East African Journal of Engineering
eaje.eanso.org
Volume 8, Issue 1, 2025
Print ISSN: 2707-5389 | Online ISSN: 2707-5397
Title DOI: https://doi.org/10.37284/2707-5397

EAST AFRICAN NATURE & SCIENCE ORGANIZATION

Original Article

Optimising Harare's Water Dissemination Network: Development of an IoT-Driven Leak Monitoring System for Sustainable Urban Water Management

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Article DOI : https://doi.org/10.37284/eaje.8.1.3344

Publication Date:

18 July 2025

Keywords:

Construction, Technology, Labour, Productivity, Safety.

ABSTRACT

Water scarcity persists as a pressing issue in Harare, exacerbated by undetected leaks within the municipal water distribution networks, which significantly contribute to non-revenue water (NRW) losses. A considerable volume of water fails to reach end-users due to these inefficiencies, intensifying supply shortages and elevating operational expenditures for water utility providers. These challenges stem primarily from deteriorating infrastructure, reliance on conventional leak detection methodologies, and inadequate management systems. As noted by Dinar (2024), effective water resource management remains a critical concern, particularly in regions facing water deficits amid escalating demand for potable water. This research project proposes the development of an IoT-enabled real-time water leakage detection system to optimise monitoring capabilities and mitigate NRW losses. The system architecture incorporates a network of sensors, microcontrollers, and IoT communication frameworks to facilitate continuous, real-time data acquisition. Strategically positioned sensors will monitor key hydraulic parameters, including flow rate, pressure, and water levels, with collected data transmitted to a cloud-based analytical platform. A dedicated web interface will be implemented to deliver instantaneous leakage alerts, dynamic graphical representations, and comprehensive diagnostic reports, thereby enabling preemptive maintenance interventions and minimising water loss. The system's efficacy will be empirically validated through prototype testing, ensuring precise leak localisation and rapid response mechanisms. In this context, the proposed method will reduce the non-revenue water in Harare by at least 20% within a year of deployment, as well as reduce the response time to leaks by at least 50%. Ultimately, this initiative aims to advance water conservation efforts, improve operational efficiency, and promote sustainable water management practices that can be deployed to large consumers of fresh water, such as industrial complexes.

Article DOI: https://doi.org/10.37284/eaje.8.1.3344

APA CITATION

Akimu, O., Rashayi, E., Gumindoga, W., Gumindoga, G. M. & Zulu, G. B. (2025). Optimising Harare's Water Dissemination Network: Development of an IoT-Driven Leak Monitoring System for Sustainable Urban Water Management. *East African Journal of Engineering*, *8*(1), 219-230. https://doi.org/10.37284/eaje.8.1.3344

CHICAGO CITATION

Akimu, Omega, Emanuel Rashayi, Webster Gumindoga, Godfrey Murairidzi Gotora and Godfrey Benjamin Zulu. 2025. "Optimising Harare's Water Dissemination Network: Development of an IoT-Driven Leak Monitoring System for Sustainable Urban Water Management". *East African Journal of Engineering* 8 (1), 219-230. https://doi.org/10.37284/eaje.8.1.3344.

HARVARD CITATION

Akimu, O., Rashayi, E., Gumindoga, W., Gumindoga, G. M. & Zulu, G. B. (2025) "Optimising Harare's Water Dissemination Network: Development of an IoT-Driven Leak Monitoring System for Sustainable Urban Water Management", *East African Journal of Engineering*, 8(1), pp. 219-230. doi: 10.37284/eaje.8.1.3344.

IEEE CITATION

O., Akimu, E., Rashayi, W., Gumindoga, G. M., Gotora & G. B., Zulu "Optimising Harare's Water Dissemination Network: Development of an IoT-Driven Leak Monitoring System for Sustainable Urban Water Management" *EAJE*, vol. 8, no. 1, pp 219-230, Jul. 2025.

MLA CITATION

Akimu, Omega, Emanuel Rashayi, Webster Gumindoga, Godfrey Murairidzi Gotora & Godfrey Benjamin Zulu. "Optimising Harare's Water Dissemination Network: Development of an IoT-Driven Leak Monitoring System for Sustainable Urban Water Management" *East African Journal of Engineering*, Vol. 8, no. 1, Jul. 2025, pp. 219-230, doi:10.37284/eaje.8.1.3344.

INTRODUCTION

The distribution network of water in the city of Harare faces significant losses due to leaks, contributing to non-revenue water. Traditional methods have proven to be inefficient, allowing water to be lost for a long period before necessary action is taken. Current estimates suggest that Harare experiences around 60% non-revenue water, largely due to undetected leaks, according to the official records of the Zimbabwe National Water Authority. Non-revenue water is water that is lost before reaching the consumer, often due to leakages, illegal connections or meter inaccuracies (Farley and Trow, 2003). These leaks exacerbate water shortages and increase operational costs. Recent advances in the Internet of Things (IoT) offer a solution by enabling real-time monitoring of water systems. By utilising sensors to monitor water flow and pressure, this system will detect leaks early in the water distribution network and transmit data to a central monitoring station, where it will be analysed to quickly identify leak signatures, allowing for prompt repair actions. Literature review examines existing research on water leakage detection, focusing on sensor-based monitoring, IoT integration, and governance challenges in water distribution systems. This script aims to develop a comprehensive, Internet of Things-based water leakage detection system designed to mitigate the NRW challenges faced by Harare's water infrastructure using a real-time-based communication as well as a friendly interface, making it a digital water system. The goal is to reduce water loss and improve water management in Harare, creating a model that could also benefit other cities facing similar challenges.

Background

Harare's ageing infrastructure, outdated maintenance practices, and inadequate monitoring result in significant water losses from frequent breakdowns in the distribution network. Traditional methods of leak detection, such as manual inspections and pressure testing, are time-consuming, labour-intensive, and often ineffective in identifying hidden leaks. This not only leads to financial loss for water utilities and delays in identifying water losses but also affects the quality of life for residents who experience unreliable water access. The proposed IoT-based project offers continuous, real-time monitoring and allows for

Article DOI: https://doi.org/10.37284/eaje.8.1.3344

faster leak detection. This script seeks to enhance the efficiency and reliability of Harare's water distribution.

Non-revenue water is a critical issue being faced in Harare which results in a number of significant challenges that are being faced by the city. Reducing water leaks will not only reduce financial losses for water utilities but also improve public health, water availability, and the longevity of infrastructure. As water availability decreases during droughts, an efficient distribution system becomes even more critical. By preventing leaks, the proposed system will ensure more consistent water access and reduce the risk of infrastructure degradation over time. A cost-benefit analysis indicates that while the initial investment in sensor networks is high, the reduction in water loss and long-term maintenance savings significantly outweigh the upfront costs.

Literature Review

Potable water constitutes a critically limited resource essential for human sustenance, yet its efficient utilisation is compromised by pervasive leakage within urban distribution networks, leading to significant wastage in the global sense, resulting in great noticeable economic losses, resource wastage, and service delivery challenges (Makaya & Hensel, 2014). In urban areas, ageing infrastructure, poor maintenance, and high-pressure conditions exacerbate water losses, with some cities experiencing Non-Revenue Water (NRW) rates exceeding 40% (Kanyepi & Tanyanyiwa, 2021).

Traditional detection methods often rely on manual inspections, which are time-consuming and often ineffective in large area networks. Recent advancements in IoT have enabled and improved leak detection. Real-time monitoring systems leveraging IoT and sensor technologies have emerged as effective solutions for early leak detection, reducing water loss, and improving maintenance efficiency (Kumar & Jagadeep, 2022). This literature review examines existing research on water leakage detection, focusing on sensor-based monitoring, IoT integration, and governance challenges in water distribution systems.

Water Monitoring Techniques

Water monitoring and leak detection are crucial for sustainable water management. Different techniques have been developed to identify, locate and monitor leaks in water supply systems. This section discusses some of the various techniques that are used in the water management systems.

Acoustic Leak Detection

Acoustic leak detection is a non-invasive diagnostic technique that utilises high-sensitivity hydrophones or piezoelectric vibration sensors to identify and localise pipeline breaches by analysing the high-frequency acoustic emissions generated by turbulent fluid flow escaping under pressure. Leaks generate specific acoustic signals due to the turbulence and pressure differences, which can be captured and analysed to locate leaks (Softdig, 2025). While effective, acoustic methods can be influenced by ambient noise, pipe material, and soil conditions. Differentiating between leak sounds and other environmental noises remains a challenge, necessitating advanced signal processing techniques.

Drone and Aerial Imaging

Drones equipped with thermal or infrared cameras can survey large areas to detect surface anomalies caused by subsurface leaks. This method is particularly useful in inaccessible or hazardous locations (Softdig, 2025). Drone-based detection is limited by flight time, weather conditions, and regulatory constraints. Additionally, interpreting aerial imagery for leak detection requires specialised analysis.

Smart Water LoRa IoT System

The Smart Water Long Range (LoRa) IoT system enables continuous monitoring of water distribution

Article DOI: https://doi.org/10.37284/eaje.8.1.3344

networks. It integrates both wired and remote identifiers for data collection, supports data analysis and provides users with timely access to water quality information. The system includes an ultrasonic water meter that helps detect leaks and promotes efficient water usage. Someone to monitor the water network continuously. According to Wang J. et al (2018), the system also incorporates artificial intelligence to enhance leakage detection and pinpoint leak locations. While the use of artificial intelligence improves performance, the overall system is expensive to implement due to its reliance on multiple IoT technologies, although similar results could be achieved with more affordable flow sensors (Islam et al, 2023).

Micro-Electro-Mechanical System Hydrophone Sensor for Water Pipeline Leak Detection

J. Xu et al (2019) employed an invasive ultrasonic hydrophone sensor, developed using micro-electromechanical systems (MEMS) technology, to detect leaks in water pipelines. Time-frequency domain analysis of transient pressure waveforms and their corresponding spectrographic representations revealed that the MEMS-based hydrophone offered advantages in both sound sensitivity and energy efficiency compared to standard commercial hydrophones. However, for accurate leak detection, the leak must be located between two hydrophones. Additionally, signal attenuation due to the type of pipe material and the distance between sensors can lead to transmission loss, increasing the risk of false leak alerts.

Smart Method to Detect Leaks (Vibratory sensors)

Fabbiano et al (2020) developed a method that uses vibratory signals to identify and locate leaks within distribution pipelines. This approach involves attaching sensors directly to the pipe infrastructure to capture changes in radial train, which may indicate the presence of leaking water. The system detects variations in energy transmitted through the pipe walls, associated with leakage activity. However, the system must be positioned very close to the leak source for accurate detection.

Internet of Things

The concept of Internet of Things (IoT) basically refers to the collection of networks with interconnected devices, sensors, and systems that can collect, exchange, and act on data, analysing, enabling easy integration of the physical and digital spaces. IoT is used for various domains which include smart cities, smart homes and buildings, traffic management, waste disposal and management, and water management. IoT technologies and innovations enable automation and optimisation of energy use, security systems, and other key functions, driving enhanced efficiency and convenience for occupants. IoT has revolutionised water monitoring by revealing data collections in real time, analysis and programmable logic-directed operation of water distribution systems. IoT integrates sensors, microcontrollers, wireless communication and cloud computing to create smart networks that detect leaks, monitor water quality and optimise distribution (Gubbi et al., 2013).

The effectiveness of data transmission in IoT depends on the choice of communication technology, protocols with different methods offering distinct advantages for various deployment scenarios. IoT uses different communication protocols like the hypertext transfer protocol, its secure version (HTTP/HTTPS), which is used for IoT devices to communicate with servers, especially in web-based applications. However, they may not be suitable for devices with limited resources due to their higher overhead (ResearchGate, 2023). Other protocols like MQTT, CoAP and AMQP may be used for IoT communication.

Effectiveness also depends on the network technologies employed. Short-range wireless technologies like Wi-Fi and Bluetooth Low Energy (BLE) provide high bandwidth connections suitable for urban deployments with reliable power supplies.

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Wi-Fi offers fast data transfer rates but consumes significant power, making it less ideal for battery operated-sensors. BLE, with its low power consumption, is suitable for indoor applications but suffers from limited range. For wider area coverage, Low-Power Wide-Area Network (LPWAN) technologies like LoRa WAN and NB-IoT have gained prominence. LoRaWAN's sub-GHz frequencies enable communication over long distances in rural areas while maintaining years-long battery life, though at lower data rates. NB-IoT leverages existing cellular infrastructure for reliable connectivity in urban environments, offering a balance between range, power consumption, and data throughput (Hunaidi O. and Chu W, 1999).

Existing System in Harare

The city of Harare lacks the required technologies to detect leaks remotely and has mostly relied on manual leak detection. The manual inspection method includes regular visual checks for wet patches or pipe bursts, mostly in areas prone to leaks (Makaya & Hensel, 2014). In Harare, residents of a particular area report to authorities when a pipe burst has occurred in that area**.** This method has proven to be very time-consuming and ineffective, as leaks may not be reported immediately, and they may be reported after a few days, during which a significant amount of water would have been lost.

The mWater application which is a mobile-based water monitoring platform is also used by field workers when a report has been made. It allows for field data collection using a smartphone and mapping water points. This helps authorities identify areas which are prone to pipe bursts which lead to leakages. It relies on manual input which leads to delays and does not have leak detection capabilities.

During a site visit at Marimba, it was informed that the Supervisory Control and Data Acquisition (SCADA) system has been used by the city for remote monitoring of water levels, pressure and flow rates. The system also allows for data logging from pumping stations and reservoirs. However, this system has proven to be very costly as it requires extensive sensor networks. The system also has limited real-time analysis as data is often reviewed periodically rather than instantaneously. It is dependent on power and internet, which are currently a challenge due to persistent load shedding in Zimbabwe.

Field Visits

The research was conducted on site visits to locations in the city of Harare in areas where pipe bursts occur, for the possible installation of the system.

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Figure 1: Site Visit at Marimba

Figure 2: Site Visit at Madokero

This review highlights the evolution of water leakage detection from traditional manual methods to complex IoT-enabled systems. While each technology offers distinct advantages, none provides a perfect solution. The most promising developments combine multiple sensing approaches with advanced data analytics, though challenges remain in making these solutions affordable and easy to maintain. The proposed system in this research project builds upon these foundations while addressing key gaps in real-time processing and practical utility integration. As water scarcity concerns grow worldwide, continued innovation in leak detection technologies will play a significant role in sustainable water management.

INTERPRETATION AND DISCUSSION

This project aims to design and deploy a real-time water leakage detection system prototype capable of accurately identifying and localising leaks within water distribution networks. The system will integrate pressure, flow, and acoustic sensors to monitor pipeline conditions, employing advanced signal processing techniques to analyse sensor data and detect leak signatures with a target accuracy of at least 85%. An IoT-based network will enable seamless real-time data transmission to a centralised monitoring platform, complemented by an intuitive web interface that provides instant alerts, detailed analytics, and visualisations to expedite maintenance responses. Ultimately, the system will be integrated into Harare’s existing water management infrastructure, targeting a 20% reduction in non-revenue water (NRW) within the first year of deployment and a 50% improvement in leak response times, thereby enhancing operational efficiency and sustainability.

Concept of Design

The proposed IoT-based water leakage detection system employs a multi-sensor approach combined with real-time data analytics to identify and locate leaks in water distribution networks. The methodology followed includes hardware selection and integration, system programming, communication setup, web development, and PCB design. The proposed system architecture comprises three functional layers: a sensing layer, which incorporates distributed sensors to acquire hydraulic data from the water distribution network; a network layer, employing microcontrollers to aggregate and transmit sensor data via wireless communication protocols; and an application layer, featuring a web-based dashboard that visualizes real-time sensor

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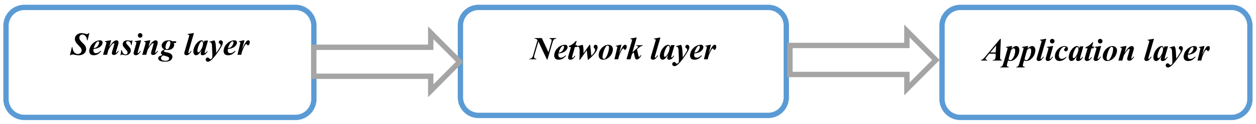
readings and leakage alerts, enabling operational monitoring and decision-making

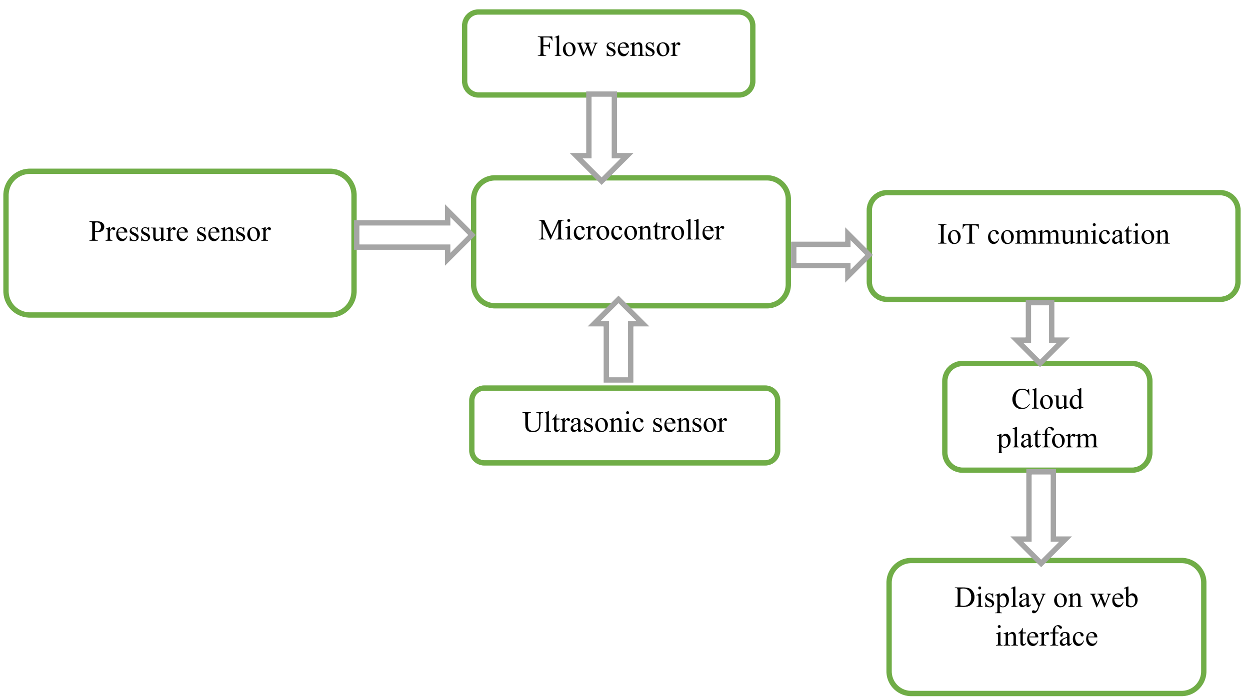


Basic Working Principle of the System:

Water flow sensors are strategically positioned to monitor flow rates within the distribution network, while ultrasonic sensors track water levels in supply tanks. These sensors interface with a microcontroller, which aggregates and transmits the collected data to a centralised database via a secure communication protocol. The database feeds into a restricted-access web interface, available only to authorised personnel, enabling real-time monitoring of system performance. In the event of anomalous sensor readings, the interface triggers alerts, signalling potential leaks and facilitating prompt intervention.

Block Diagram

Below is a block diagram for the system. It shows the flow of data from the sensors to the data being displayed on the web interface.



Hardware Components for Prototype

ESP32 Dev Module

The core microcontroller integrates dual-core processing capabilities with built-in Wi-Fi and Bluetooth. The ESP32 is responsible for reading data from the connected sensors, processing the data, and transmitting it over Wi-Fi to a web interface for real-time monitoring. It was selected due to its affordability, support for the Arduino IDE, and integrated wireless capabilities.

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Water Flow Sensors (YF-S201)

This sensor operates using a Hall-effect mechanism that produces digital pulses proportional to the water flow rate. These pulses can be easily read and interpreted by the ESP32. It measures the rate of water flow through different sections of the pipe network. The sensor provides reliable, real-time flow rate data. Anomalies in flow rates indicate possible leakages.

This sensor works by emitting ultrasonic waves and measuring the time taken for the echo to return after bouncing off the water surface. It provides a non-contact method for determining water levels inside or above pipe sections or a supply tank. This complements the flow sensor data. The choice of using this sensor is based on its easy availability on the market as well as its vast documentation of literature. Moreover, it is easy to interface.

Circuit Diagram

Initially, a circuit schematic diagram and a PCB were designed in EasyEDA, intended to integrate the ESP32 chip and a SIM7080G NB-IoT module for long-range communication in real-world deployments. However, due to financial constraints, the schematic and the PCB could not be ordered and manufactured. As a result, the researcher used locally available components for the prototype, that is, the ESP32 Dev Module. Despite the absence of NB-IoT, the system still effectively demonstrates real-time leakage monitoring capabilities using available resources. The circuit that was then used was designed and Proteus and it was for the ESP32 dev module.

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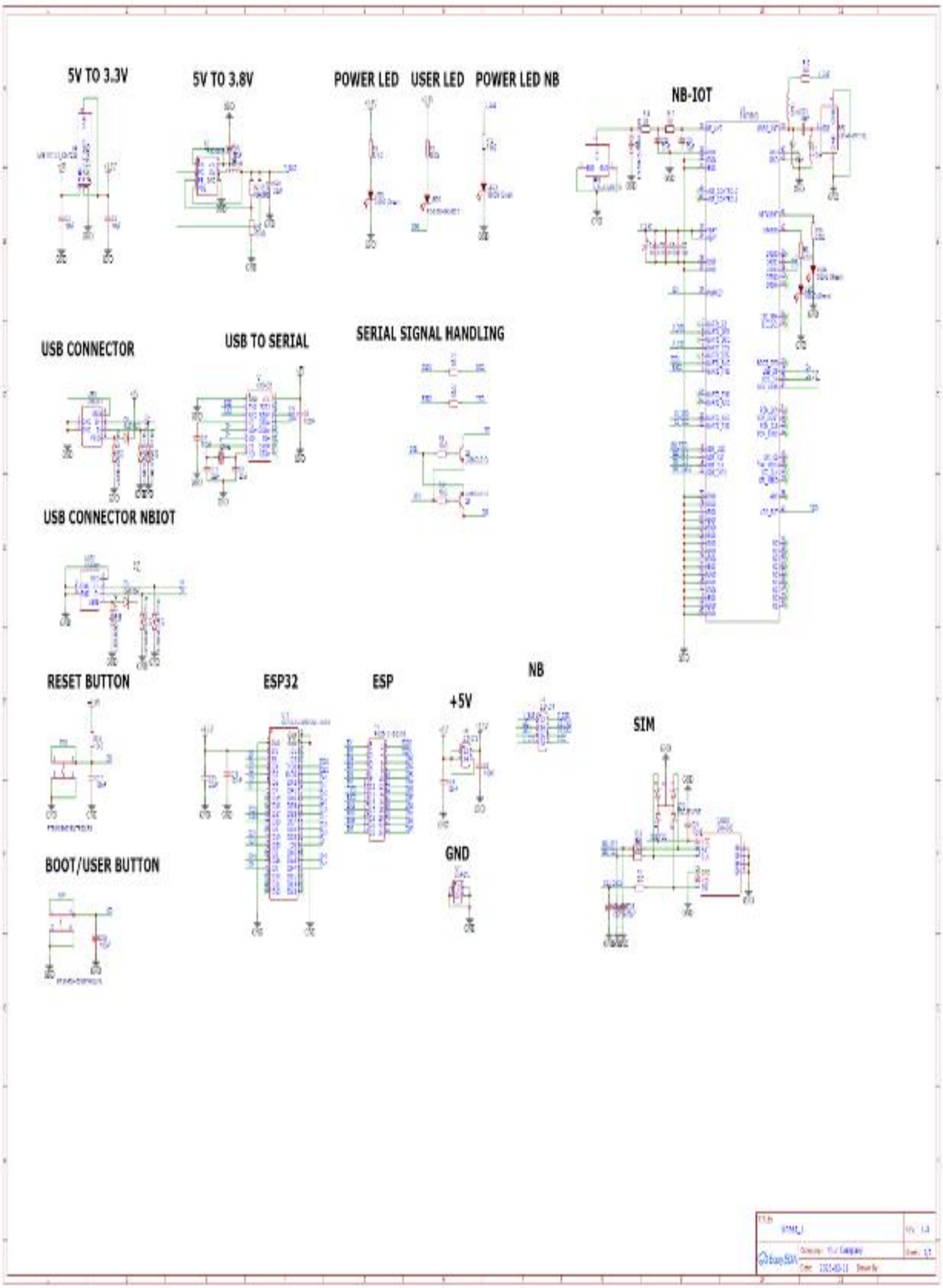
Figure 3: PCB Designed in EasyEDA



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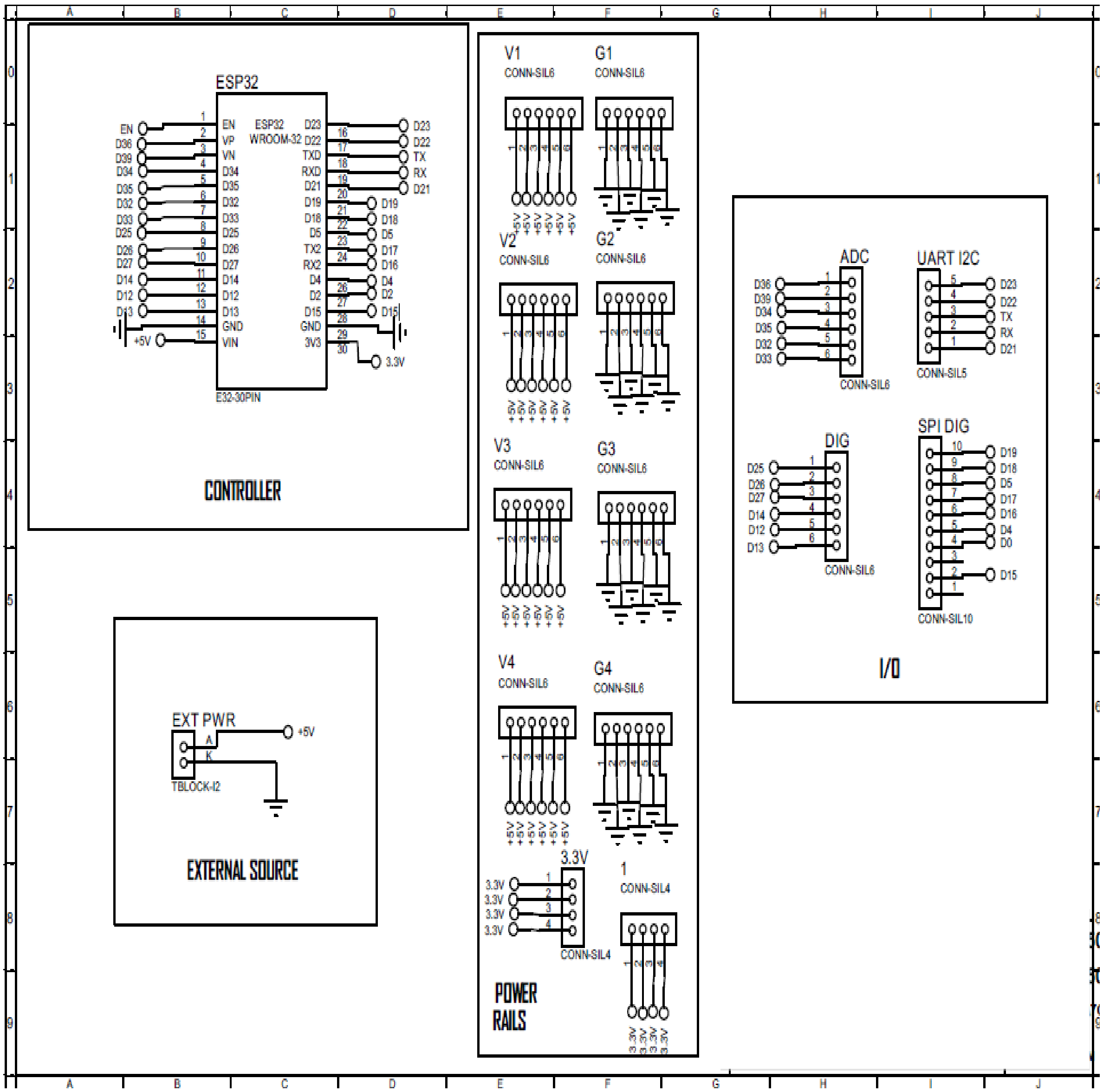


Software Development

The software development component for the real-time water leakage detection system was carried out in two stages.

Programming the ESP32

Arduino programming platform IDE accommodates writing, compilation and uploading of the embedded C/C++ code that runs on the ESP32. This code handles essential tasks such as reading data from the water flow and ultrasonic sensors, processing sensor signals, packaging data into a structured format and transmitting the data via the ESP's built-in wi-fi module to a web server in real time. The transmission was implemented using standard HTTP POST/GET requests, with the data structured in JSON format to ensure compatibility and efficiency. The ESP32 was programmed to perform continuous monitoring and detect abnormal water flow patterns or water level changes that might indicate leakage. The code includes libraries for the SIM800 GSM module as an alternative way

East African Journal of Engineering, Volume 8, Issue 1, 2025
Article DOI: https://doi.org/10.37284/eaje.8.1.3344

if one wants to get notified on their mobile phone. Below is the code on the ESP32.

Web Interface Development

On the server side, a MySQL database was set up to store incoming data from the ESP32. A server-side script, written in PHP, was used to insert the real-time sensor data into the database. Another backend script was responsible for fetching the most recent data from the database at short intervals and returning it to the client browser in real time. This formed the middle layer of the system architecture that links the microcontroller with the web interface.

The front end of the web interface, which was developed using HTML, CSS, and JavaScript within Visual Studio Code, is responsible for displaying the data in a user-friendly format. JavaScript, often with the help of the Fetch API, regularly requests updated sensor readings from the server-side script. This allows the dashboard to reflect real-time changes without requiring the user to manually refresh the page. The dashboard displays flow rate, water level status, and leakage alerts, allowing users to monitor the pipeline in real time.

PRESENTATION OF RESULTS

3D Circuit Diagram

Below is the 3D version of the circuit that was designed by the researcher. The first one is the 3D model for the circuit that was designed in EasyEDA and could not be ordered due to financial constraints.

Figure 5: 3D Model of the Circuit Designed in EasyEDA

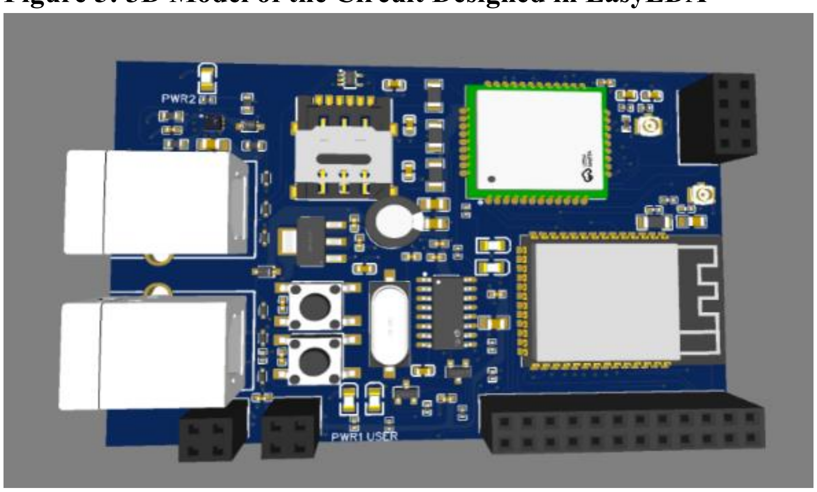
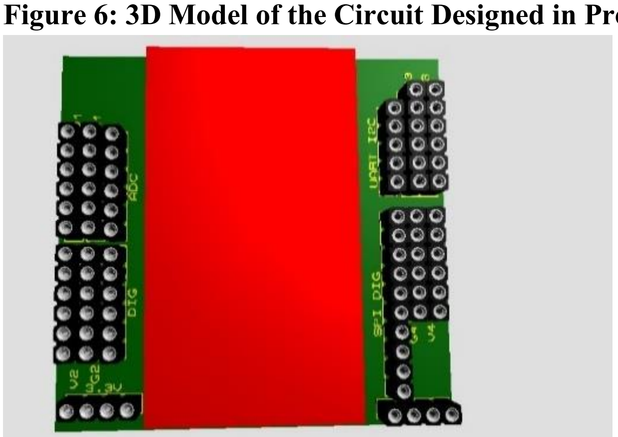


Figure 6: 3D Model of the Circuit Designed in Proteus



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The second one is the alternative 3D model of the circuit that the researcher used in the prototype and it was designed in Proteus.

Web Interface

Below is an image that shows the web interface that displays real-time sensor data and visually indicates the presence of a leak using status alerts. The effective use of the visual on the dashboard is to make it easy to interpret, perform data analysis and to easily automate and control the water network.

Figure 7: Web Interface Before Leak is Detected

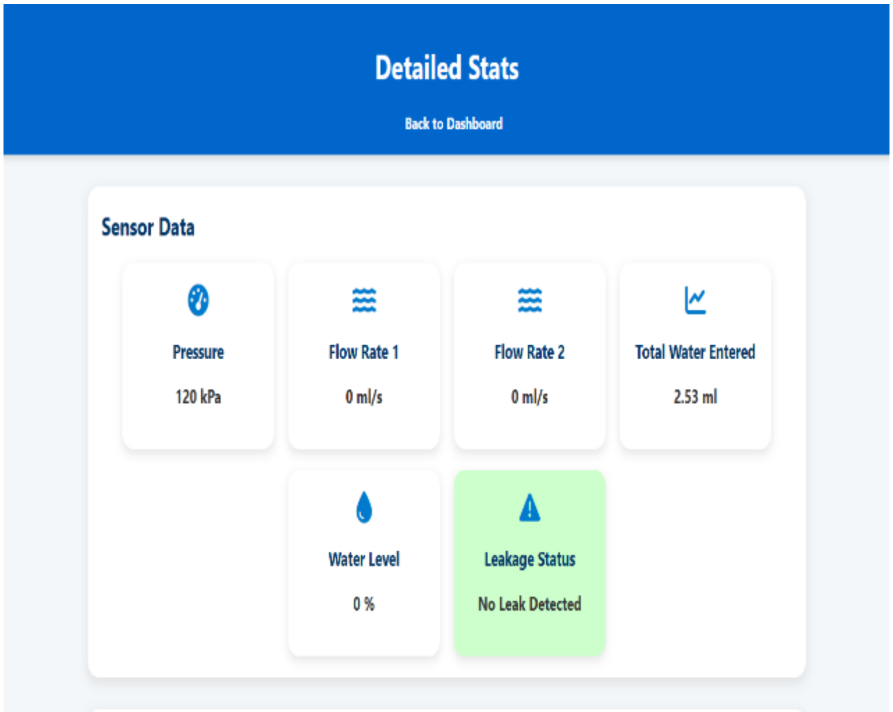

Figure 8: Web Interface After Leak is Detected

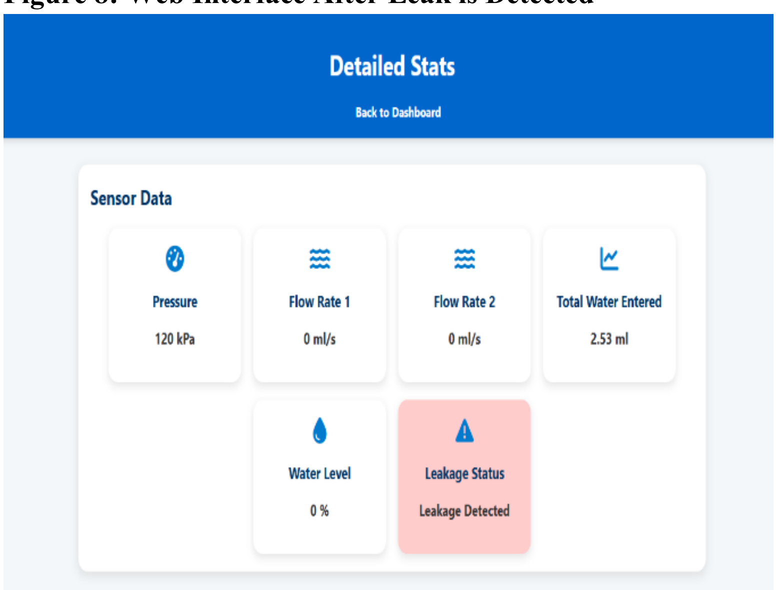

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Figure 9: Graph of Flow Rate Over Time

System Integration

All hardware and software components were successfully integrated. Water flow and level data were monitored live on the dashboard, with leakage scenarios simulated and accurately detected by the system.

Figure 10: System Integration

Implementation of the System

The system was successfully installed at Madokero. Below are the actual materials used for implementation and the images after the successful installation

System Specifications

- 350W solar panel.
- 12/24V solar charge controller (ITF)
- 12V, 100ah Polaris LiFePO4 battery.
- Ultrasonic clamp on flow meter set (display unit; M2 clamp on transducers) [T-Measurement].
- 0-10bars line pressure sensor (Huaibei Automation).
- 4/5G Telemetry unit (Tenda mobile wi-fi, 2.4GHz)

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Figure 11: Ultrasonic Clamp

Figure 12: Functional System

Figure 13: Solar Panel

The impact of the prototype is to easily detect water leaks, informing the control room of further action.

CONCLUSION

The development and implementation of a real-time water leakage detection system using low-cost, IoT-enabled technologies has proven to be a feasible and impactful solution for addressing water losses in urban infrastructure like Harare's. The developed prototype achieved the core objective of real-time leak detection, and the software system was able to display alerts and sensor data through a user-friendly dashboard. While financial constraints prevented the integration of pressure sensors and NB-IoT connectivity, the system still demonstrated reliable detection of leaks through changes in flow rate and water levels. Overall, the project addressed multiple goals, including system integration, real-time communication, and interface usability, offering a foundation for reducing non-revenue water and improving response times to leakage events. In addition, the system can adopt the use of narrowband Internet of Things to improve range, reliability and energy efficiency of data transmission. It can integrate signal processing algorithms or machine learning models that could refine the system's ability to distinguish between normal variations and actual leak events, increasing detection accuracy and minimising false alarms. For higher detection accuracy and the ability to pinpoint leak locations, it is recommended to use advanced machine learning to improve the precision of the water rationing network. These would enhance leak signature analysis and improve system precision.

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