International Journal of Creative and Open Research in Engineering and Management
ISSN: 3108-1754 (Online)
Volume 02 Issue 09 September-2026 | Impact Factor: 3.5

IOT-Enabled Smart Water Management System for Multi-Household Residential Societies: Design, Implementation, and Experimental Validation

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How to Cite this Article:

Mhaiskar, P., Sonare, J. S., Khobragade, A. L., Ayate, H. S., Wanjari, C. V. & Patle, S. S. (2026). IOT-Enabled Smart Water Management System for Multi-Household Residential Societies: Design, Implementation, and Experimental Validation. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(9), 1-9. https://doi.org/10.55041/ijcope.v2i9.155

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Abstract

Water distribution within multi-unit residential housing societies is commonly unmetered, manually operated, and prone to overflow, dry-running, and undetected pipeline leakage. This paper presents the design, hardware implementation, and experimental validation of an ESP32-based IoT-enabled smart water management system that unifies non-contact ultrasonic overhead-tank automation, per-household turbine-based sub-metering with per-capita quota enforcement (135 L/person/day, as per BIS IS 1172:1993), differential mass-balance pipeline leak detection, solid-state IRFZ44N MOSFET actuation, and real-time analog Total Dissolved Solids (TDS) potability monitoring. Telemetry and control are exchanged over a full-duplex WebSocket server broadcasting 1 Hz JSON frames across a dual-mode (SoftAP + Station) Wi-Fi link to a mobile/web dashboard. A custom two-layer PCB was designed in KiCad and fabricated in-house, and the complete system was validated on a physical scale prototype of a two-household society. Experimental results show 0.0% level-measurement error after five-sample median filtering, flow-metering error within ±0.7% of the reference volume, and leak-isolation response within 1.2 s of an induced $|\Delta Q|$ = 1.4 L/min fault. The results confirm that the proposed architecture is a low-cost, cloud-independent, and scalable solution for automated, transparent, and conservation-oriented residential water management.

Keywords— Internet of Things; ESP32; smart water management; ultrasonic level sensing; flow sub-metering; leak detection; WebSocket telemetry; Total Dissolved Solids

I. INTRODUCTION

Rapid urbanization has shifted residential living from independent dwellings to high-density cooperative housing societies and apartment towers, where water received from municipal mains or borewells is collected in underground sumps, pumped to a shared overhead tank, and gravity-fed to individual flats. Because most societies lack per-flat sub-metering, municipal water charges and tanker costs are folded into a flat maintenance fee and divided equally among residents, removing any incentive for conservation — a textbook "Tragedy of the Commons." Overhead tank operation is typically left to manual supervision or mechanical float switches, both of which are prone to overflow, dry-running, and mechanical failure, while hidden pipeline fractures and loose joints cause silent, unmetered water loss.

This paper addresses these gaps with an ESP32-centric embedded IoT platform that automates overhead-tank level control, meters and rations household consumption, isolates pipeline leaks in real time, monitors drinking-water quality, and exposes all of this through a low-latency local WebSocket telemetry link — without dependence on a third-party cloud broker. The remainder of the paper is organized as follows.

Section II reviews related work. Section III presents the methodology, covering the system architecture, the governing mathematical models, the circuit and PCB implementation, the IoT communication architecture, and the fabricated physical prototype. Section IV reports and discusses the experimental results, and Section V concludes the paper and outlines the future scope.

II. LITERATURE REVIEW

The Bureau of Indian Standards (IS 1172:1993) fixes a domestic water-supply norm of 135 litres per capita per day (lpcd) for buildings with full flushing systems, and is adopted directly as the per-flat quota basis in this work [1]. Al-Khafaji and Al-Dhahir demonstrated an automated IoT metering architecture combining Hall-effect flow sensors with solenoid actuation for household-level water accounting [4], while Wadekar et al.

examined quota-based automated billing and shut-off strategies for shared residential supply [5]. For leak detection, Boorugu and Ramesh surveyed wireless-sensor-based pipeline monitoring techniques [6], and the PIPENET system of Stoianov et al. established sampling thresholds for localized rupture detection using differential flow measurement [7] — the same $Q_{in}-Q_{out}$ mass-balance principle adopted here.

Webster's sensor handbook [8] and Sydenham and Thorn [9] provide the theoretical basis for ultrasonic time-of-flight ranging and digital noise filtering used in the tank-level subsystem. WHO drinking-water guidelines [10] and the work of Barron and Ashton on electrochemical conductivity sensing [11] inform the TDS-based potability classification. Finally, the WebSocket protocol (RFC 6455) [12] is adopted over HTTP polling or MQTT to avoid external broker dependency while retaining full-duplex, low-latency (<50 ms) telemetry. Across this body of work, the individual building blocks — flow metering, level sensing, leak detection, and water-quality sensing — are well established in isolation; the gap this paper addresses is their unification into a single low-cost, solid-state-actuated, locally networked residential platform.

III. METHODOLOGY

A. System Architecture

The system is built around a dual-core ESP32-WROOM-32 microcontroller (240 MHz, 520 KB SRAM, 4 MB flash) that performs all sensor acquisition, quota computation, leak-detection logic, and network telemetry [2]. Figure 1 shows the five functional layers of the design: a power supply layer providing regulated 12 V and 5 V rails, an input sensor layer (ultrasonic, flow, and TDS sensors), the ESP32 central control unit, an output actuator layer (pump and solenoid valves via MOSFET drivers), and a mobile app/admin dashboard for monitoring and control.

Figure 1. System block diagram of the IoT-enabled smart water management platform.

B. Hardware Bill of Materials

Table I summarizes the principal components. An HC-SR04 ultrasonic sensor performs non-contact overhead-tank level sensing; three YF-S201 Hall-effect turbine sensors provide per-flat and leak-differential flow metering; a Gravity analog TDS probe monitors water potability; and two normally-closed 12 V solenoid valves together with a 12 V DC pump are switched through IRFZ44N power MOSFET stages [3] rather than electromechanical relays.

Table I: Key Hardware Components

Component	Part No.	Function
Main controller	ESP32-WROOM-32	Sensing, control logic, WebSocket server
Level sensor	HC-SR04	Overhead tank ultrasonic ranging (2–400 cm)
Flow sensors (×3)	YF-S201	Flat 1, Flat 2 inlet, Flat 2 pipe-end metering
Water quality sensor	Gravity Analog TDS	0–1000 ppm potability sensing
Actuators	12 V pump, 2× NC solenoid	Tank fill and per-flat supply cutoff
Switching stage	IRFZ44N MOSFET + 1N4007	Solid-state low-side actuation
Power supply	12 V/3 A SMPS + buck	12 V, 5 V and 3.3 V regulated rails

C. Ultrasonic Level Sensing and Median Filtering

The distance d from the HC-SR04 transducer to the water surface is obtained from the echo time-of-flight t_{echo} using the speed of sound in air (≈ 0.0343 cm/µs):

$$d\ (\text{cm}) = t_{echo}\ (\mu\text{s}) \times 0.01715 \quad (1)$$

To reject acoustic reverberation and surface-wave noise, five readings are captured every 5000 ms, sorted, and the median value is retained [8], [9]:

$$d_{tank} = \text{median}\{d_1, d_2, d_3, d_4, d_5\} \quad (2)$$

The calibrated tank level (in %) is then mapped between the empty distance d_{min} = 22.0 cm and the full distance d_{max} = 2.0 cm:

$$\text{Level}\ (\%) = [(d_{min} - d_{tank}) / (d_{min} - d_{max})] \times 100 \quad (3)$$

D. Volumetric Sub-Metering and Quota Enforcement

Each YF-S201 sensor generates pulses proportional to the instantaneous flow rate, with a calibration factor K_{factor} = 7.5 pulses/s per L/min:

$$Q\ (\text{L/min}) = f_{pulse} / K_{factor} \quad (4)$$

Over a 1.0 s integration window, the incremental and cumulative consumption volumes are:

$$V_{used}(t) = \Sigma\ [(Q/60) \times \Delta t] \quad (5)$$

For a household with M occupants and an emergency reserve V_{emerg}, the remaining daily quota is obtained from the BIS norm of 135 lpcd [1]:

$$V_{remain} = \max(0, (M \times 135.0 + V_{emerg}) - V_{used}) \quad (6)$$

E. Differential Mass-Balance Leak Detection

On the Flat 2 branch, an inlet sensor (Q_2) and a pipe-end sensor (Q_3) enable conservation-of-mass leak detection, following the differential-flow principle established in [7]:

$$\Delta Q_{leak} = Q_2 - Q_3 \quad (7)$$

A leak is flagged — triggering the alert LED and de-energizing Solenoid 2 — when Q_2 > 0.5 L/min and ΔQ_{leak} > 0.35 L/min simultaneously; otherwise the line is reported as normal.

F. TDS Potability Conversion

The 12-bit ADC voltage V_{in} = (ADC/4095) × 3.3 V from the TDS probe is converted to parts-per-million using an empirical, temperature-compensated cubic polynomial [11]:

$$TDS_{ppm} = (133.42V_{in}^3 - 255.86V_{in}^2 + 857.39V_{in}) \times 0.5 \quad (8)$$

Readings below 300 ppm are classified as safe for drinking, consistent with WHO guidance [10].

G. Circuit Design and PCB Implementation

The control-unit schematic (Figure 2) was designed in KiCad and is organized into three functional blocks. The communication section places the ESP32-WROOM-32 module with its status LEDs, boot/reset push-buttons, and UART header. The power section regulates the incoming 12 V barrel-jack supply down to 5 V (LM7805) and 3.3 V (AMS1117) rails for logic and sensor excitation. The driver section switches the pump and two solenoid valves using three IRFZ44N low-side N-channel MOSFETs, each with a series gate resistor and screw-terminal output header [15].

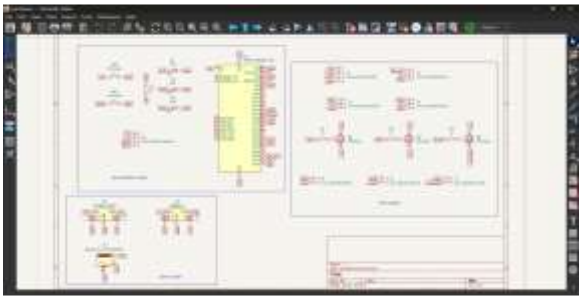

Figure 2. KiCad schematic of the ESP32 control unit showing the communication, power, and MOSFET driver sections.

A two-layer PCB (Figure 3) was routed for the control board, placing the ESP32 module centrally with sensor and actuator connectors along the board edges to minimize trace crossovers. The board was fabricated in-house and reflow/hand-soldered; the completed prototype (Figure 4) shows the copper routing for the sensor headers, MOSFET driver footprints, and regulator sections.

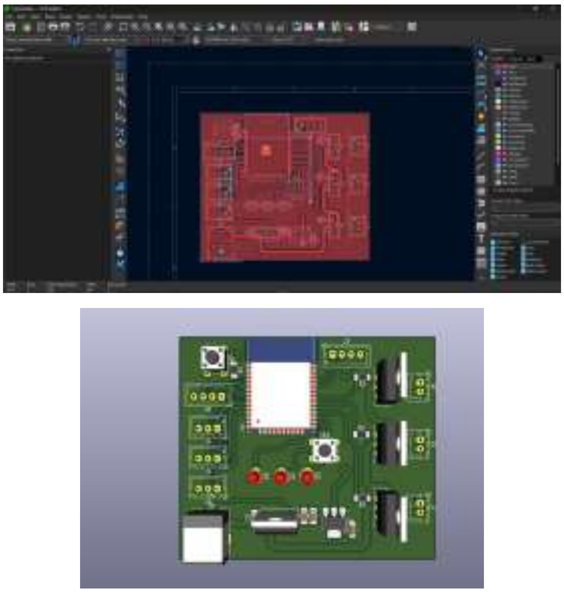

Figure 3. (a) PCB copper-layer routing in KiCad. (b) 3-D rendered view of the populated control board.

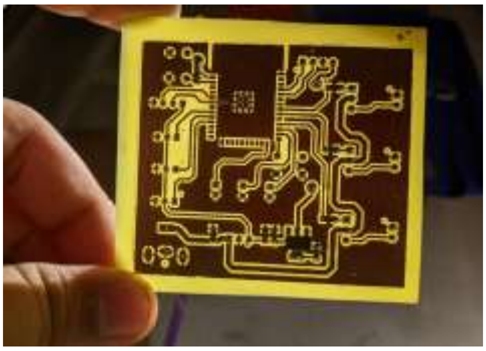

Figure 4. Fabricated control-unit PCB prior to component population.

The pump and solenoid valves are switched using IRFZ44N power MOSFETs in a low-side topology instead of electromechanical relays, eliminating contact arcing and bounce while giving sub-microsecond, wear-free switching. With $R_{DS(on)}$ = 17.5 mΩ and a 2 A load, the conduction loss is $P = I^2 R_{DS(on)}$ ≈ 0.07 W, so no heatsinking is required [3]. An anti-parallel 1N4007 flyback diode across each inductive load clamps back-EMF during turn-off, and a gate pull-down resistor prevents a floating gate at power-up.

H. Software and IoT Communication Architecture

The firmware initializes the ESP32 in WIFI_AP_STA mode. In SoftAP mode it broadcasts the SSID AquaSmart_System at

192.168.4.1 for direct offline field access; in Station mode it joins the society router via DHCP, printing the assigned IP address to the serial console on boot.

A persistent, full-duplex WebSocket server [12], [14] on port 81 broadcasts a JSON telemetry frame [13] once per second, containing tank percentage, pump and valve state, TDS reading, and per-flat usage, limit, remaining quota, flow rate, valve, and leak-status fields. A companion command protocol (LOGIN, REGISTER, CALIBRATE_EMPTY/FULL, START_DISPENSE, togglePump, toggleValve, emergency1, festivalOn/Off, and similar commands) allows the mobile/web dashboard to authenticate users, calibrate the tank, trigger preset or hold-to-pour dispensing, and grant emergency or festival overrides. User accounts, quotas, and tank calibration constants are retained in non-volatile (NVS) flash memory across power cycles.

I. Physical Prototype

A scaled physical model of a two-household society was fabricated to validate the complete system end-to-end (Figure 5). It comprises a labeled source tank and society overhead tank, a pump room, the ESP32 control unit enclosure, PVC plumbing risers feeding two representative houses (House-1 and House-2), and the associated flow-sensor and solenoid-valve hardware along each distribution branch.

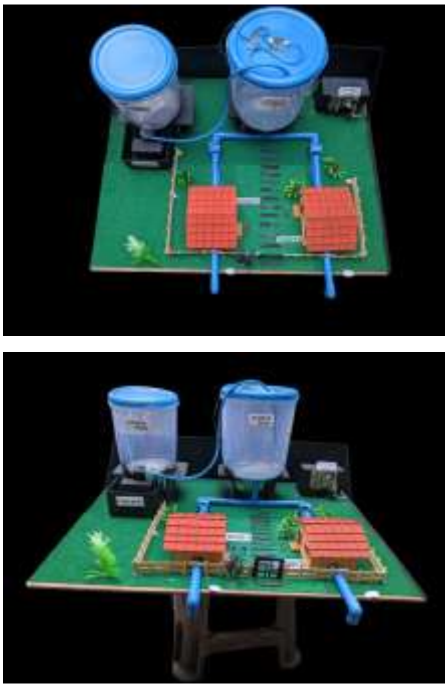

Figure 5. Physical working prototype of the two-household society water distribution model: (a) top view, (b) isometric view showing the source tank, society tank, control unit, and House-1/House-2 branches.

IV. RESULTS AND DISCUSSION

The complete system was assembled on an experimental flow bench comprising a source reservoir, a 22.0 cm overhead tank, the 12 V pump, two simulated flat distribution lines with YF-S201 sensors and solenoid valves, an inline leak-test valve, the TDS probe, and the ESP32/IRFZ44N control board.

A. Tank Level Calibration

The five-sample median filter suppressed acoustic reflection spikes, and the calibrated level readings matched the expected values with 0.0% error at all five test points from empty to full tank (Table II).

Table II: Ultrasonic Tank-Level Calibration

Water Height	Distance (d)	Measured Level	Error
Empty	22.0 cm	0.0%	0.0%
Quarter	17.0 cm	25.0%	0.0%
Half	12.0 cm	50.0%	0.0%
Three-quarter	7.0 cm	75.0%	0.0%
Full	2.0 cm	100.0%	0.0%

B. Flow Metering Accuracy

Dispensed volumes were cross-checked against a

calibrated beaker across 1 L, 2 L, and 5 L targets, yielding a percentage error within ±0.7% (Table III), confirming the accuracy of the pulse-integration model of (5).

Table III: Volumetric Flow Metering Accuracy

Target Volume	Pulse Count	Calculated Volume	Error
1.00 L	452	1.004 L	+0.40%
2.00 L	898	1.995 L	−0.25%
5.00 L	2265	5.033 L	+0.66%

C. Leak Detection, TDS, and Telemetry Performance

With an induced leak of ΔQ = 1.4 L/min (exceeding the 0.35 L/min threshold), the system latched the alert LED and de-energized Solenoid 2 within 1.2 s, halting further loss. WebSocket telemetry sustained a stable 1 Hz update rate with round-trip latency below 45 ms over local Wi-Fi, and the calibration constants and user credentials persisted correctly across repeated power cycles, confirming NVS retention.

D. Discussion

Taken together, the results indicate that the three measurement subsystems meet the accuracy requirements of residential-scale water accounting. The 0.0% level error confirms that median filtering of the ultrasonic echo, as recommended for time-of-flight ranging in [8] and [9], is sufficient to suppress surface-wave and reverberation noise without additional hardware. The sub-1% volumetric error places the turbine sub-metering within the tolerance expected of the Hall-effect metering approaches reported in [4] and [5], while the 1.2 s leak-isolation response demonstrates that the differential mass-balance criterion of [7] remains effective at the short pipe lengths typical of a housing society riser. Because telemetry is served locally over WebSocket rather than through an external broker [12], the measured round-trip latency stays below 45 ms and the platform continues to operate during internet outages, which is the principal practical distinction from the cloud-dependent architectures surveyed in Section II.

V. CONCLUSION

This paper presented the design, circuit implementation, and experimental validation of an ESP32-based IoT smart water management system that unifies overhead-tank automation, per-household sub-metering and quota enforcement, differential leak detection, solid-state MOSFET actuation, and TDS-based potability monitoring behind a local, cloud-independent WebSocket telemetry layer. Experimental results demonstrate accurate, jitter-free tank-level sensing, sub-1% flow-metering error, leak isolation within 1.2 s, and low-latency (<45 ms) real-time telemetry, validating the platform as a practical, scalable blueprint for water-conscious residential infrastructure.

Planned extensions include LoRaWAN connectivity for multi-tower deployments, on-device TinyML models for anomaly-based consumption profiling, solar-backed power for outage resilience, additional pH, turbidity, and chlorine sensing, and integration with UPI-based automated billing.

ACKNOWLEDGMENT

The authors thank the Department of Electrical Engineering, Tulsiramji Gaikwad Patil College of Engineering and Technology, Nagpur, for providing the laboratory facilities and technical support required for the fabrication and testing of the prototype.

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