Smart Water Meter System for Leakage Prediction and Automatic Flow Control Using AIoT

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Abstract Water is a vital global resource, yet substantial amounts are lost daily due to undetected pipeline leakages and human negligence. Traditional mechanical water meters lack the capability to detect abnormal water flow, shifting the financial burden of wasted water onto consumers. To address this critical issue, this research aims to develop an intelligent smart water meter system capable of monitoring water usage, preventing unnecessary water loss, and autonomously cutting off the water supply when an anomaly occurs.

To achieve this, the proposed system integrates Internet of Things (IoT) technologies with an artificial intelligence (AI) predictive model. The hardware architecture utilizes a NodeMCU ESP8266-12E microcontroller to manage a YF-S201 Water Flow Sensor, a Pressure Transmitter Sensor, and a Solenoid Valve. Furthermore, a Mini Hydro Generator Turbine is incorporated to harvest kinetic energy and recharge the system's battery during active water usage. On the software side, a cross-platform mobile application developed using Flutter allows users to monitor real-time sensor data, review historical usage, and remotely configure operational modes. The core autonomous anomaly detection is driven by a rule-based AI model that calculates the Simple Moving Average (MA) and Standard Deviation (SD) of historical fluid pressure data over a rolling four-week period to continually establish a dynamic pressure threshold.

Experimental testing demonstrated the high reliability and efficiency of the proposed system. Hardware functionality tests yielded a 0% error rate for user commands and data synchronization via RESTful APIs. The water flow measurement maintained a highly accurate Mean Absolute Error (MAE) of 2.67% at low and medium flow capacities. Crucially, the predictive AI model was evaluated across 105 distinct real-world events over a continuous 7-day period. The model achieved an impressive average accuracy of 92.29%, successfully ordering the microcontroller to close the solenoid valve without human intervention whenever the real-time pressure dropped below the dynamic baseline. Ultimately, this intelligent system provides a sustainable, highly effective solution for autonomous water management and leakage prevention.

Keywords: Smart Water Meter, Internet of Things (IoT), Artificial Intelligence (AI), Anomaly Detection, Moving Average

1. Introduction

Water is a vital global resource, yet a significant amount of it is lost unnecessarily due to human negligence, such as leaving taps open, and undetected pipeline leakages [6]. Currently, the majority of households rely on traditional mechanical water meters, which are only capable of measuring volume and cannot detect abnormal water flow or leakages. Consequently, water service providers continue to bill based on total recorded consumption, which shifts the financial burden of wasted water entirely onto the consumers.

To address this issue, there has been a growing technological shift toward Internet of Things (IoT) based smart water management systems. Recent studies have demonstrated the effectiveness of integrating microcontrollers and sensors for real-time water monitoring. For instance, Ahmed and Alfred (2022) [1] utilized the NodeMCU ESP8266-12E alongside water flow sensors to track water usage and communicate data via MQTT protocols. Similarly, AL-Madhrahi et al. (2021) [2] presented an energy-efficient IoT smart meter system designed for smart city environments. Furthermore, Andhare et al. (2021) [4] highlighted the benefits of automated meter reading systems that are capable of remote water supply disconnection, while Pralad et al. (2020) [5] and Anandhavalli et al. (2018) [3] developed IoT systems that allow users to track their daily water utilization to transparently monitor billing and prevent overcharging.

Despite these remarkable advancements, existing systems primarily focus on remote monitoring and manual control. They generally lack the artificial intelligence (AI) capability to autonomously predict and halt water flow during anomalous events without user intervention. Therefore, this project proposes the development of a predictive smart water meter system to effectively prevent unnecessary water loss and improve water management efficiency.

The proposed system employs a NodeMCU ESP8266-12E to control a solenoid valve for water flow regulation and integrates a predictive AI model. By utilizing moving average and standard deviation calculations based on historical usage data, the model predicts normal pressure thresholds and autonomously cuts off the water supply when an anomaly—such as a continuous leakage—is detected. Additionally, the hardware is paired with a cross-platform mobile application developed using Flutter. This application empowers users to monitor real-time flow rates, review daily and monthly water usage history, estimate monthly service costs, and control the water supply remotely.

The primary objectives of this research are as follows:

1. To reduce undesirable and unnecessary water loss.

2. To develop an intelligent device capable of autonomously cutting off the water supply when abnormal usage is detected.

By achieving these objectives, this project aims to provide a novel guideline for future water management systems, demonstrate the efficient use of predictive machine learning models in IoT hardware control, and stimulate user awareness regarding sustainable water consumption behaviors.

2. Literature Review and Related Theories

A brief description of the experimental procedure and analysis and sufficient information for others to be able to reproduce the experiments. The development of an intelligent water management system requires a multidisciplinary approach that integrates fluid dynamics, statistical prediction algorithms, and Internet of Things (IoT) technologies. This section reviews the foundational theories, technological components, and existing research relevant to the proposed smart water meter.

2.1 Theoretical Framework

To accurately measure and predict water usage, the system relies on fundamental physics and statistical mathematics. Flow rate is utilized to measure the volume of fluid passing through a specific cross-sectional area per unit of time. Meanwhile, fluid pressure—the perpendicular force applied per unit area—is continuously monitored, typically measured in pounds per square inch (PSI).

To enable the artificial intelligence (AI) to predict anomalies, the system employs statistical models. The Moving Average (MA) is calculated to track continuous data trends over specific timeframes. This is paired with the Standard Deviation (SD), which measures the dispersion of historical data points from the mean. Together, these formulas create the dynamic threshold used by the AI to identify irregular water pressure patterns.

2.2 Related Research

Recent literature has heavily explored the integration of IoT in water management. Ahmed and Alfred (2022) [1] demonstrated the reliability of utilizing a NodeMCU ESP8266-12E paired with water flow sensors to monitor usage, utilizing MQTT protocols to transmit data to cloud platforms efficiently. Addressing the challenge of power consumption in smart meters, AL-Madhrahi et al. (2021) [2] developed an efficient data collection algorithm that reduced energy usage by up to 93% in smart city environments.

To improve administrative control, Andhare et al. (2021) [4] engineered an automated reading system that transmitted data wirelessly to a central database and allowed for the remote disconnection of the water supply. From a consumer-facing perspective, Pralad et al. (2020) [5] and Anandhavalli et al. (2018) [3] developed alert systems that replaced traditional analog meters, enabling users to transparently monitor their daily water utilization and billing rates to prevent overcharging.

Despite these significant contributions, existing systems predominantly focus on manual remote control and passive data monitoring. There is a distinct research gap regarding systems equipped with artificial intelligence capable of autonomously predicting anomalies and cutting off the water supply without human intervention.

2.3 Proposed Technological Integration

To address the limitations found in existing literature, this project proposes an integrated hardware and software architecture. The hardware is driven by the NodeMCU ESP8266-12E microcontroller, which manages a YF-S201 Water Flow Sensor, a Pressure Transmitter Sensor, and a Solenoid Valve to regulate fluid flow physically. To resolve the energy consumption issues highlighted by AL-Madhrahi et al. (2021) [2], a Mini Hydro Generator Turbine is installed within the flow pump to harvest kinetic energy and recharge the system's battery during active water usage.

On the software side, the data is processed through a MySQL relational database hosted on a Web Hosting server. The user interface is built using Flutter, an open-source cross-platform framework, providing users with a seamless mobile application to monitor real-time sensor data, review historical usage, and configure automatic or manual water cutoff settings.

3. Research Methodology and System Design

This section outlines the architectural design and methodological approach used to develop the smart water meter system, encompassing hardware integration, software architecture, and the predictive mathematical model for automatic anomaly detection.

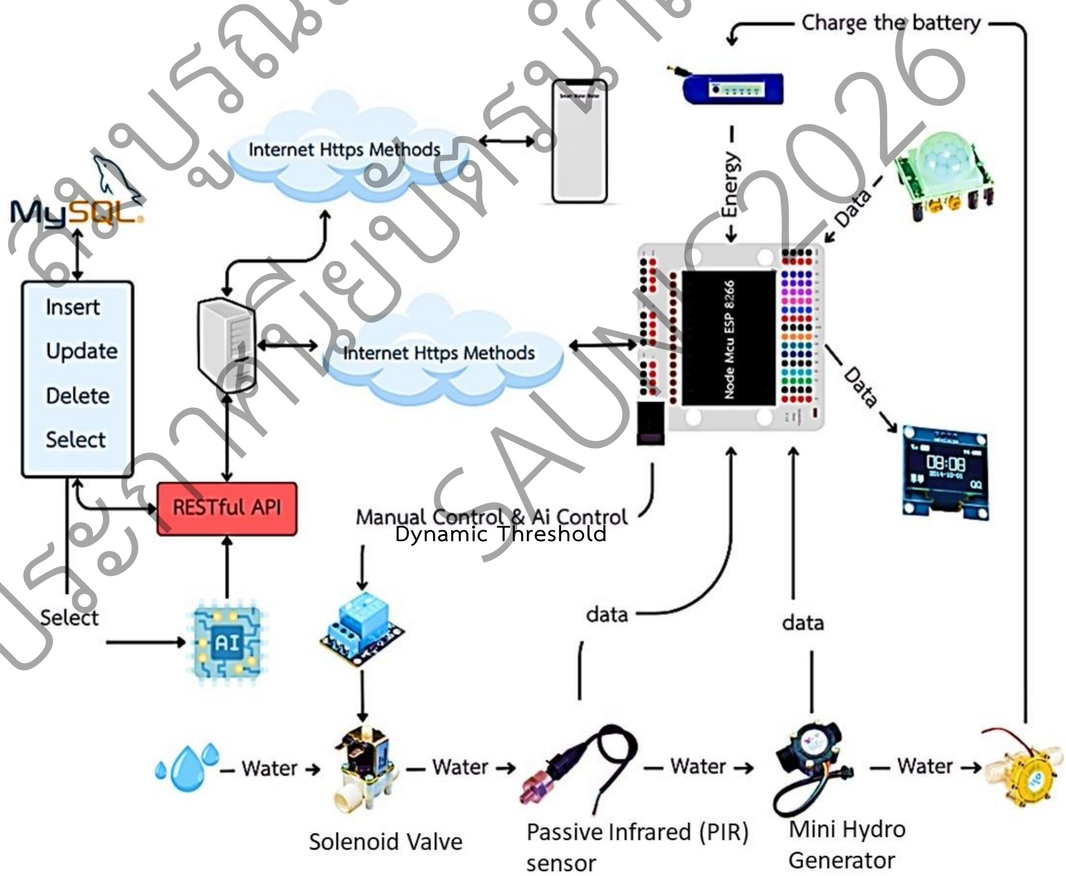

Fig 1. System Framework

3.1 Research Framework

The system framework is designed to autonomously control and monitor water flow using Internet of Things (IoT) architecture, as shown in figure 1. When water enters the system, a Solenoid Valve controls the flow, while a Pressure Transmitter Sensor and a YF-S201 Water Flow Sensor capture real-time pressure and flow rate data. This data is transmitted via a NodeMCU ESP8266-12E microcontroller to a MySQL database server using a RESTful API in JSON format. The server processes this data through a predictive AI model. Simultaneously, a Mini Hydro Generator Turbine harnesses kinetic energy from the water flow to recharge the system's battery.

3.2 Functional and Non-Functional Requirements

To ensure the system meets its objectives, specific requirements were established:

• Functional Requirements (FR): The system must autonomously predict and cut off the water supply during abnormal usage events. Additionally, it must allow users to manually open or close the valve via a mobile application, schedule operational times, summarize daily and monthly water usage, calculate monthly billing costs, and send alert notifications during anomalies.

• Non-Functional Requirements (NFR): The hardware must be highly durable and visually modern. The system must also provide real-time, accurate readings of sensor values, such as fluid pressure and flow rate, with minimal latency.

3.3 Hardware Design

The physical unit was engineered with a focus on self-sustainability and real-time responsiveness, as shown in figure 2. The central processing unit is the NodeMCU ESP8266-12E, powered by a 12V 12100 mAh battery. The microcontroller interfaces with a Relay module to actuate the Solenoid Valve for water regulation. To optimize power consumption, a Passive Infrared (PIR) sensor is utilized to detect user presence; it acts as a switch to activate the local OLED display only when a user is nearby. The entire hardware ensemble is enclosed in a waterproof casing, with PVC piping (capable of withstanding 600 PSI) directing water through the flow and pressure sensors, as well as the Mini Hydro Generator.

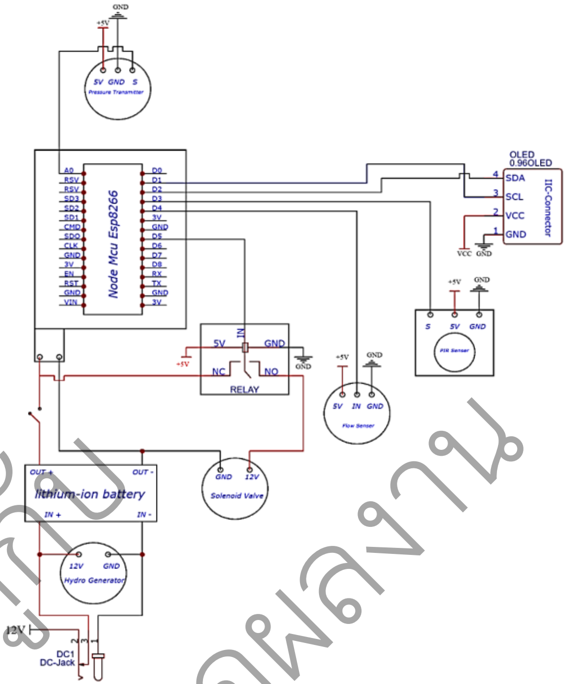

Fig. 2 Circuit Diagram

3.4 Software Design and UML Architecture

The software ecosystem integrates a relational MySQL database with a mobile application developed using the Flutter cross-platform framework. Unified Modeling Language (UML) diagrams were extensively utilized to map the system's architecture:

• Use Case Diagrams: Define user interactions, such as logging in, registering, controlling the valve, setting timers, and viewing historical data, as shown in figure 2.

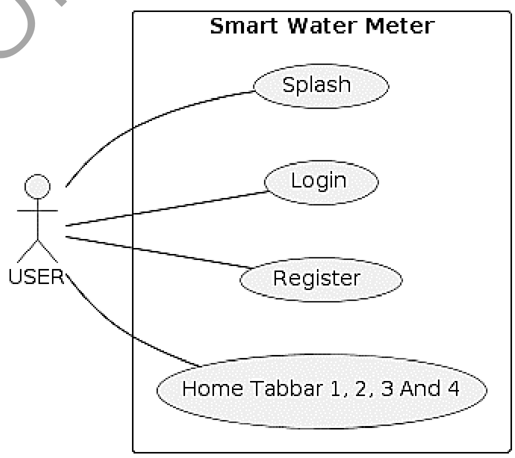

Fig. 3 Use Case Diagram

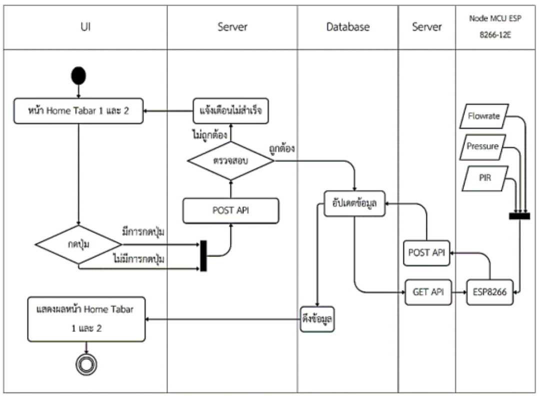

Fig. 4 Example of Sequence Diagram

• Class Diagrams: Map the object-oriented structure of the Flutter application, dividing components into UI rendering classes (StatefulWidgets), Data Models for JSON parsing, and API Services for backend communication.

• Sequence & Activity Diagrams: Detail the asynchronous workflows, such as the microcontroller's routine of POSTing sensor data to the server, retrieving the AI's valve command, and updating the mobile app's real-time state, as shown in figure 4.

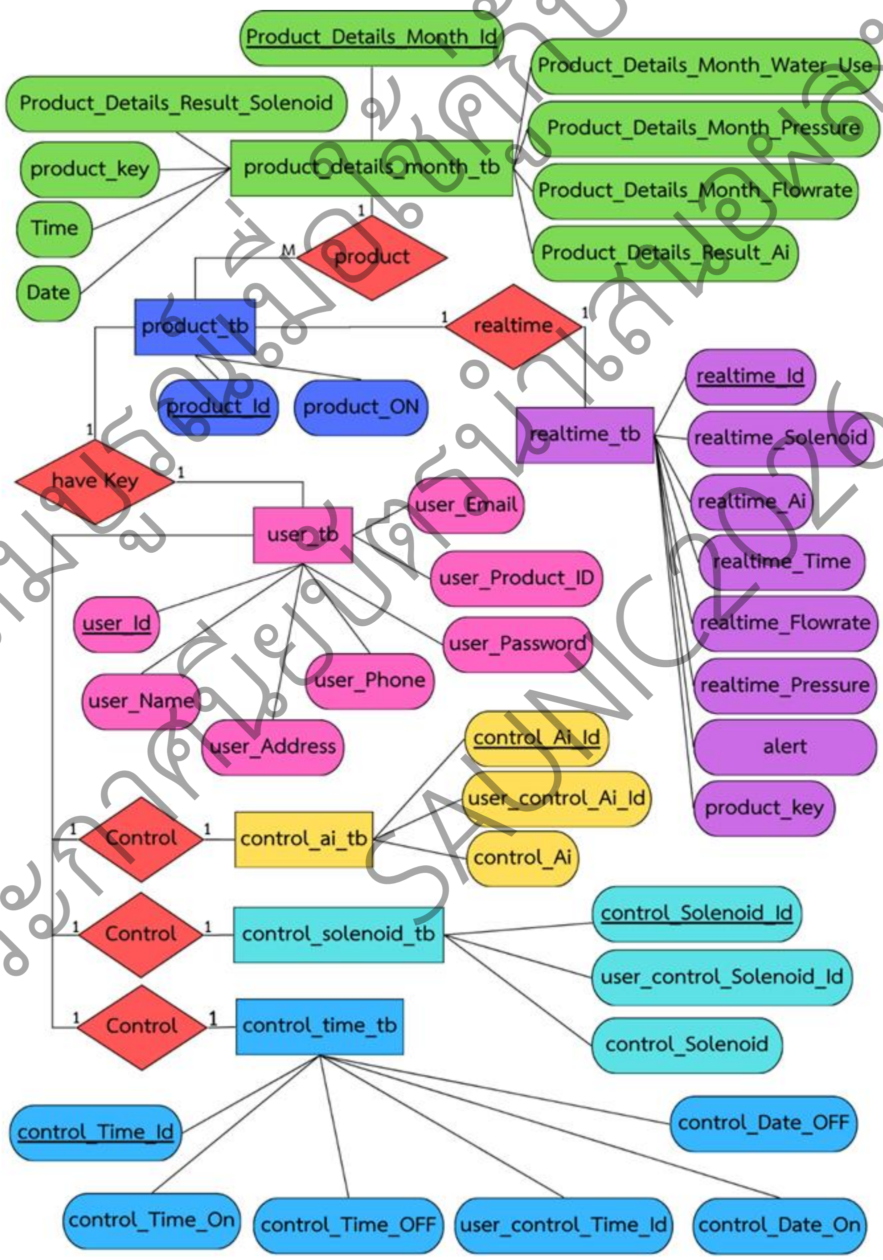

Fig. 5 Entity Relationship Diagram (ERD)

3.5 User Interface (UI) Design

The mobile application serves as the primary administrative dashboard for the user. Beyond the initial Splash, Login, and Registration screens, as shown in figure 6, the core interface is divided into a bottom navigation bar with four primary tabs:

1) Tab 1 (Home/Control): Displays real-time flow rate and pressure gauges. It includes toggle buttons for switching between Normal and Auto modes, and allows manual valve overrides.

2) Tab 2 (Timer Configuration): Allows users to set specific start and end dates/times for automated water dispensing.

3) Tab 3 (Analytics): Visualizes historical water consumption through bar charts and summarizes estimated monthly billing, as shown in figure 6.

4) Tab 4 (Profile): Manages user account details and hardware linkage keys. Pop-up dialogs are actively utilized across the app to push critical alerts, such as immediate notifications when abnormal water usage is detected.

(a) (b) (c) (d)

Fig. 6 Example of User Interface

3.6 Mathematical Formulation and Predictive Model

A rule-based predictive model was formulated to govern the autonomous anomaly detection system. The algorithm analyzes historical fluid pressure data over a rolling four-week period to establish a dynamic baseline for normal usage.

First, the Simple Moving Average (MA_P) is calculated to identify the expected pressure at a specific minute (1):

$$MA_P = \frac{x_1+x_2+\ldots+x_n}{n} \quad (1)$$

Next, the Standard Deviation (SD_P) of the historical data is calculated to account for natural usage variance (2):

$$SD_P = \sqrt{\sum\frac{(x_i-MA_P)^2}{(n-1)}} \quad (2)$$

Finally, the system establishes a Dynamic Threshold Model by subtracting the SD_P from the MA_P (3):

$$Dynamic\ Threshold = MA_P - SD_P \quad (3)$$

Explanation of the Model: The AI recalculates this threshold for every minute of the day based on past behavior. If the real-time pressure measured by the transmitter drops below this calculated Dynamic Threshold, the system identifies an anomaly (such as a burst pipe or a continuous leak) and instantly signals the NodeMCU ESP8266-12E to close the solenoid valve, thereby preventing severe water loss.

4. Results and Discussion

This section presents the performance evaluation of the proposed smart water meter system. The testing protocol was divided into three primary phases: basic functional testing, hardware measurement accuracy, and the efficiency of the predictive anomaly detection model.

Fig. 7 Examples of installation and testing in real-world settings.

4.1 System Installation and Functional Testing

Initial trials were conducted to verify the stability of the hardware and the data synchronization between the NodeMCU ESP8266-12E and the Flutter mobile application. Ten test iterations were performed for device power cycles, real-time sensor data display (Flow rate and Pressure), and operational mode toggling (Manual, Timer, and Automatic). The system successfully executed all commands with a 0% error rate, demonstrating that the data transmitted via the RESTful API successfully matched the readings displayed on the user interface without packet loss.

4.2 Measurement Accuracy Analysis

To evaluate the precision of the YF-S201 Water Flow Sensor, experiments were conducted by filling a standard 0.60-liter container at three different solenoid valve capacities: 30%, 60%, and 100%. Ten iterations were recorded for each capacity level to calculate the absolute error.

The results indicated that at 30% and 60% valve capacities, the system maintained a highly accurate Mean Absolute Error (MAE) of 2.67%. However, when the valve was opened to 100% capacity, the MAE increased to 11.66%. This suggests that while the sensor is highly reliable at low to medium fluid velocities, extreme flow rates introduce minor calculation discrepancies, likely due to the physical limitations of the Hall Effect sensor's internal turbine tracking rapidly passing water.

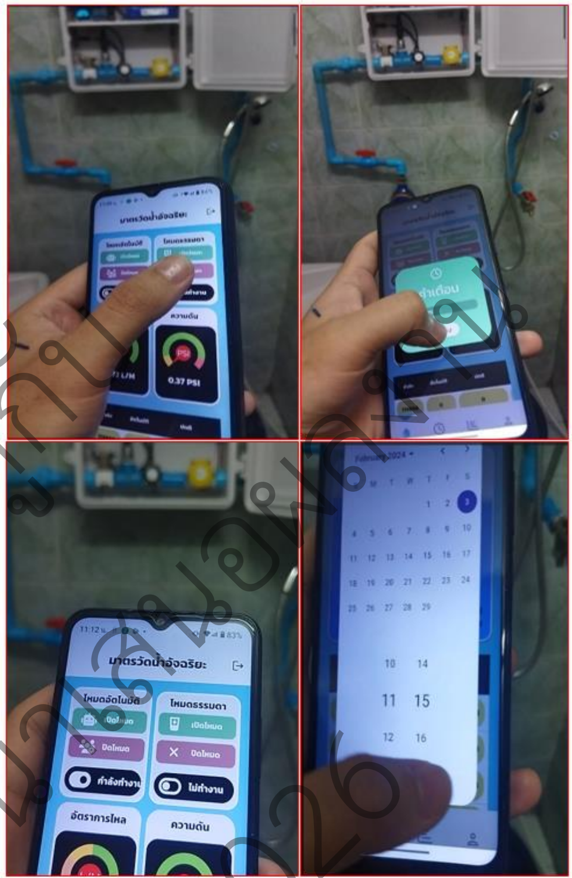

Fig. 8 An example of testing the system via a smartphone screen.

4.3 Predictive Model Performance Evaluation

The core innovation of this system is its autonomous anomaly detection. The rule-based predictive model (utilizing Simple Moving Average and Standard Deviation) was evaluated over a continuous 7-day period (March 4–10, 2024), utilizing historical usage data spanning the previous four weeks. The model recalculates the dynamic threshold every minute, automatically triggering a valve shut-off if real-time pressure drops below this threshold.

The performance of the model was analyzed using a Confusion Matrix to determine Accuracy, Precision, Recall, and the F1 Score:

• High-Performance Days: On Wednesday (March 6) and Sunday (March 10), the model achieved flawless detection metrics, recording 100% across Accuracy, Precision, Recall, and F1 Score. On these days, the system perfectly identified True Positives (correctly cutting off water during anomalies) and True Negatives (maintaining flow during normal usage).

• Variance and Anomalies: On Monday (March 4), the system yielded a 73% Accuracy and a 33% F1 Score, indicating instances of False Positives where the system was overly sensitive. Conversely, on Tuesday (March 5) and Saturday (March 9), the system stabilized, achieving an Accuracy of 93% and F1 Scores of 80% and 91%, respectively.

• Environmental Impact: Some data discrepancies, such as the 87% accuracy recorded on Thursday (March 7), were traced to historical data corruption. Moisture-induced rust on the Pressure Transmitter Sensor's connection pins slightly distorted pressure readings, temporarily skewing the dynamic threshold.

Overall, the predictive algorithm achieved an average accuracy of approximately 92.29% over the 105 tested events. The results firmly establish that integrating moving average statistical models with IoT edge-computing can reliably prevent accidental water loss without requiring manual user intervention.

5. Conclusion

The smart water meter system developed in this study successfully demonstrated its capability to autonomously identify and mitigate abnormal water flow, offering a highly effective solution for sustainable water management. Through rigorous testing, the system flawlessly executed user commands across manual, timer, and automatic operational modes via the cross-platform mobile application.

In its automatic mode, the integration of an artificial intelligence predictive model—utilizing Simple Moving Average and Standard Deviation calculations based on historical usage data—proved highly reliable. By continuously recalculating dynamic pressure thresholds, the system successfully ordered the NodeMCU ESP8266-12E to cut off the water supply when the real-time pressure dropped below the expected baseline. Evaluated across 105 distinct events, the predictive model achieved an impressive average accuracy of 92.29%, confirming that the integration of statistical machine learning with IoT edge-computing can significantly reduce unnecessary water loss without requiring manual human intervention.

5.1 Limitations and Challenges

During the development and testing phases, three primary challenges were identified:

1. Environmental Pressure Variance: Testing the device in low-pressure pipe environments obscured data trends, making it difficult for the predictive model to sharply differentiate between normal usage and minor anomalies.

2. Hardware Degradation: A minor physical leak at the Pressure Transmitter Sensor's connection point introduced moisture, leading to rust. This temporarily skewed the sensor's pressure readings and distorted the model's accuracy on specific testing days.

3. Network Dependency: Unstable internet connectivity occasionally interrupted data transmission to the server, causing gaps in the historical dataset required for the AI's moving average calculations.

5.2 Recommendations for Future Work

Based on the experimental outcomes, the following recommendations are proposed for future implementations:

• The hardware should ideally be installed at nodes with consistently high water pressure to ensure optimal sensor reading clarity and precise model trend analysis.

• All hardware connection points, particularly around the Pressure Transmitter Sensor, must be heavily waterproofed and strictly verified prior to deployment to prevent moisture-induced data corruption.

• A stable, high-bandwidth local network infrastructure is crucial to ensure seamless RESTful API communication between the IoT edge devices and the centralized database.

6. References

[1] Ahmed, S. I., & Alfred, Q. M. (2022). Design of smart water metering flow control and quality measurement using IoT communication. *Computer Science & Engineering: An International Journal (CSEIJ), 12(1)*. https://shorturl.asia/e5Nav

[2] AL-Madhrahi, R., Al-Qurabat, A. K., & Abdulbaqi, A. S. (2021). An efficient IoT-based smart water meter system of smart city environment. *International Journal of Advanced Computer Science and Applications (IJACSA)*. https://shorturl.asia/2p5u6

[3] Anandhavalli, D., et al. (2018). Smart meter for water utilization using IoT. *International Research Journal of Engineering and Technology (IRJET).* https://shorturl.asia/qO0Cu
[4] Andhare, A. A., et al. (2021). Automated water meter reading system. *International Research Journal of Engineering and Technology (IRJET).* https://shorturl.asia/FQgTY
[5] Pralad, D. R., et al. (2020). IoT based water monitoring and alerting system. *International Journal of Advanced Trends in Computer Science and Engineering (IJATCSE)*. https://shorturl.asia/Eph3n
[6] Otanasap, N., Chalermsuk, C., & Bungkomkhun, P. (2019). A Survey of IoT: Advances in Smart and Dynamic Environmental Monitoring. In *8th International Conference on Environmental Engineering, Science and Management.*