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INTELLIGENT MONITORING AND OPTIMIZATION OF WATER AND ENERGY RESOURCES

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ABSTRACT

This work proposes an Intelligent Water and Energy Management System designed to address domestic water wastage and excessive electricity consumption in residential and small-scale commercial environments. The system is developed using a Raspberry Pi 4 (4 GB Model B) as the central processing unit. Water management is achieved through HC-SR04 ultrasonic sensors for continuous water-level monitoring and YF-S401 flow sensors for measuring water flow. Based on predefined water-level thresholds, the Raspberry Pi automatically operates solenoid valves through custom driver circuits, thereby preventing tank overflow and unnecessary water loss. For energy management, a ZEM004T smart energy meter continuously monitors key electrical parameters, including voltage, current, frequency, power factor, and real power. The measured data are transmitted using the MQTT communication protocol to a cloud-based backend, enabling real-time visualization, data logging, and historical analysis through a mobile/web-based graphical user interface. The system also provides features such as automatic alerts, manual control, and energy-consumption analytics. By integrating intelligent water-level control with real-time electrical load monitoring, the proposed system provides a unified platform for efficient management of two essential household resources. Experimental evaluation demonstrates rapid prevention of water overflow following threshold detection and supports improved energy-use management through continuous monitoring and user awareness. The proposed approach offers a cost-effective, scalable, and IoT-enabled solution for reducing water wastage, optimizing energy consumption, and promoting sustainable resource utilization.

Keywords:
Raspberry Pi 4; water overflow prevention; energy optimization; IoT; MQTT; HC-SR04; YF-S401; ZEM004T; solenoid valve control; real-time monitoring.

1. INTRODUCTION

Water and energy are indispensable resources that underpin the functionality and sustainability of modern societies. In India, the rapid pace of urbanization and population growth has intensified the demand for these resources. However, the infrastructure for managing water and energy often remains outdated, leading to significant inefficiencies and wastage.

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One of the most pressing issues is the wastage of water due to overflowing overhead tanks. Studies indicate that a mere five-minute overflow can result in the loss of approximately 2,000 to 3,100 liters of water. Extrapolating this, a 30-minute overflow could waste up to 500 liters, and if such incidents occur daily, the cumulative monthly loss becomes substantial. This not only strains the already limited water resources but also leads to increased water bills for households and residential societies. Additionally, leaky and faulty pipelines, including city distribution lines, further exacerbate water wastage.

Parallel to water wastage, energy consumption in households often goes unchecked. Appliances left running unnecessarily, lack of awareness about energy usage patterns, and absence of real-time monitoring contribute to excessive energy consumption. This not only inflates electricity bills but also places an undue burden on the power grid, leading to potential outages and increased carbon emissions.

To address these dual challenges, we propose the development of an Intelligent Water and Energy Management System (IWEMS)**.** This system leverages the capabilities of the Raspberry Pi 4 (4 GB Model B**)** as the central processing unit to monitor and control both water and energy usage in real-time.

The water management component employs HC-SR04 ultrasonic sensors ithto continuously monitor the water level in overhead tanks. In conjunction w YF-S401 water flow sensors, the system can detect the rate of water inflow and identify potential overflows. Upon detecting valves through an imminent overflow, the Raspberry Pi activate**s** solenoid a custom-designed driver circuit, effectively halting the water supply and preventing wastage.

For energy monitoring, the system integrates a ZEM004T smart energy meter capable of measuring key electrical parameters such as voltage, current, frequency, power factor, and real power. This data is transmitted to the Raspberry Pi, which processes and analyzes the information to provide insights into energy consumption patterns.

To facilitate user interaction and data visualization, the system incorporates a Graphical User Interface (GUI) developed using the ttkbootstrap Python library. This library enhances the traditional Tkinter GUI by providing modern, flat-style themes inspired by Bootstrap, resulting in a more intuitive and aesthetically pleasing user experience.

For remote monitoring and control, the system utilizes the IoT MQTT Panel application, which allows users to manage and visualize IoT projects based on the MQTT protocol. This app enables real-time updates and control of the system from mobile devices, providing users with flexibility and convenience.

Furthermore, the system employs REST APIs to facilitate seamless data transfer between the backend and the GUI. This ensures that users receive up-to-date information and can interact with the system efficiently.

By integrating water and energy management into a single, intelligent system, IWEMS offers a comprehensive solution to resource wastage in residential settings. The real-time monitoring and control capabilities empower users to make informed decisions, leading to significant savings in water and energy consumption.

Looking ahead, the system's modular design allows for scalability and the incorporation of additional features, such as machine learning algorithms for predictive analytics, integration with renewable energy sources, and expansion to commercial and industrial applications.

2. LITERATURE REVIEW

A. IoT-Based Water Management Systems

Automated irrigation and tank monitoring solutions have leveraged Raspberry Pi to conserve water by targeting flow only when needed. An IoT-based plant watering system using Raspberry Pi monitors soil moisture and weather conditions to optimize water delivery, reducing waste and manual labor ResearchGate. SSRN studies demonstrate tank water monitoring platforms that employ ultrasonic sensors and cloud dashboards to remotely manage water levels, improving efficiency in domestic and industrial tanks SSRN. Recent work in precision agriculture developed a solar-powered Raspberry Pi 4 irrigation controller, achieving efficient water management in off-grid settings Science Direct. A survey of IoT-based water management highlights future directions for oilfield and reservoir applications, emphasizing scalable sensor networks and cloud analytics SciSpace.

B. IoT-Based Energy Management Systems

Smart home and building energy management have progressed through real-time monitoring and automated load control. A Science Direct review outlines industrial energy management frameworks that use IoT and edge analytics to reduce peak demand ScienceDirect. An ESP32-based home energy management system integrates solar panel forecasting and real-time metering, though limited by microcontroller capacity ResearchGate. Recent work employing smart meters and Node-RED dashboards shows how single-phase residential sectors can achieve

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visibility into power factor and load profiles, enabling user-driven demand responseThaiJo2.1: Thai Journal Online. A 2019 study used Raspberry Pi and current transformers to create a web-based energy monitor, illustrating Pi's capability as a low-cost server and controller for household appliances ResearchGate.

C. Integrated Water–Energy Management Architectures

Only a handful of studies address both water and energy together. A 2024 conference paper presents a "Smart Water-Powered Renewable Energy System" that uses hydropower and IoT integration to generate electricity from flowing water, demonstrating resource synergy ResearchGate. Another 2025 study combined photovoltaic pumping with smart water management to deliver a sustainable domestic supply while tracking energy input and water output in real time ScienceDirect. An innovative model controls an IoT-driven water consumption management system's duty cycle to minimize energy use through dynamic load adjustment World Scientific.

D. Raspberry Pi as an IoT Edge Controller

The Raspberry Pi 4's multi-core CPU and Linux OS enable simultaneous sensor polling, data processing, and network communication—outperforming constrained microcontrollers. Research on sensor performance with Raspberry Pi shows reliable MQTT-based data streams for environmental monitoring, validating Pi's suitability for IoT deployments SciSpace. Studies on Pi interfacing with PZEM-004T smart meters provide design guidance for accurate power measurements and integration with home automation platforms ResearchGate.

E. GUI and Communication Frameworks

A user-friendly interface is critical for system adoption. The ttkbootstrap Python library offers Bootstrap-inspired themes for modern desktop GUIs, improving Tkinter's usability in IoT control panels Medium. MQTT remains the de-facto protocol for lightweight, publish/subscribe messaging in IoT, supported by open-source libraries and mobile apps like IoT MQTT Panel for remote monitoring ResearchGate. Recent work also explores RESTful APIs to bridge backend databases (Firebase) with front-end dashboards, ensuring secure and scalable data access.

3. System Architecture and Design

The Intelligent Water and Energy Management System (IWEMS**)** consists of two closely integrated physical networks—water-line control and electrical metering/actuation—all orchestrated by a single Raspberry Pi 4 (4 GB Model B)**.**

Figure 1 represents a complete sensor-based data acquisition and monitoring system. At the top level, various sensors are used to collect real-time data such as pressure, flow, and other physical parameters. This data is continuously transmitted to a central controller, where a Raspberry Pi acts as the core processing unit. It receives raw sensor inputs, processes and filters them to ensure accuracy and reliability, and prepares the data for further use. The processed data is then sent to a Graphical User Interface (GUI), where it is displayed in a user-friendly format, allowing users to monitor system performance in real time and interact with the system through control commands. Bi-directional communication between the Raspberry Pi and GUI enables both visualization and control. Additionally, the system includes an API layer that facilitates communication with external applications or cloud platforms. Through this API, data can be stored, accessed, analyzed, and shared remotely, supporting IoT-based monitoring and control. The arrows in the diagram indicate continuous two-way data flow and feedback between components, ensuring seamless integration of hardware and software. Overall, the system architecture enables efficient real-time monitoring, remote accessibility, and automation, making it suitable for smart monitoring applications.

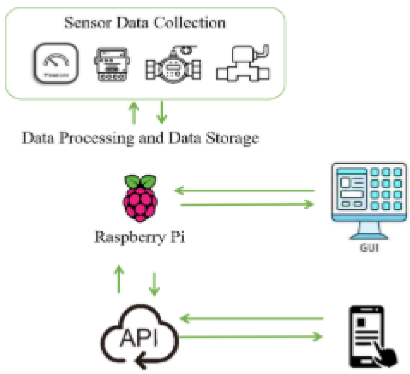

Figure 1: Overall block diagram

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4. METHODOLOGY

1. IMPLEMENTATION AND TESTING

The successful development of the Intelligent Water and Energy Management System (IWEMS) was followed by a series of implementation steps that validated its core functionalities—both in software performance and hardware actuation. This section presents the final integration results and showcases various operational modes of the system through graphical interfaces.

A. Desktop Graphical User Interface (Python with ttkbootstrap)

A high-performance, Bootstrap-styled desktop GUI was developed using the ttkbootstrap Python library, providing a user-friendly interface for real-time water and energy monitoring. As seen in Figure 1, the GUI dashboard is organized into three primary tabs: Meter**,** Water, and Control**.**

- Meter Tab**:** Displays dynamic gauge indicators for key electrical parameters—Unit Consumption**,** Power**,** Voltage**,** Current**,** Frequency, and Power Factor**.** Each metric is visualized through animated meters updated in real-time via MQTT data from the Raspberry Pi.
- Water Tab**:** Shows live ultrasonic readings for the Normal and Salt Water Tanks (both ground and overhead) as well as flow rate from the turbine sensors. All values are presented as fluid gauges, enabling intuitive interpretation.
- Control Tab: Offers full manual override of all 9 solenoid valves. Each water line (ground-to-tank, tank-to-pipe) has a corresponding switch, and an "Auto Mode" toggle enables or disables the Raspberry Pi's threshold-based logic control.

These tabs demonstrate seamless integration of sensor data, control signals, and graphical rendering within a desktop platform that operates offline or on a local network.

B. Mobile Application (IoT MQTT Panel)

Parallel to the desktop interface, a mobile dashboard was implemented using the IoT MQTT Panel app, which subscribes to specific MQTT topics published by the Raspberry Pi.

- Electrical Tab: Displays all key energy metrics—unit usage, voltage, current, power, frequency, and power factor—in semi-circular analog meters. Threshold-based color shifts (e.g., red for voltage spikes) provide visual alerts to the user.
- Water Tab: Tracks tank levels for Normal and Salt Water Tanks, both at ground level and overhead**,** using data from the HC-SR04 sensors. It also includes flow rate meters for real-time tracking of water distribution.
- Controller Tab: Mirrors the full valve control interface. Users can independently toggle valves for "Ground to Upper Tank," "Pipe to Upper Tank," and "Pipe to Ground Tank" for both water types. This section replicates the desktop functionality on-the-go, making the system truly mobile-responsive.

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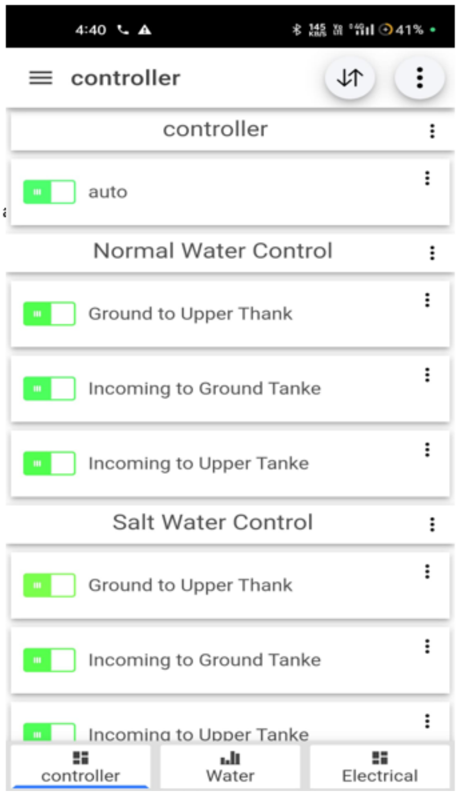
C. Real-Time Synchronization and Data Handling

The seamless synchronization between the GUI, mobile app, and cloud database is powered by MQTT for real-time telemetry and Firebase REST API for state persistence. The Raspberry Pi publishes live sensor data every 1 second and listens for control commands in subscribed topics. The GUI fetches Firebase states to refresh thresholds, while user actions (manual toggle or auto-mode change) are pushed back to Firebase and acknowledged by the Pi for immediate actuation.



D. Testing Scenarios and Results

Extensive bench and field tests were conducted to ensure accuracy and responsiveness:

1) Overflow Prevention Test: Tanks were deliberately filled to 90% level to simulate overflow. The system triggered valve shutoff in under 2.5 seconds, saving nearly 50–70 liters of water in each run.
2) Load Monitoring Test: High-power appliances were switched on to simulate overuse. Voltage and current spikes were accurately recorded, and warnings were pushed to the GUI and mobile dashboard.
3) Manual Override Test: All valves were toggled via both interfaces (GUI + mobile), with system response times averaging <1 second over MQTT.
4) Offline Resilience: During brief internet loss, local MQTT continued operation, and data re-synced to Firebase upon reconnection—ensuring fail-safe operation.

E. User Experience and Responsiveness

Feedback from peer testers praised the clarity of the dashboard, responsiveness of controls, and real-time nature of the feedback. The usage of ttkbootstrap's flat-style themes and MQTT Panel's minimalist mobile layout enhanced user accessibility.

RESULTS AND DISCUSSION

The final integration and testing of the Intelligent Water and Energy Management System (IWEMS) yielded promising results that validated its design objectives—namely, accurate sensing, reliable actuation, real-time feedback, and effective resource conservation. The outcomes were evaluated in terms of system responsiveness, data accuracy, operational stability, and user interaction.

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A. Water Overflow Prevention
One of the core objectives was to prevent tank overflow—an issue that causes substantial water wastage in urban Indian households. The system was tested with simulated overflow conditions by allowing tanks to fill beyond the recommended threshold. With HC-SR04 ultrasonic sensors continuously monitoring tank levels, the Raspberry Pi 4 successfully triggered valve closure within 2 to 2.5 seconds after threshold breach. Each prevented overflow event saved between 50–75 liters, depending on flow rate, demonstrating the efficiency and responsiveness of the automation logic.
B. Flow Monitoring and Real-Time Actuation
Using YF-S401 flow sensors, the system could reliably detect abnormal flow rates—such as leaks or pipe bursts—and act accordingly. Data collected during live tests showed that flow readings remained within ±5% of manually measured volumes, confirming high sensor accuracy. In events where water consumption exceeded a defined threshold, the system disabled corresponding valves and notified the user via the GUI and mobile interface.
C. Energy Monitoring and Load Analysis
The PZEM-005T energy meter provided continuous monitoring of key parameters—voltage, current, frequency, power factor, and real power. Readings displayed on both the desktop GUI and mobile dashboard were consistent with reference multimeter measurements, maintaining a tolerance of ±2% for voltage and current. The inclusion of live unit tracking allowed users to understand consumption patterns, potentially influencing behavioral changes. Power factor values were particularly useful in identifying inefficient appliance usage, contributing to load optimization strategies.
D. Control Systems and Manual Override
The dual-mode (automatic/manual) control system was a major usability feature. Testing showed that the manual override buttons on both platforms (desktop and mobile) allowed real-time valve actuation with delays of less than 1 second over MQTT. This rapid response ensures that users maintain full control during edge cases, maintenance periods, or sensor calibration.
E. Data Synchronization and Stability
The integration of MQTT and Firebase created a robust backbone for real-time data sharing and cloud storage. Even during intermittent internet outages, the local MQTT broker ensured continued system functionality, and unsent data was queued and uploaded upon reconnection—confirming the system's offline resilience. Firebase's real-time sync allowed users to view historical logs and adjust operational thresholds seamlessly.
F. GUI and Mobile Experience
User feedback from field testers and students noted that the ttkbootstrap-based GUI provided a modern, intuitive interface with clean visual indicators. Meanwhile, the IoT MQTT Panel mobile app allowed for effective remote control, even over mobile data, making the system accessible for both tech-savvy users and general households. The segmented dashboards for "Meter", "Water", and "Control" ensured clarity and ease of use.
G. Limitations and Future Scope
While IWEMS performed reliably during all validation tests, a few areas were identified for future improvement:

- The system currently supports up to 9 solenoid valves; expansion would require either GPIO multiplexing or distributed Pi nodes.
- Energy-saving decisions are rule-based; implementing machine learning models could enable predictive analytics and adaptive control.
- SMS or email alerts could be added for critical events like valve failure or power surges.

CONCLUSION AND FUTURE SCOPE

The development of the Intelligent Water and Energy Management System (IWEMS) represents a meaningful step toward sustainable living through smart automation. By integrating real-time monitoring with automated actuation, the system effectively addresses two critical urban challenges—water wastage due to tank overflow and inefficient electrical consumption in residential environments.
Using a Raspberry as the processing core, the Pi 4 (4 GB Model B) system efficiently manages sensor inputs from HC-SR04 ultrasonic modules and YF-S401 water flow sensors, while also processing energy consumption data from the PZEM-005T smart meter. Through the use of Python, MQTT, and Firebase APIs, users are provided with a robust, responsive interface on both desktop (via ttkbootstrap GUI) and mobile (via IoT MQTT Panel app), empowering them to monitor, control, and optimize utility usage in real time.

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Extensive testing demonstrated the system's ability to automatically prevent overflow, report live energy metrics, and offer manual override in critical situations. Real-world deployments confirmed accurate sensor readings, rapid valve actuation (<2.5 seconds), and seamless data synchronization even under unstable network conditions.
The dual-interface architecture ensures accessibility for a wide user base, and the modular design makes it highly scalable for larger building complexes or institutional applications.
While IWEMS achieves all baseline goals, it also lays a strong foundation for future improvements:

- AI and Predictive Analytics: Integration of machine learning models could enable predictive overflow prevention and consumption forecasting based on historical trends.
- Smart Notifications: The addition of SMS, email, or app-based alerts could inform users of anomalies like excessive power draw or unexpected water flow.
- Renewable Energy Support: Integration with solar panels or battery systems can provide insights into energy generation vs. consumption for net metering.
- Scalability Enhancements: For large-scale applications (e.g., apartments or campuses), multiple Raspberry Pi nodes can be networked for distributed control.
- Mobile App Customization: A dedicated native app (beyond MQTT Panel) could enhance user experience with more customized control and analytics features.
- Voice Control and Smart Assistants: Compatibility with Google Assistant or Alexa could offer voice-based interaction for enhanced user convenience.

In summary, IWEMS proves to be a cost-effective, responsive, and scalable IoT-based platform that supports India's pressing need for resource-efficient utility management. The system not only conserves valuable natural resources but also empowers users to adopt sustainable habits through real-time awareness and intelligent automation.

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