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AQUASENSE: Smart Water Leakage Detection System

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***Abstract*— Even the smallest of the smallest unnoticed water leaks contribute significantly to the wastage of precious water in our homes or industries. Traditional monitoring systems are often expensive, difficult to install, inaccurate, or require constant maintenance. To address this, a smart water leakage detection system- AQUASENSE, which can also effectively provide real-time insights into water flow using affordable IoT technology, is being considered. By measuring the flow at both inlets and outlets in a pipeline, the system can detect unusual usage patterns and, in turn, alert users to potential leaks immediately. Users are notified through an application interface, making it easy for them to track their water consumption and take corrective actions. This prototype can be effectively implemented for use in homes, apartment complexes, and industrial settings.**

***Keywords*— Water leaks, wastage, AQUASENSE, IoT, inlets, outlets, alert.**

I. Introduction

Water, being one of the most precious natural resources, its cautious usage in our daily lives has undoubtedly become important in addressing the challenges of global water scarcity. Traditional water monitoring practices often rely on manual inspection or high-cost hardware systems, both of which are limited to the problem of accessibility, affordability, and precision. With the growth of the Internet of Things (IoT), it is now possible to develop affordable, real-time monitoring systems for domestic and industrial water usage [1]. This paper proposes AQUASENSE, a water flow monitoring and leakage detection system designed using the ESP8266 microcontroller, which in turn measures the flow of water at both the inlet and outlet water pipes. The flow is measured based on the Hall-effect-based flow sensors, and the ESP8266 ensures seamless data transmission via Wi-Fi. The recorded data is accessible through an application-based interface that enables users to track flow rates and consumption patterns in real-time. Furthermore, the application also notifies the users when the system starts detecting water losses. Apart from being a simple water monitoring system, AQUASENSE focuses on being sustainable and scalable. This system can actually be used in households, apartments, and industrial facilities, as well as in agriculture, making it adaptable to varying scales of operation. The system architecture is also designed with keeping its extensibility in mind, supporting its diverse future scope. With the effective utilisation of predictive machine learning algorithms, AQUASENSE can be enhanced to detect leakage patterns, forecast demand, and optimise water distribution, contributing to improved resource management and safety.

II. Literature Review

Many research efforts have been undertaken to address the critical issue of water leakage in distribution networks, leveraging the advancements in IoT, sensor technology, and machine learning.

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These studies aim to enhance detection accuracy, improve resource efficiency, and reduce operational costs.

This study by Ayamga et al. introduces an IoT-based water leakage detection and localisation system called iWaLDeL. Utilising YF-S201 flow rate sensors and a static detection strategy, the system monitors real-time flow data to identify pressure anomalies that indicate leakages. With a network of strategically placed sensors communicating with a central hub, the model enhances response time and system scalability. The prototype validation shows promising results, making the solution viable for smart infrastructure applications focused on water conservation and pipeline maintenance.[1]

This research by Marathe et al. proposes an IoT-driven approach that combines NodeMCU, flow sensors, and cloud-based monitoring to detect leakages within a smart city infrastructure. Notably, the system includes a user interface that provides real-time alerts and leak localization using the Google Maps API, thereby enabling quick response from maintenance teams. The low cost and scalability of the setup position it as an effective solution for urban environments, where constant monitoring and timely interventions are essential.[2]

In the work by Islam et al., the authors design an intelligent water leakage detection system integrating IoT and machine learning. Unlike traditional threshold-based detection systems, this approach uses historical data patterns to forecast expected flow values and identify discrepancies. The study demonstrates the robustness of machine learning models, especially Random Forest, in predicting anomalies caused by leakage. By combining real-time sensor input and predictive analytics, the proposed system improves accuracy and adaptability over time, proving effective even in dynamically changing flow environments.[3]

Another notable contribution is the survey by Moubayed et al., which analyses the limitations of existing detection technologies and explores future research avenues. The paper highlights challenges in hardware deployment, communication bottlenecks, and sensor precision. It advocates for advanced techniques such as data fusion and federated learning, which can harness distributed data sources while maintaining privacy and improving scalability. This work is instrumental in identifying gaps in current methods and guiding researchers toward more collaborative and intelligent leakage detection ecosystems.[4]

Finally, Adedeji et al. provide an overview of leakage detection and localisation algorithms in water piping systems. The study categorises existing methods and emphasises the importance of integrating reliable algorithms that balance detection accuracy with computational efficiency. Key insights include the potential of hybrid approaches and the need for real-time system adaptability. This foundational work offers a broad perspective on algorithmic strategies and underlines the necessity for multi-disciplinary approaches involving sensors, network theory, and AI.[5]

The importance of this research area cannot be overstated, as water scarcity and infrastructure inefficiencies continue to pose significant challenges globally. With ageing pipelines, increasing urban demand, and climate-related uncertainties, timely detection and management of water leakages are essential for sustainable resource utilisation. IoT-enabled smart systems not only reduce economic losses but also promote environmental conservation by ensuring every drop of water is accounted for. As such, continued innovation and investment in intelligent water monitoring solutions are vital for achieving long-term water security.

III. Methodology

The methodology for this project focuses on designing and deploying a smart water monitoring and leakage detection system using the ESP8266 microcontroller, flow sensors, and a relay-controlled pump. The system combines real-time data collection, cloud-based communication, and mobile app control to deliver a smooth and automated way to monitor water flow and identify issues. It begins with hardware setup and sensor connection, followed by programming the ESP8266 to read and analyse flow sensor data. In addition to this, the system includes developing logic for motor control based on flow rate comparisons and integrating the overall hardware with a Flutter-based mobile app for real-time user interactions and manual overrides.

Figure 1 illustrates a comprehensive flow of a water leakage detection and motor control system integrated with IoT and app-based user interaction. The process begins with system initialization, followed by data acquisition, where flow sensors read water flow, calculate flow rate, and convert it to litres per minute. These values are logged, stored in CSV format, and used for further analysis and machine learning. The system continuously monitors for discrepancies in inlet and outlet flow rates to detect leakage.

If a leak is detected, the system triggers a relay to cut off motor power and sends a status update to the user via the mobile app. The user is notified and given the option to reset or resume monitoring from the app. This loop ensures safety by powering off the system if no intervention occurs. The architecture integrates real-time sensing, automated motor control, and remote user communication, making it efficient for smart water management solutions.

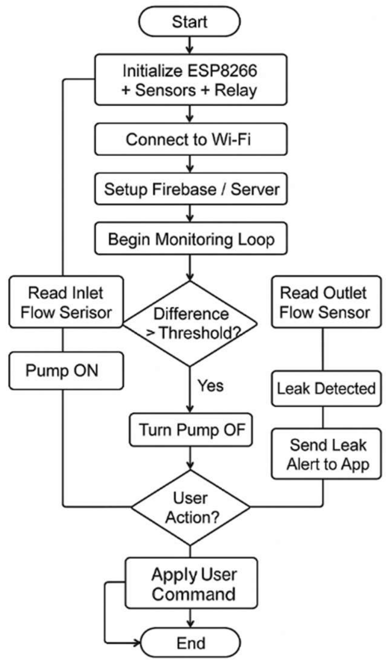

Figure 1. Flow chart depicting the project structure

A. Circuit Description

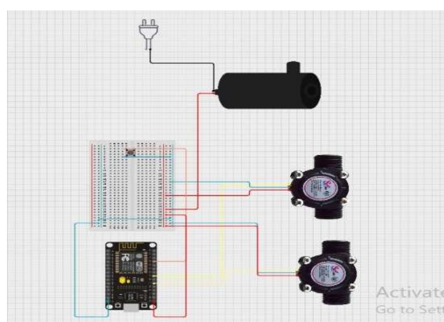

Figure 2. Schematic of the project

Figure 2 consists of an ESP8266 (NodeMCU) microcontroller, two YF-S201 water flow sensors, a 4-channel relay module, and a water pump. The flow sensors are connected to the digital pins of the ESP8266 to measure water flow at two different points (inlet and outlet). These sensors output pulses proportional to the flow rate. Power for the sensors and ESP8266 is provided through a common 5V and GND line connected via a breadboard.

For network communication, the ESP8266 uses its onboard Wi-Fi module to connect to a local access point. Once connected, it hosts a local web server to serve flow data via HTTP. The entire circuit is compact enough to fit on a small breadboard or a custom PCB for field deployment.

Description of the Components:

- ESP8266 (NodeMCU): A Wi-Fi-enabled microcontroller used for real-time data processing and communication. It reads signals from the water flow sensors, processes the data, and controls the relay module accordingly.
- YF-S201 Water Flow Sensors: These are Hall-effect-based sensors that measure the flow rate of water. They generate pulses in proportion to the amount of water passing through them, which can be interpreted by the microcontroller to calculate flow rates.

- 4-Channel Relay Module: This module allows the ESP8266 to control high-voltage devices like the water pump. It acts as an electrically operated switch that isolates the low-voltage control side from the high-voltage power side.
- Water Pump: An AC-powered device used to circulate water. It is controlled by the relay module, which turns it on or off based on the readings from the flow sensors.
- Breadboard and Connecting Wires: Used to establish temporary and flexible electrical connections among the components for prototyping and testing purposes.

B. Coding and Testing

To provide real-time monitoring and leak alerts, a mobile application was developed using Flutter, an open-source UI toolkit by Google for building natively compiled applications for Android and iOS from a single codebase. The app interfaces with the ESP8266 microcontroller over a local Wi-Fi network using HTTP GET requests.

The simple Flutter application consists of a home screen that allows the user to initiate leak detection by fetching the inlet and outlet flow rates from the microcontroller's /flow endpoint. Once the data is received, the app parses the JSON response and displays both inlet and outlet values in liters per second. A conditional check determines whether the difference between the two exceeds a predefined threshold (0.002 L/s), indicating a possible leak.

Pseudo Code:

```
Initialize pins for flow sensors, relay module, and Wi-Fi
Set up interrupts for both flow sensors
Initialize variables to count pulses
Function onSensor1Pulse:
  Increment counter1
Function onSensor2Pulse:
  Increment counter2
Setup:
  Begin serial communication
  Connect to Wi-Fi
  Attach interrupts to flow sensor pins
  Set relay pin as OUTPUT
  Turn relay OFF (pump OFF)
Loop:
  Reset counters
  Wait for a fixed time interval (e.g., 1 second)
  Calculate flow rate from pulse counts
  If the flow rate from both sensors is within the expected range:
    Turn the relay ON (start pump)
  Else:
    Turn relay OFF (stop pump)
Send flow rate data to the cloud or display
Start App
Connect to Firebase
On Home Screen:
  Fetch current flow rate values from Sensor 1 and Sensor 2
  Display values in real-time
  Show pump status (ON/OFF)
  Provide a manual control switch for the pump
If manual pump control is toggled:
  Send ON/OFF command to ESP8266 via cloud
If the data logging screen is selected:
  Retrieve historical flow data from the cloud
  Plot a graph of flow rates over time
Set timer or auto-refresh:
  Update sensor readings every few seconds
```

This code outlines a structured approach for implementing an IoT-based water flow monitoring and motor control system using the ESP8266 microcontroller. It begins by initialising pins for two flow sensors and a relay module, and setting up interrupts to accurately count sensor pulses in real time. The setup routine establishes serial communication, connects the ESP8266 to Wi-Fi, attaches the sensor interrupts, and configures the relay to control a water pump, which is turned off by default. In the main loop, the system resets pulse counters, waits for a fixed interval, and calculates the flow rate from the pulse counts. Based on the comparison of flow rates from the inlet and outlet sensors, it decides whether to turn the pump on or off, ensuring safe operation and leak detection. The real-time flow data is sent to a cloud platform, Firebase. The associated mobile application displays current flow rates, pump status, and offers manual control of the pump. It also allows users to access historical data visualisations and automatically refreshes readings periodically, ensuring a comprehensive, real-time, and user-friendly smart water management solution.

C. Working

The project utilises YF-S201 Hall Effect Water Flow Sensors, which operate on the principle of electromagnetic induction. Inside each sensor is a rotor with embedded magnets. As water flows through the sensor, the rotor spins. Every rotation of the rotor triggers a Hall effect sensor, generating a pulse signal. The frequency of these pulses is directly proportional to the rate of water flow. By counting the number of pulses over time, the flow rate (in litres per minute) and total volume can be calculated. This makes the sensor highly suitable for real-time flow monitoring in pipelines.

Two such sensors are connected in parallel to the NodeMCU, each measuring flow through a separate pipe. The NodeMCU ESP8266 microcontroller collects digital pulses from both sensors and calculates real-time flow rates. This data is processed and then transmitted over Wi-Fi using the built-in capabilities of the ESP8266. The microcontroller communicates with an IoT platform such as Firebase, which acts as a middleware between the hardware and the mobile application.

A relay module, also controlled by NodeMCU, is used to switch the water pump ON or OFF. The relay receives a digital HIGH/LOW signal from the NodeMCU and toggles the AC-powered motor accordingly. The motor is responsible for driving water through the sensor pipeline system

The mobile application built using Flutter interfaces with the cloud in real-time to:

- Display live flow rates
- Show water consumption history
- Send alerts or trigger events based on threshold values

To enhance the smartness of the system, a supervised machine learning model is integrated for predictive analysis. The model is trained on historical flow rate data, motor usage time, and user control patterns. The goal is to predict optimal water usage times or detect anomalies such as:

- Unusual spikes in flow (indicative of leakage)
- Decreased flow (possible clog or empty tank)
- User water consumption trends

The ML model is trained offline using Python libraries like scikit-learn and deployed on a server or cloud function. Real-time sensor data sent by the NodeMCU is processed by this model to generate intelligent recommendations, which are then pushed back to the mobile app as alerts or auto-action triggers.

In conclusion, this project successfully demonstrates that low-cost hardware, when augmented with intelligent data processing and machine learning, can yield a powerful diagnostic tool for water conservation. While logistic regression provides a balance between accuracy and efficiency, future work will explore hybridised models, adaptive learning on microcontrollers, and system-level integration into smart irrigation or municipal water networks, further pushing the boundaries of intelligent resource monitoring.

IV. RESULTS AND DISCUSSIONS

The integration of Machine Learning and statistical analysis significantly enhanced the system's ability to detect water leaks and monitor flow consistency. This data is then transmitted via Wi-Fi to a cloud database, Firebase, from where it is accessed by the Flutter app. The app displays the current status (leak detected or not), allowing users to manually override the pump operation or rely on the system's automatic shutoff feature when a leak is detected. This ESP–Flutter integration ensures that leak alerts are communicated instantly, empowering users to act accordingly.

A. Statistical Analysis of Flow Sensor Data

A descriptive summary of the dataset indicates clear trends that differentiate leakage from non-leakage conditions. The mean inlet flow rate was 1.348 L/s (standard deviation: 0.089), while the outlet flow rate had a mean of 0.949 L/s with a larger standard deviation of 0.314. These statistics suggest greater variability in outlet readings, especially during leak events. The statistical summary is shown below:

TABLE I. SUMMARY OF STATISTICAL VALUES

Statistic	Inlet Inputs	Outlet Inputs	Leak Detected
count	200.000	200.000	200.000
mean	1.348	0.949	0.500
std	0.089	0.314	0.501
min	1.202	0.408	0.000
25%	1.267	0.653	0.000
50%	1.356	0.956	0.500
75%	1.423	1.242	1.000
max	1.497	1.459	1.000

The dataset was balanced, with an average leak detection value of 0.5, indicating an equal distribution of leak and no-leak instances.

B. Correlation Matrix and Histogram Analysis

The heatmap shown in Figure 3 highlights the relationships between the recorded variables. A strong negative correlation of −0.93 was observed between the outlet flow rate and the leak detection label. This implies that when the outlet readings dropped, the system more often marked the condition as a leak. whereas what we consider, the inlet flow rate showed only a weak correlation of 0.08 with leak detection, suggesting that inlet measurements alone do not provide a reliable indication of leakage. The histogram shown in figure 4 depicts flow rate differences present a bimodal distribution, with two distinct peaks — one in the lower range (~0.1 L/s) and another in the higher range (~0.7 L/s). This indicates two operational conditions: one where the system operates within normal expected flow differences, and another where significant differences signal possible leak events or faults in flow regulation. This distribution further validates the leak detection logic, as abnormal differences directly relate to leak occurrences.

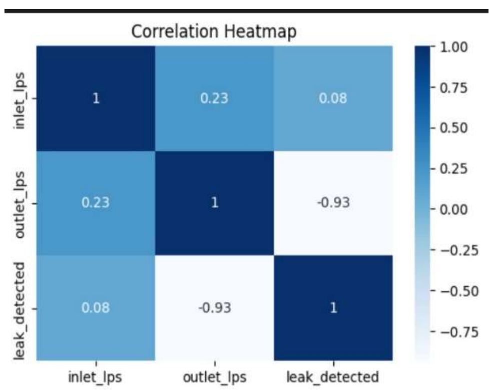

Figure 3: Correlation Heatmap

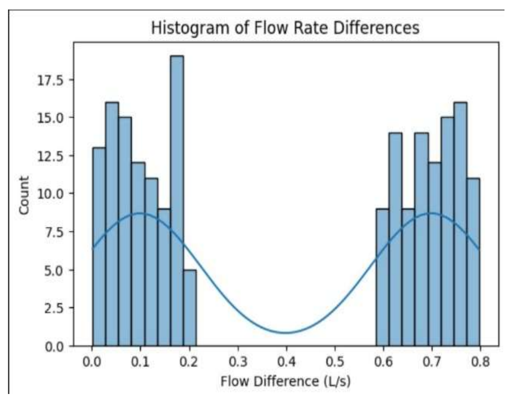

Figure 4: Histogram

To relay this information to the user, a real-time connection was established between the ESP microcontroller and a Flutter-based mobile application. The ESP reads flow data and detects leaks using sensor input and decision logic. On the implementation side, flow data from the ESP microcontroller was forwarded through Wi-Fi to a Firebase cloud database. The companion Flutter application retrieved this data in real time and displayed the system status, i.e., whether a leak was detected. Users could either stop the pump manually through the app or allow the system to perform an automatic shutdown when abnormal flow was detected. This ESP–Flutter link ensured that alerts reached the user immediately, making the system both responsive and practical for remote monitoring. It also enhances accessibility, allowing remote monitoring from any location with internet connectivity.

The system described in this work can be taken forward in several ways. One clear direction is to use more advanced machine learning models, which could learn long-term water usage habits and provide early warnings before major leaks occur. These models could also help in improving water efficiency by suggesting better usage patterns and sending alerts that are more meaningful to the end user.

Another area of development is multi-zone monitoring. Instead of tracking only a single inlet and outlet, several points in the network can be observed at once. This would make the approach more suitable for apartment complexes, industries, or larger buildings where the water distribution is more complicated. Linking the system with smart home platforms and voice assistants, such as Alexa or Google Home, would further enhance usability. For regions with limited internet coverage, modules such as GSM or LoRa can be added to enable the transmission of alerts and data even without Wi-Fi. Beyond homes and industries, this technology may also be useful in special cases like trains, aircraft, or mobile healthcare units, where water is limited and leaks must be detected immediately. In the longer run, the framework could also connect with city-level water systems to support predictive maintenance and better resource planning. Such integration would help conserve water on a larger scale and make the technology valuable not just for individuals but also for public infrastructure.

V. Conclusion

This study introduces a practical framework for detecting water leakage using two flow sensors, one at the inlet and the other at the outlet of a pipe system. The ESP8266 microcontroller was employed to capture and log flow data in real time, with the readings systematically stored in a CSV format for further processing. These records served as the training dataset for a machine learning model aimed at estimating the expected outlet flow based on inlet measurements and prior trends. Deviations between predicted and actual outlet values were treated as potential indicators of leakage or inefficiency.

A logistic regression model was utilised owing to its computational efficiency, straightforward implementation, and suitability for resource-constrained platforms. The model established a correlation between inlet and outlet flow variations while tolerating minor fluctuations and short-term disturbances, thereby enabling reliable anomaly identification.

The proposed methodology offers two primary advantages. First, it allows for reliable leak detection without the need for costly pressure sensors or camera-based systems. Second, the heavier machine learning computations are handled during the training phase on a remote system, while the microcontroller only runs lightweight anomaly detection logic. This ensures that the solution remains responsive and efficient, with the option to compress and deploy the trained model on the edge device or use it periodically for diagnostics. During testing, the framework successfully identified simulated leaks and disturbances, with its predictions aligning well with human observations of flow differences. Moreover, the modular design makes it adaptable for larger networks, whether in households, buildings, or agricultural setups.

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