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Smart Metering System for Water Distribution in Rural Areas

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Abstract

Water scarcity and inefficient distribution remain major challenges in rural areas due to manual monitoring and uncontrolled consumption. This research proposes a Smart Metering System for Water Distribution in Rural Areas, which integrates IoT-based automation to improve water management. This system features an automated overhead tank management module that monitors water level and controls the pump, ensuring optimal distribution while notifying Public Works Department (PWD) officers. A consumption-based billing mechanism, employing flow sensors, measures individual household usage, and generates accurate bills. The smart solenoid valve control regulates the flow of water to domestic tanks based on real-time levels, preventing waste. In addition, a dashboard for PWD officers provides real-time monitoring of tank level, pump status, and household consumption patterns. The system also incorporates automated notifications to inform household about water usage and billing, while alerting PWD officers about important issues. This approach ensures efficient water distribution, reduces waste, and improves transparency in rural water management.

Keywords: Smart Metering, IoT-based water management, consumption-based billing, automated tank control, solenoid valve regulation, real-time monitoring and rural water distribution.

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1. Introduction

Water scarcity and inefficient distribution system poses significant challenges in rural areas, where manual monitoring methods often lead to overuse, wastage, and supply inconsistencies. Many rural communities rely on intermittent water supply, where water distribution is regulated by local authorities but lacks real-time monitoring and automated control [6-8]. Without an efficient management system, it becomes difficult to ensure equitable water distribution, track individual consumption, and prevent excessive usage. Traditional water distribution system depends on manual intervention for overhead tank monitoring and billing, leading to inaccuracies and delays in consumption tracking. Additionally, unregulated water flow results in losses due to overflow, leakage, and unauthorized usage. The absence of automated billing mechanisms further complicates fair distribution, as households are often charged based on fixed rates rather than actual consumption [9-11].

To address these challenges, this research proposes a Smart Metering System for Water Distribution in Rural Areas, integrating Internet of Things (IoT) technologies for real-time monitoring, consumption-based billing, and automated control. The proposed system consists of:

- **Automated Overhead Tank Management –** Monitors water levels, controls the pump, and sends status notifications to Public Works Department (PWD) officers
- **Consumption-Based Billing –** Measures household water usage using flow sensors and generates accurate bills
- **Smart Solenoid Valve Control –** Regulates water flow to domestic tanks based on their level, preventing overflow and wastage
- **Dashboard for PWD Officers –** Provides real-time monitoring of tank levels, pump status, and household consumption
- **Automated Notifications –** Sends water usage updates, billing information to households, and alerts PWD officers about critical issues

By implementing this IoT-based smart metering system, rural communities can achieve efficient water distribution, prevent excessive consumption, and improve transparency in water management. The system not only reduces water wastage but also enables authorities to make data-driven decisions for sustainable resource allocation.

2. Literature Review

Water distribution systems have been a significant area of research due to the growing demand for efficient water management. Many studies have proposed various IoT-based solutions to address water distribution issues, focusing on smart metering, flow control, and monitoring.

Ibrar et al. [1] proposed a design for Smart Water Metering, Flow Control, and Quality Measurement System using IoT communication. Their system aims to optimize water distribution by measuring water quality and controlling flow with the help of smart meters, thus improving efficiency and reducing water wastage. This study highlights the importance of integrating IoT in water management to enhance real-time monitoring and control.

Ipseeta et al. [2] presented a Design and Real-Time Implementation of Smart Water Management using LabVIEW and IoT. Their system combines hardware and software to monitor water consumption and automate control processes, which significantly improves the overall water management in rural and urban areas. The real-time implementation ensures that water usage is accurately tracked, and control measures are applied effectively.

Irmansyah et al. [3] developed a Water Distribution Monitoring System for regional drinking water companies, leveraging IoT technology to monitor the distribution system in real-time. The system ensures better coordination between departments and timely identification of issues related to water supply, leading to more efficient resource allocation.

Swarnapali et al. [4] explored a Real-Time Synchronized Monitoring system to track water consumption and detect leaks in the urban water supply of Sri Lanka. By integrating IoT and synchronized monitoring, their solution improves leak detection and water consumption tracking, significantly reducing wastage and improving supply reliability.

D. Devasena et al. [5] proposed an IoT-based Water Distribution System that automates water distribution and optimizes the supply. The system uses sensors and control mechanisms to monitor the water levels, detect faults, and regulate the water supply, reducing manual intervention and ensuring a more efficient system.

These studies demonstrate the significant potential of IoT technologies in addressing challenges in water distribution, metering, and quality monitoring. However, challenges remain in integrating these solutions into rural water systems where infrastructure limitations exist. This research builds upon these findings to propose a smart metering system specifically designed for rural water distribution.

3. System Architecture

The block diagram in Figure 1 illustrates the proposed IoT-based water management system using an ESP32 microcontroller for real-time data acquisition and control. The system includes automated overhead tank management using an ultrasonic sensor and relay-controlled pump, and a consumption-based billing mechanism using flow sensors to track household usage. Smart solenoid valves prevent overflow by regulating water flow based on tank level. Data is transmitted through MQTT and visualized on a real-time dashboard for Public Works Department (PWD) officers. The system also sends automated notifications about low water level, pump failures, and abnormal consumption, enhancing efficiency and transparency in rural water distribution.

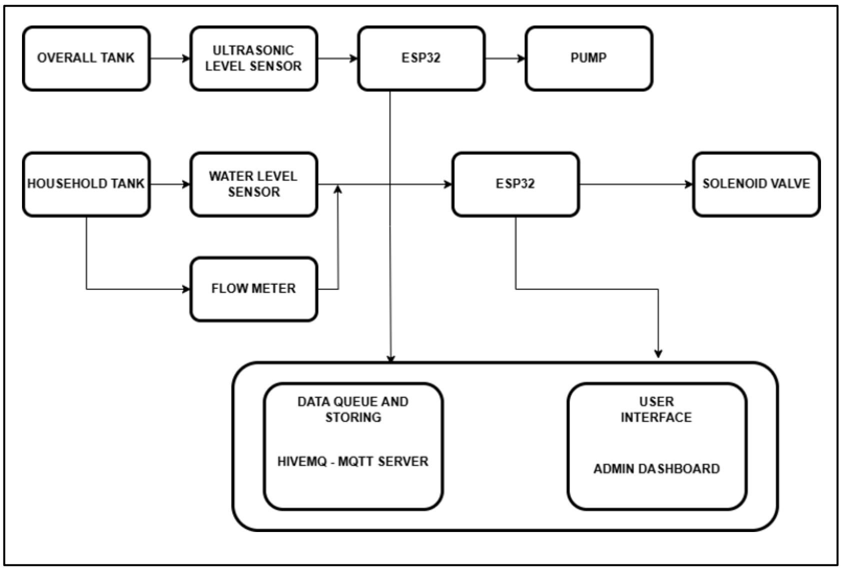

Figure 1. Block Diagram of the Proposed Smart Water Metering System

3.1 Methodology for Overhead Tank

The proposed system in Figure 2 automates overhead tank management using an ESP32 microcontroller, ultrasonic sensor, and a cloud-connected dashboard. The ESP32 monitors real-time water level and controls the pump based on predefined thresholds activating it when the level is low and turning it off when full to prevent overflow and reduce manual intervention. Collected data is transmitted to the cloud, allowing PWD officers to monitor tank status remotely. The system also provides automated alerts via SMS or mobile app for low levels, pump failures, or abnormal fluctuations, ensuring transparency and timely response.

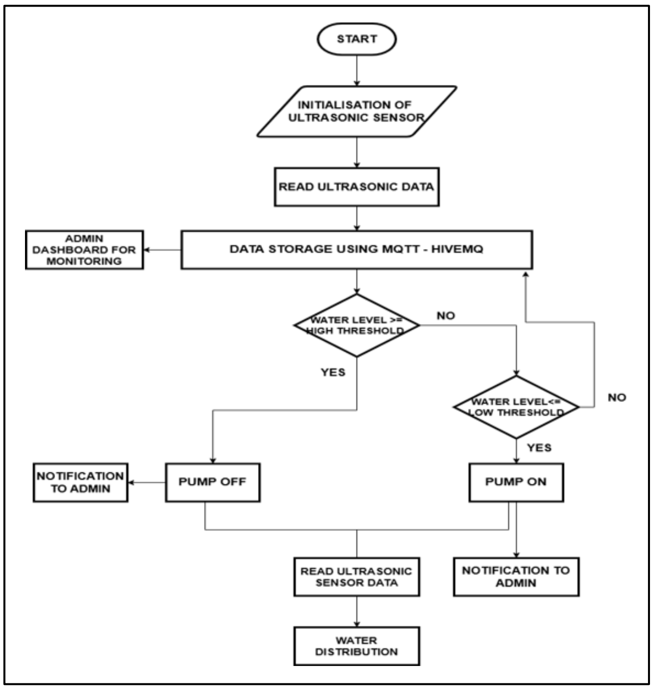

Figure 2. Methodology of Overhead Tank

3.2 Methodology for Domestic Tank and Consumer Billing

The domestic water management system in Figure 3 automates water distribution and billing at the household level. Each unit includes a domestic tank, flow sensor, and solenoid valve, all controlled by an ESP32. The valve opens or closes based on tank level, preventing overflow, while the flow sensor tracks consumption. The ESP32 calculates usage and generates bills according to predefined tariffs, sending the details via SMS and displaying them on a dashboard. This IoT-based solution ensures fair billing, reduces wastage, and supports sustainable water management.

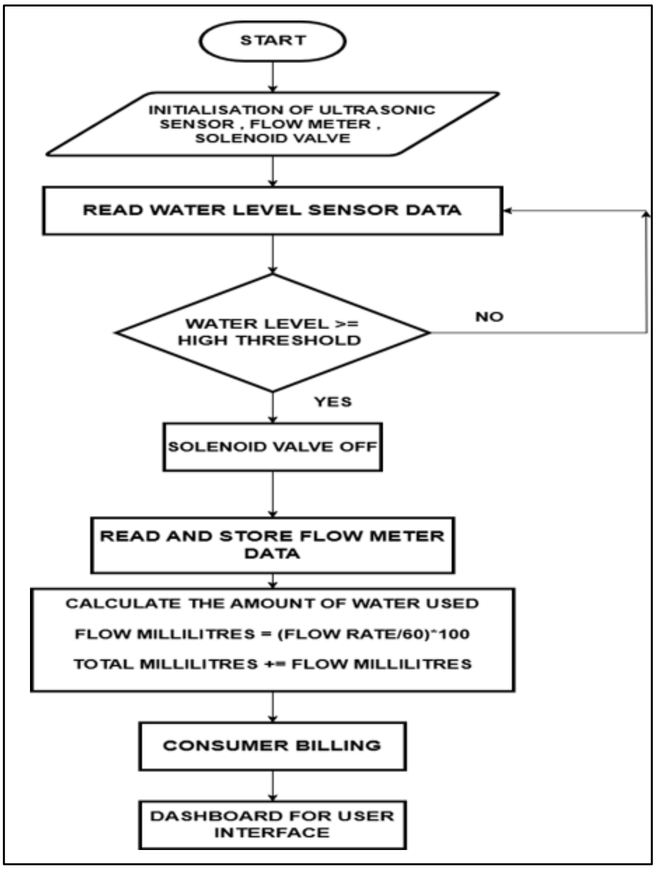

Figure 3. Methodology for Domestic Tank

4. Software Implementation

The software implementation of the proposed smart water metering and management system utilizes a combination of programming environments and technologies. These include the Arduino IDE for ESP32 programming, Node.js for data transmission to the MQTT server, and Next.js for designing the user interface. Each software component plays a vital role in ensuring the smooth operation of the system, providing users and Public Works Department (PWD) officers with real-time data and control.

4.1 Arduino IDE and Embedded C Programming

The ESP32 microcontroller is programmed using the Arduino IDE, which provides a user-friendly platform for developing control logic in Embedded C. It enables precise handling of sensor data and actuator control, allowing seamless automation of water distribution processes based on real-time input.

4.2 Node.js and MQTT Communication

Node.js serves as the backend framework for managing communication between the ESP32 microcontroller and the server. Its event-driven architecture supports scalable handling of multiple ESP32 devices, enabling easy expansion of the system. Node.js transmits data to the MQTT-based HiveMQ Cloud, ensuring real-time updates on water usage, tank levels, and pump status for monitoring, analysis, and accurate billing.

4.3 User Interface (Dashboard)

The system's dashboard is built using Next.js as shown in Figure 4, a React-based framework that enables dynamic, real-time interaction and server-side rendering. Designed for both consumers and PWD officers, the dashboard displays live data on water levels, pump status, and household consumption. It also provides billing details and automated alerts for critical events. By leveraging MQTT-based real-time updates, the interface ensures accurate visualization to support efficient decision-making and water management.

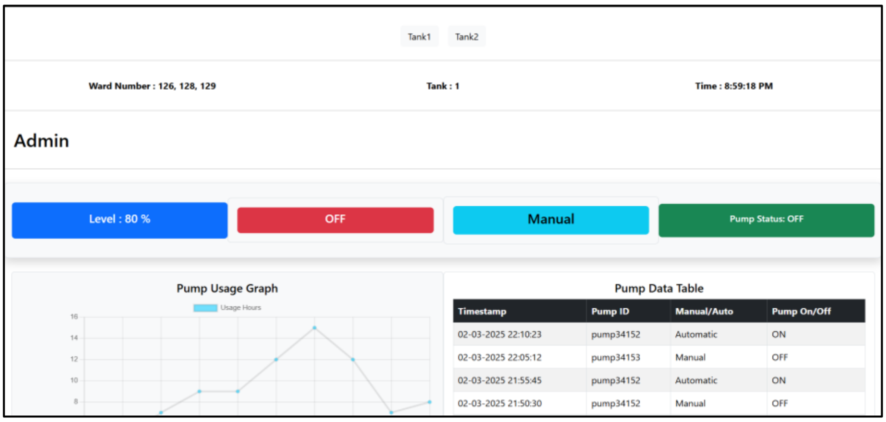

Figure 4. Web Dashboard for User Interface

4.4 Mobile Notification System

To enhance user engagement and promote transparency, the system integrates the Circuit Digest Messaging Service for real-time SMS alerts as shown in Figure 5. Data from the flow sensor, processed by the ESP32 and transmitted through MQTT using HiveMQ, triggers automated messages to households. Notifications include consumption volume and billing amount. This eliminates manual billing, reduces errors, and encourages responsible water usage. The messaging service improves communication, automates notifications, and adds a user-friendly layer to the system, making it efficient and scalable for deployment in both rural and urban areas.

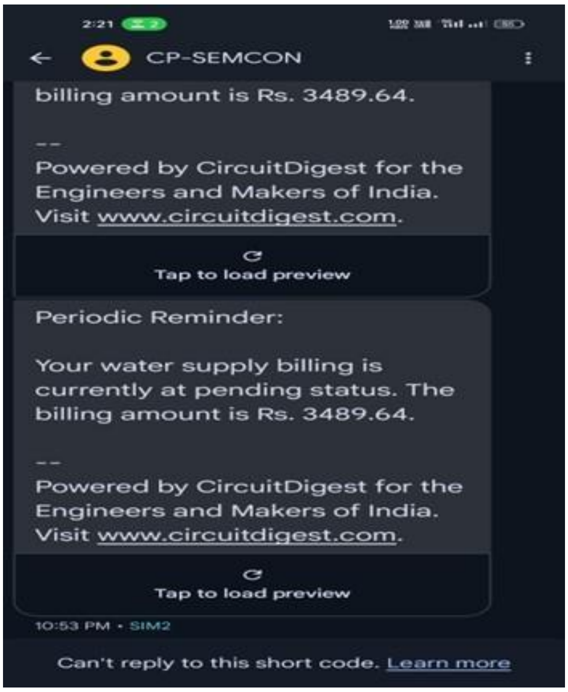

Figure 5. Mobile Notification Message

4.5 Integration of Software Components

The seamless integration of these software components ensures the efficient functioning of the system. The Arduino IDE is used to program the ESP32, which interfaces with hardware components like sensors and valves. The data from the microcontroller is sent via Node.js to the MQTT server, where it is stored and processed. The Next.js based dashboard retrieves this data and presents it to users in a visual format, enabling real-time monitoring and billing. This combination of software technologies creates a robust, scalable, and efficient system for water distribution and consumption management.

5. Results and Discussion

This section presents the implementation and performance of two integrated IoT-based modules overhead tank automation and household-level water monitoring using ESP32, sensors, and cloud services.

5.1 Overhead Tank Monitoring and Control

The overhead tank system shown in Figure 6 uses an ultrasonic sensor and ESP32 microcontroller to automate pump control based on water level. When the water level falls below a set threshold, the ESP32 activates the pump through a relay, turning it off once the tank is full.

Figure 6. Hardware Setup for Overhead Tank

Real-time water level and pump status are transmitted to the HiveMQ Cloud through MQTT, allowing Public Works Department (PWD) officers to monitor tank status on a dashboard developed with Next.js shown in Figure 7 and 8. The software backend, built using Node.js and PostgreSQL, ensures reliable data management and control logic. Socket.io integration enables instant updates and alerts, enhancing responsiveness. This system prevents overflow, reduces manual intervention, and ensures uninterrupted supply.

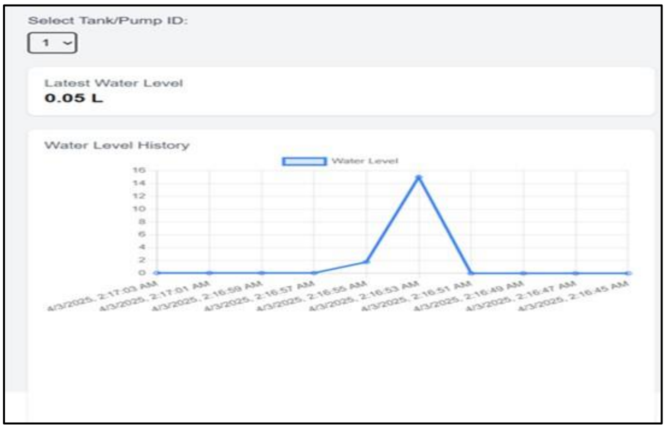

Figure 7. Dashboard for Level Monitoring in Overhead Tank

Latest Pump Status

ON

Pump Logs

Timestamp	Pump ID	Status
4/3/2025, 2:17:03 AM	1	ON
4/3/2025, 2:17:01 AM	1	ON
4/3/2025, 2:16:59 AM	1	ON
4/3/2025, 2:16:57 AM	1	ON
4/3/2025, 2:16:55 AM	1	ON
4/3/2025, 2:16:53 AM	1	OFF
4/3/2025, 2:16:51 AM	1	ON
4/3/2025, 2:16:49 AM	1	ON
4/3/2025, 2:16:47 AM	1	ON
4/3/2025, 2:16:45 AM	1	ON

Figure 8. Dashboard for Pump Status Indication in Overhead Tank

5.2 Household Monitoring and Billing System

Each household unit is equipped with a water level sensor, flow sensor, and solenoid valve controlled by an ESP32 shown in Figure 9. The system ensures that water is supplied only when needed, preventing wastage.

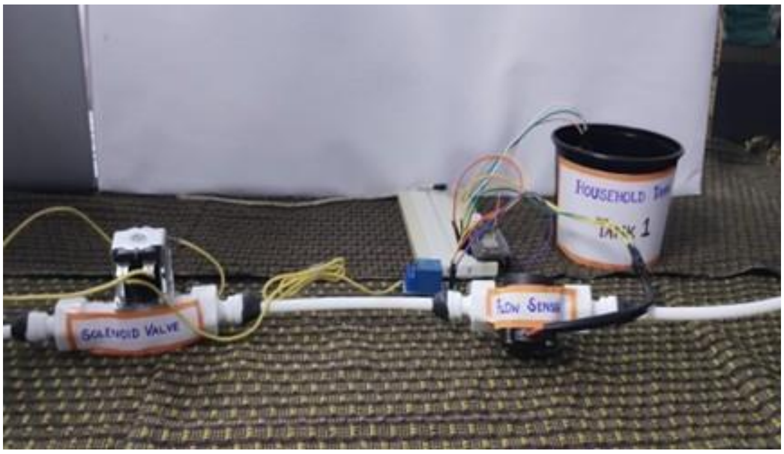

Figure 9. Hardware Setup for Household Tank

Consumption data from the flow sensor is used to calculate bills, which are displayed on a real-time dashboard shown in Figure 10. MQTT protocol ensures efficient data transmission, while Node.js and PostgreSQL manage backend operations, billing, and data storage. The Next.js-based interface provides households with transparent consumption details and alerts. Socket.io ensures low-latency communication and immediate feedback.

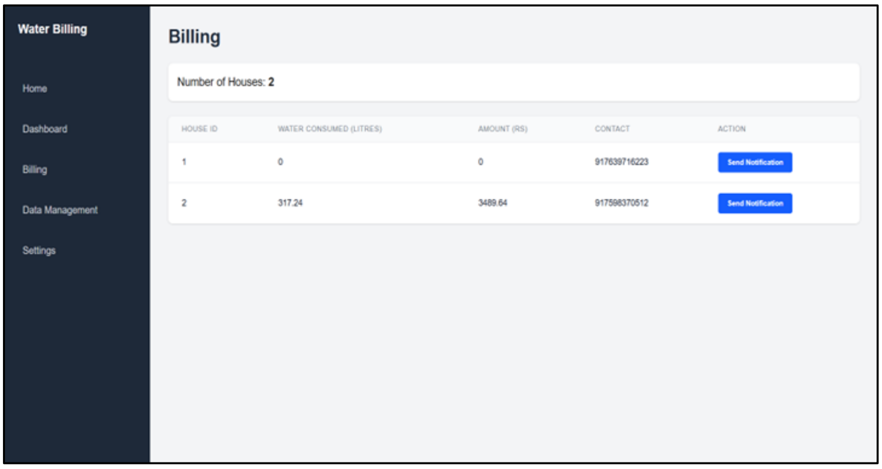

Figure 10. Dashboard for Billing Service

5.3 Scalability and Performance

Both systems are modular and scalable, allowing seamless addition of new households or tanks without structural changes. Node.js and MQTT handle concurrent data streams efficiently, ensuring the system remains responsive. Battery backup and solar power options ensure continuous operation in rural areas prone to power outages. Data reliability, automation accuracy, and real-time alerts collectively demonstrate the system's effectiveness in improving rural water distribution and conservation.

6. Conclusion

This study presents an IoT-based smart metering system for automated water distribution and billing, ensuring efficient water management for both public authorities and consumers. The proposed system continuously monitors overhead tank water level in real-time and provides automated alerts to the Public Works Department (PWD) officers, enabling timely interventions to prevent shortages and overflows. Additionally, the system automates the regulation of underground storage tanks for consumers, ensuring an uninterrupted water supply. Automated billing notifications based on individual water consumption simplify the payment process, enhance transparency, and improve user experience. By reducing manual intervention, minimizing water wastage, and streamlining billing operations, this system significantly enhances operational efficiency. Future enhancements, such as predictive analytics for demand forecasting and real-time leak detection, could further strengthen water conservation efforts and optimize resource utilization on a larger scale.

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