28:44 AM	0%	1	OFF	Normal	Remove
11:28:37 AM	100%	0	ON	LEAK DETECTED!	Remove
11:28:32 AM	0%	1	OFF	Normal	Remove
11:28:27 AM	0%	1	OFF	Normal	Remove
11:28:21 AM	0%	1	OFF	Normal	Remove
11:28:16 AM	0%	1	OFF	Normal	Remove
11:28:10 AM	0%	1	OFF	Normal	Remove
11:28:04 AM	0%	1	OFF	Normal	Remove
11:28:00 AM	0%	1	OFF	Normal	Remove
11:27:53 AM	0%	1	OFF	Normal	Remove
11:27:48 AM	0%	1	OFF	Normal	Remove
11:27:42 AM	0%	1	OFF	Normal	Remove
11:27:36 AM	0%	1	OFF	Normal	Remove
11:27:31 AM	0%	1	OFF	Normal	Remove
11:27:26 AM	0%	1	OFF	Normal	Remove

Figure7: Automated Shut-Off Valve Control and Status Interface

Overall, the functional evaluation showed that real-time monitoring, leak detection, automated shut-off, alert generation, data logging, web monitoring, and water filtration all passed the prototype tests. The findings therefore demonstrate the functional feasibility of integrating IoT monitoring, automated pipeline isolation, and water filtration within a single smart water management system.

5. Conclusion and Recommendations

5.1 Conclusion

The study concluded that the developed Smart Underground Water Filtration System provides a practical approach for reducing water loss and improving water quality at WASAC Remera Branch. By integrating IoT sensors, an ESP32 microcontroller, automated shut-off technology, GSM/Wi-Fi communication, and multi-stage water filtration, the system enabled real-time pipeline monitoring, leak detection, automatic isolation of damaged sections, and water filtration. Prototype testing confirmed that the system successfully performed its intended functions, demonstrating its potential to reduce Non-Revenue Water (NRW), improve operational efficiency, enhance water quality, and support reliable water distribution management.

5.2 Recommendations

WASAC should conduct pilot deployments of the developed system in selected high-leakage water distribution zones before considering large-scale implementation. The organization should progressively adopt IoT-based pipeline monitoring, automated shut-off mechanisms, and integrated filtration technologies to improve leak detection, reduce water loss, and protect water quality. WASAC technical personnel should also receive regular training in operating and maintaining these technologies, while government agencies and policymakers should support investment and policies that promote smart water infrastructure in Rwanda.

5.3 Suggestions for Future Research

Future studies should test the system on a larger scale under actual water distribution conditions and assess its long-term reliability, scalability, maintenance requirements, economic feasibility, and environmental impact. Further research could also integrate Artificial Intelligence and Machine Learning for predictive pipeline maintenance, investigate communication technologies such as LoRaWAN, NB-IoT, and 5G, and evaluate more advanced filtration technologies for removing chemical, metallic, and microbial contaminants.

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