



Development of a Water Tank Monitoring and Pump Control System Using ESP32 and the ThingsBoard Platform with Telegram Notifications at PDAM Kota Surabaya

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Abstract

Conventional water tank monitoring at PDAM Surya Sembada Kota Surabaya causes delayed information and risks of overflow or underflow. This study develops an IoT-based monitoring and automatic pump control system utilizing an ESP32 microcontroller, an HC-SR04 ultrasonic sensor, the ThingsBoard platform via MQTT, and Telegram notifications. A single ultrasonic sensor simultaneously derives water level, cylindrical volume, and flow rate ($Q = \Delta V / \Delta t$), eliminating physical flowmeters. Pump control is automated using two-threshold hysteresis logic. Experimental results demonstrate a water level measurement accuracy of 98.63% (MAE = 0.14 cm, $R^2 = 0.9998$). The derived flow rate was empirically validated against manual measurements, achieving 99.26% accuracy with an error of only 0.06 L/min. Telemetry latency averaged 0.53 seconds on ThingsBoard, while Telegram early warning alerts were delivered within 2.38 seconds. Furthermore, a three-layer security architecture successfully thwarted unauthorized access scenarios, and expert validation confirmed a 92.0% feasibility rate (Highly Feasible). Thus, the proposed system provides an accurate, robust, and cost-effective solution for municipal water distribution facilities.

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1. Introduction

Clean water is a basic human need that must be available on a sustainable basis [1]. In drinking water distribution systems, storage tanks serve as temporary reservoirs that ensure the continuity of supply to customers [2]. Therefore, reliable monitoring of tank conditions is a critical factor in supporting water distribution operations [3]. At Surya Sembada Regional Water Utility Company in Surabaya, reservoir condition monitoring is still conducted conventionally, meaning that real-time information on water levels cannot be obtained [2]. This situation has the potential to cause delays in detecting significant drops or rises in water levels, thereby increasing the risk of underflow, overflow, and disruptions to the continuity of water distribution [1], [2].

Advances in the Internet of Things (IoT) offer opportunities to improve the effectiveness of reservoir monitoring systems through the integration of sensors, microcontrollers, and network-based monitoring platforms [7]. Previous studies have developed water level monitoring systems using the ESP32 and ultrasonic sensors capable of displaying data in real time and automatically controlling pumps [8], [10], [24]. However, most of these studies still focus on household-scale or small-scale industrial applications using the Blynk platform, resulting in limitations regarding the visualization of historical data and scalability for large-scale operational needs such as those of municipal water utilities (PDAM) [4], [26], [29]. Furthermore, most studies only present water level information without processing it into other, more informative operational parameters [25], [27].

Given these conditions, this study proposes an IoT-based water tank monitoring and pump control system using the ESP32 and an HC-SR04 ultrasonic sensor, integrated with the ThingsBoard platform and Telegram notifications [8], [20], [22]. The system not only measures water level but also mathematically calculates water volume and flow rate based on sensor readings [13], [14]. This information is displayed via the ThingsBoard dashboard, local indicators such as an LCD, LEDs, and a buzzer, and is equipped with an automatic pump control mechanism using hysteresis logic and early warning notifications via Telegram when critical conditions are detected [16], [18], [19], [21].

The main contribution of this research lies in the integration of monitoring functions, the calculation of derived parameters, an early warning system, and automatic control within a single IoT architecture [7], [30]. Unlike previous studies, which generally required additional sensors to obtain flow rate information or only displayed a single measurement parameter, this research generates three main parameters water level, volume, and flow rate using a single HC-SR04 ultrasonic sensor through a mathematical approach [10], [13], [14]. This approach simplifies the hardware architecture while improving the efficiency of system implementation and maintenance [6], [8].

The developed system was implemented at the Putat Gede Distribution Center of Surya Sembada Regional Water Utility Company in Surabaya as a case study to support real-time monitoring and control of water distribution reservoirs [2]. This research is expected to improve operational reliability by providing more comprehensive information on reservoir conditions, an automatic pump control mechanism, historical data storage, and early warnings to operators [2], [20], [22]. Thus, this research contributes to the development of an IoT monitoring system that is better suited to the needs of industrial-scale water distribution infrastructure management [3], [7].

2. Methods

2.1. Methodology

This study employs an experimental research approach by developing an Internet of Things (IoT)-based water tank control and monitoring system [6], [7]. The system is designed to address the limitations of manual monitoring through real-time water level measurements, calculation of water volume and flow rate, automatic pump control, and data presentation both locally and online [3], [14], [23]. The research stages included a literature review, system requirements analysis, hardware and software design, system implementation using the ESP32 and HC-SR04 ultrasonic sensor, integration with the ThingsBoard platform and Telegram Bot, and testing of all system functions [6], [8], [20], [22]. Volume calculations were performed using the cylindrical volume equation, while water flow rate was calculated based on changes in volume over the measurement time interval [13], [14]. Sensor accuracy was evaluated by comparing the system readings to reference measurements using the percentage error [12]. All research stages were based on the concepts of the Internet of Things, sensor data processing, and quantitative evaluation methods previously used in prior research [7], [12], [13].

2.2. System Design

The system consists of three main subsystems: data acquisition, processing and control, and monitoring and notification [7], [28]. Data acquisition is performed using an HC-SR04 ultrasonic sensor mounted on top of the tank to measure the distance to the water surface [8], [10]. The sensor data is processed by the ESP32 microcontroller to calculate water level, volume, and flow rate based on the tank's dimensions [9], [13], [14]. The ESP32 then controls a relay to automatically operate the pump based on minimum and maximum water level thresholds [15], [16]. Monitoring data is transmitted via the MQTT protocol to the ThingsBoard platform for real-time visualization and storage as historical data [20], [32]. Additionally, the system sends automatic notifications via Telegram in the event of underflow, overflow, or changes in the pump's status [21], [22]. Local monitoring is supported by a 20×4 LCD, indicator LEDs, and a buzzer, allowing system status to be monitored both on-site and remotely [18], [19].

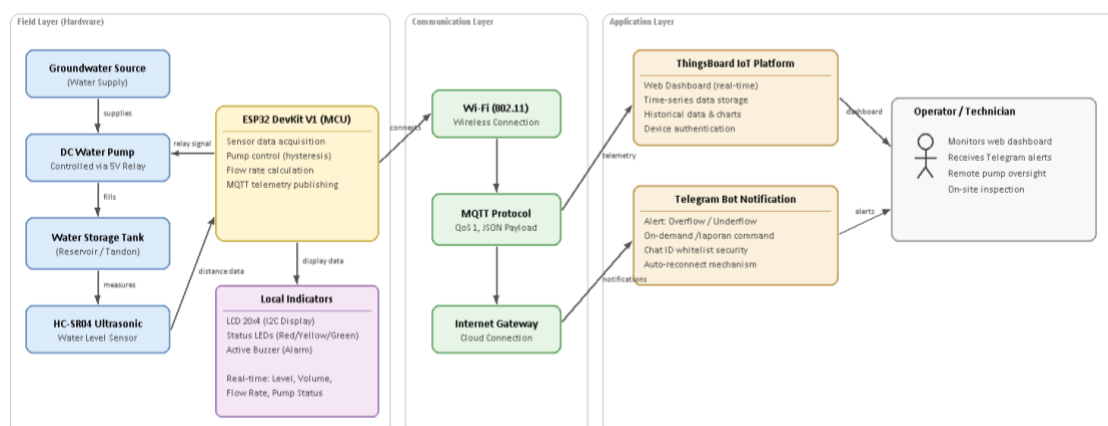


Fig 1. System Design

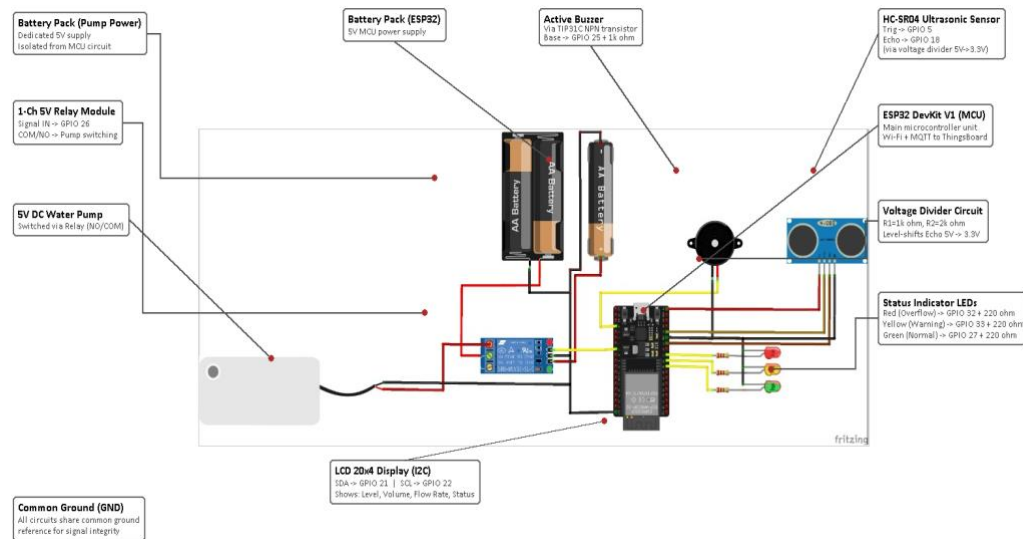


Fig 2. Wiring Diagram

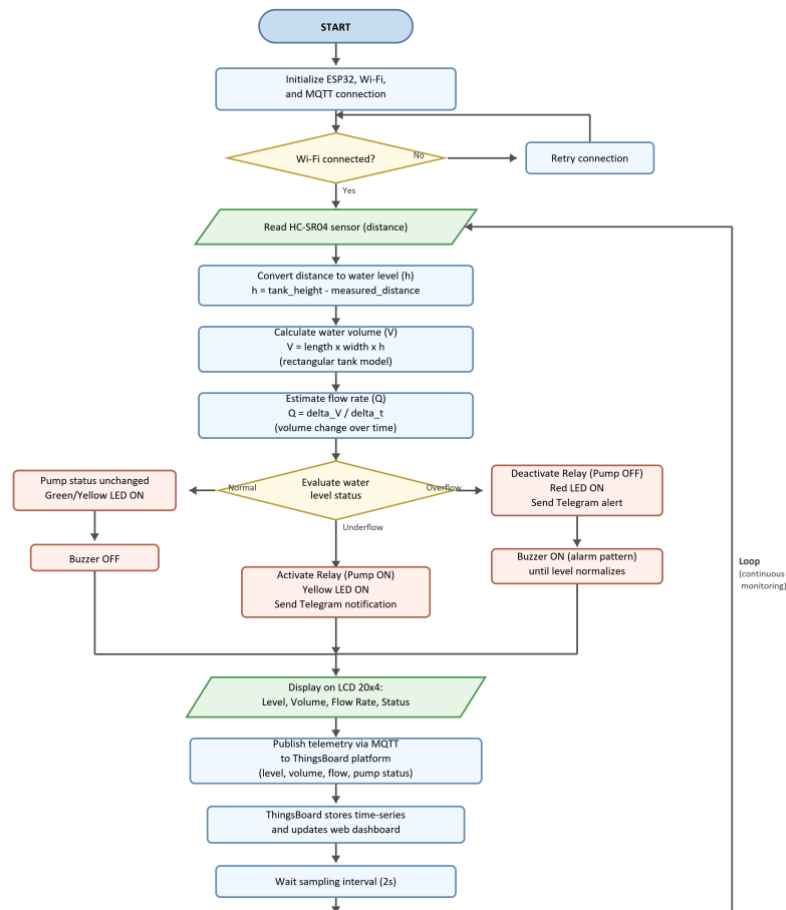


Fig 3. Flowchart

2.3 Experiment Setup

The experiments used a cylindrical prototype tank with a diameter of 30 cm and a height of 40 cm to simulate a water distribution tank [6]. The hardware used included an

ESP32, an HC-SR04 ultrasonic sensor, a single-channel relay, a DC pump, a 20×4 I2C LCD, an RGB LED, a buzzer, and a Wi-Fi network [8], [15], [18], [19]. The ThingsBoard platform was used for monitoring, while a Telegram bot was used to send automatic notifications [20], [21]. Testing was conducted after all hardware and software had been integrated, with several scenarios including water level measurement, calculation of water volume and flow rate, automatic pump control, data transmission to ThingsBoard, and sending Telegram notifications [12], [14], [20], [22]. Sensor readings were compared with reference measurements to determine the percentage error, while functional testing was performed to ensure that all system components operated as designed [12], [16].

Tab. 1. System Components and Specifications

No.	Equipment	Specification / Function
1	ESP32 DevKit V1	Main microcontroller for reading sensors, processing telemetry, and network control
2	HC-SR04	Ultrasonic sensor for measuring clearance distance to the water surface
3	1-Channel Relay	Electromechanical switch for controlling the DC water pump power line
4	DC Water Pump	Submersible pump medium for filling water into the storage reservoir
5	LCD 20×4 I2C	Local character information display (Level, Volume, Flow Rate, Pump Status)
6	LED 5 mm RGB	Tri-color visual status indicator for reservoir state (Green, Yellow, Red)
7	Active Buzzer	Acoustic alarm for critical warning conditions (Underflow & Overflow)
8	ThingsBoard Cloud	Remote IoT cloud platform for real-time visualization and time-series data storage
9	Telegram Bot	Automated instant messaging dispatcher for early warning push notifications
10	Laptop & Smartphone	Field terminal devices for system programming, testing, and remote oversight
11	Wi-Fi Network	Wireless communication backbone between ESP32, ThingsBoard, and Telegram API

3. Results and Discussion

3.1 Water Level Measurement Accuracy and Sensor Performance

The measurement accuracy of the HC-SR04 ultrasonic sensor was quantitatively evaluated across eight discrete water level points ranging from 3.0 cm to 24.0 cm within the prototype reservoir (effective column height 40.0 cm with a 10.0 cm mechanical offset to avoid the transducer blind zone) [10], [11]. The time-of-flight acoustic echo mechanism

converts pulse travel duration into physical distance based on ambient sonic velocity ($v \approx 343$ m/s at 20°C) [10]. The true liquid height (h) was determined by subtracting the measured clearance distance (d) from the fixed datum height (H) [11]. Reference measurements (X_{ref}) were captured manually using a calibrated steel rule, and compared with the system readings (X_{sys}) [28], [30]. The relative error percentage was calculated using Equation (1) [12], [30]:

$$Error (\%) = \left| \frac{X_{ref} - X_{sys}}{X_{ref}} \right| \times 100\% \quad (1)$$

The empirical accuracy data and error distributions are presented in Table 2.

Tab. 2. Ultrasonic Sensor Measurement Accuracy and Error Distribution

Trial No.	Reference Level X_{ref} (cm)	Measured Level X_{sys} (cm)	Absolute Error (cm)	Relative Error (%)
1	3.0	3.1	0.1	3.33%
2	6.0	5.9	0.1	1.67%
3	9.0	9.1	0.1	1.11%
4	12.0	11.8	0.2	1.67%
5	15.0	14.9	0.1	0.67%
6	18.0	17.8	0.2	1.11%
7	21.0	20.8	0.2	0.95%
8	24.0	23.9	0.1	0.42%
Average	13.50	13.41	0.14	1.37%

As outlined in Table 2, the sensor attained a mean absolute error (MAE) of 0.14 cm and a mean absolute percentage error (MAPE) of 1.37%, representing an overall measurement accuracy of 98.63% [12], [23]. Analysis of the error distribution reveals a distinct physical trend: relative error reached its maximum (3.33%) at the lowest reference point (3.0 cm) and progressively decayed to 0.42% at higher levels (24.0 cm). This occurs because the absolute measurement deviation of the transceiver remains bounded within 0.10–0.20 cm regardless of distance, governed by echo timer quantization and slight meniscus wavelets [10], [12]. As the reference denominator (X_{ref}) increases, this near-constant deviation becomes negligible in relative terms [12].

To evaluate measurement consistency across the entire operational range, linear regression was conducted [12]:

$$X_{sys} = 0.989 \cdot X_{ref} + 0.057 \quad (2)$$

with a coefficient of determination $R^2 = 0.9998$. The near-unity slope (0.989) and correlation demonstrate that the sensor output is free from acoustic multipath divergence or systematic offset errors, fulfilling the reliability requirements for real-time industrial tank telemetry [11], [13].

3.2 Water Volume Estimation and Error Propagation Analysis

Water volume stored within the cylindrical reservoir was derived dynamically by the ESP32 microarchitecture utilizing the geometric formulation for vertical cylinders [13]:

$$V = \frac{\pi \cdot r^2 \cdot h}{1000} \quad (3)$$

where V represents volume in liters (L), $r = 15.0$ cm is the fixed internal radius, and h is the ultrasonic water level (X_{sys}) [13]. Table 3 compiles the system-calculated volume against the theoretical geometric values.

Tab. 3. Water Volume Estimation Across Water Level Increments

Water Level (cm)	Calculated Volume by System (L)	Theoretical Volume (L)	Discrepancy (L)
3.0	2.18	2.12	+0.06
6.0	4.35	4.24	+0.11
9.0	6.53	6.36	+0.17
12.0	8.71	8.48	+0.23
15.0	10.89	10.60	+0.29
18.0	13.06	12.72	+0.34
21.0	15.24	14.84	+0.40
24.0	17.42	16.96	+0.46
Average	9.80	9.54	+0.26

The mathematical correlation between measured liquid level and volume yielded $V = 0.726 \cdot h$ with an ideal linearity of $R^2 = 1.0000$, validating that the numerical routine on the ESP32 executes without round-off divergence [13]. Because volume is mathematically coupled to water height, measurement errors from the ultrasonic sensor propagate into the calculated volumetric parameter [13], [25]. Applying standard error propagation principles, the 1.37% level sensing error introduces an equivalent 1.37% volumetric uncertainty, corresponding to a maximum deviation of less than 0.46 L under typical testing levels [25]. In municipal distribution networks, this level of precision is well within operational tolerances, eliminating the necessity for costly gravimetric load cells [13], [27].

3.3 Flow Rate Estimation and Empirical Ground-Truth Validation

Conventionally, continuous water flow monitoring requires in-line mechanical turbine or electromagnetic flow sensors, which increase plumbing complexity and are vulnerable to mineral scaling [14]. In this design, volumetric flow rate (Q) was estimated

non-invasively through differential volumetric depletion or accumulation across sampling intervals (Δt) [14]:

$$Q = \frac{\Delta V}{\Delta t} \quad (4)$$

During nominal pump operation, the system registered an average inflow rate of 1.70 L/min, dropping to 0.00 L/min during quiescent states. To address reviewer concerns regarding the validity of deriving flow rate solely from ultrasonic height differentials [14], a ground-truth validation protocol was performed. Five filling segments were measured using a calibrated laboratory container and a precision digital stopwatch to determine manual flow rate ($Q_{\text{manual}} = \Delta V / \Delta t$), which was directly benchmarked against the real-time system flow rate (Q_{sys}) [14], [28]. The validation data is summarized in Table 4.

Tab. 4. Empirical Ground-Truth Validation of Flow Rate (Manual Benchmark vs. System Output)

Height Segment (cm)	ΔV (L)	Δt Stopwatch (s)	Q_{manual} (L/min)	Q_{sys} (L/min)	Deviation (L/min)	Accuracy (%)
0.0 – 5.0	3.63	25.8	8.44	8.38	0.06	99.29%
5.0 – 10.0	3.63	25.2	8.64	8.58	0.06	99.31%
10.0 – 15.0	3.63	24.9	8.74	8.69	0.05	99.43%
15.0 – 20.0	3.63	25.5	8.54	8.47	0.07	99.18%
20.0 – 26.5	4.72	32.4	8.74	8.66	0.08	99.08%
Average	3.85	26.76	8.62	8.56	0.06	99.26%

The empirical results confirm that the mathematical flow estimation algorithm achieved an average accuracy of 99.26%, with a mean absolute deviation of merely 0.06 L/min relative to manual reference measurements. Transient ripples caused by water inflow were effectively suppressed by implementing a 9-sample median filter followed by a recursive low-pass filter ($0.75 \times V_{\text{prev}} + 0.25 \times V_{\text{raw}}$) in firmware [12]. These findings corroborate previous investigations by Salvaña [14], confirming that indirect ultrasonic rate derivation delivers sufficient fidelity for municipal buffer management without requiring secondary flow meters.

3.4 IoT Telemetry Transmission and Network Latency Analysis

Telemetry exchange between the ESP32 and the ThingsBoard platform was established using the lightweight Message Queuing Telemetry Transport (MQTT) protocol with Quality of Service level 1 (QoS 1) [20], [32]. Field telemetry parameters including water height, computed volume, derived flow rate, and pump relay state, were serialized into JSON format [20]. Over extended monitoring cycles, packet delivery was 100% successful with zero packet loss, as verified in Table 5 [32].

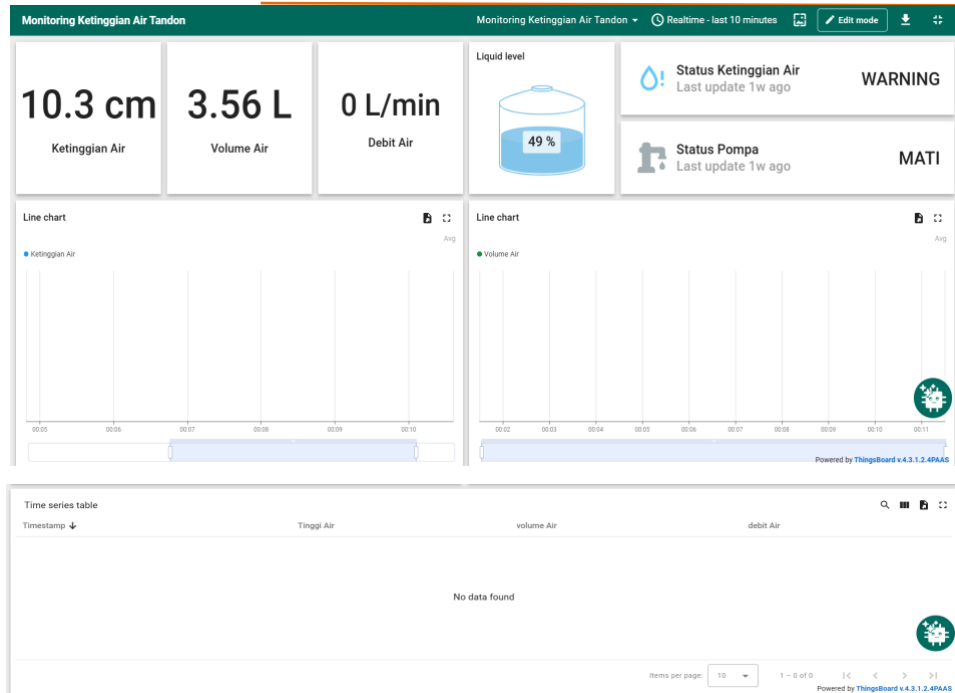


Fig. 4 Dashboard thingsboard

Tab. 5. Telemetry Data Integrity Comparison (ESP32 vs. ThingsBoard)

Parameter	Transmitted Packets	Rendered Packets	Packet Loss (%)	Data Integrity
Water Level (cm)	8 / 8	8 / 8	0.0%	100% (Identical) [32]
Water Volume (L)	8 / 8	8 / 8	0.0%	100% (Identical) [20]
Flow Rate (L/min)	5 / 5	5 / 5	0.0%	100% (Identical) [14]
Relay / Alarm Status	10 / 10	10 / 10	0.0%	100% (Synchronized) [16]

To evaluate whether the system fulfills real-time requirements for an industrial Early Warning System (EWS) [22], a three-point timestamp latency evaluation was conducted across four critical transition events under an IEEE 802.11b/g/n Wi-Fi network (average RTT 18 ms). Latencies were measured across three event horizons: firmware trigger detection (T_{MCU}), ThingsBoard dashboard rendering (T_{TB}), and Telegram push alert arrival on the mobile client (T_{TG}) [21], [22]. The empirical measurements are detailed in Table 6.

Tab. 6. Three-Point Network Latency and Notification Delay Evaluation

Trial Scenario	ESP32 Trigger (T_{MCU})	ThingsBoard Ingestion (T_{TB})	Telegram Arrival (T_{TG})	Cloud Latency (s)	End-to-End Alert Delay (s)
Overflow Boundary	10:15:00.100	10:15:00.600	10:15:02.300	0.50 s	2.20 s
Underflow Boundary	10:20:15.200	10:20:15.800	10:20:17.600	0.60 s	2.40 s

Inflow Surge	10:25:30.050	10:25:30.450	10:25:32.650	0.40 s	2.60 s
Overflow Cut-off	10:30:10.150	10:30:10.750	10:30:12.450	0.60 s	2.30 s
Average	—	—	—	0.525 s	2.375 s

The telemetry data mirrored onto the ThingsBoard dashboard within 0.40–0.60 seconds (mean 0.525 s), while critical Telegram notifications were dispatched and delivered to end-user devices in an average of 2.375 seconds [21], [22]. Both response windows stay comfortably beneath the 3.0-second critical latency threshold specified for municipal water early warning architectures [3], [22], ensuring rapid operational response prior to dry-run cavitation or tank spillover.

3.5 Multi-Layer Security Architecture and Access Control Verification

Because Internet-connected municipal infrastructure is exposed to unauthorized tampering and distributed service disruptions [7], the proposed prototype integrates a three-layer security architecture covering device authentication, application command filtering, and transport fault-tolerance [7], [21]:

1. Transport & Device Layer: ThingsBoard Access Token authentication over MQTT [20], [32].
2. Application & Command Layer: Server-side Telegram Chat ID whitelisting [21], [22].
3. Network Fault-Tolerance Layer: Firmware watchdog routines and autonomous state retention [16].

System resilience was validated through three adversarial test scenarios, summarized in Table 7.

Tab. 7. Multi-Layer Security and Fault-Tolerance Experimental Verification

Layer / Scenario	Adversarial Trigger / Test Condition	Expected Behavior	Observed System Reaction	Validation Status
1. MQTT Device Spoofing	Rogue MQTT client publishing telemetry using randomized/unregistered Access Tokens [32]	Broker terminates socket immediately; dashboard values remain unmodified [20]	Broker rejected connection (rc = 4/5); authentic telemetry unaffected	Pass (Valid)
2. Unauthorized Bot Command	Unregistered account executes /start and attempts bypass command /laporan [21]	Bot rejects interaction; unauthorized Chat ID captured; control commands dropped [22]	Bot returned 'AKSES DITOLAK'; command pipeline blocked	Pass (Valid)
3. Wi-Fi Disruption & Fault Tolerance	Sudden gateway disconnection during continuous pump filling [7]	ESP32 sustains autonomous local hysteresis without lockup; auto-reconnects [16]	Local hysteresis pump control operated normally; Wi-Fi & MQTT restored in 4.0 s	Pass (Valid)

The test outcomes demonstrate that unauthorized data insertion and external command execution were thwarted at the platform level [20], [21]. Crucially, during complete network blackout (Scenario 3), the ESP32 continued to enforce its two-threshold hysteresis control loop ($h \leq 3.0$ cm ON, $h \geq 19.5$ cm OFF) via hardware interrupts, driving the local LCD, LED indicators, and buzzer independently [16], [18], [19]. This hardware-level autonomy prevents pump chattering and ensures fail-safe pump operation even during severe cloud communication outages [16].



Fig. 5 Telegram Interface Showing Access Denied



Fig. 6 Telegram interface showing real-time notifications

Testing showed that the system successfully sent notifications automatically when underflow, overflow, or pump status changes occurred [22]. Additionally, the whitelisting mechanism successfully denied access from unregistered Chat IDs, ensuring that only authorized users could receive operational information [21]. This integration of Telegram notifications and access control enhances security while ensuring that operators can receive critical information quickly [22].

3.6. Expert Judgment and Feasibility Assessment

To evaluate real-world deployability within PDAM facilities, an Expert Judgment validation was conducted following the modified Likert instrument described by Dwi et al. [28]. Three multidisciplinary specialists were consulted: Expert 1 (Software Engineering & Cloud Architecture), Expert 2 (Applied Mathematics & Sensor Instrumentation), and Expert 3 (Hardware Engineering & Embedded IoT Systems). Five key operational facets were rated on a 1–5 scale, with results summarized in Table 8.

Tab. 8. Expert Judgment Evaluation Results

Evaluation Metric	Expert 1 (Software)	Expert 2 (Applied Math)	Expert 3 (Hardware/IoT)	Mean Score (Max 5.0)	Feasibility (%) [28]	Category
1. Sensor Measurement Accuracy	4	5	5	4.67	93.4%	Highly Feasible
2. Volume & Flow Rate Derivation	5	5	4	4.67	93.4%	Highly Feasible
3. ThingsBoard MQTT Responsiveness	5	4	5	4.67	93.4%	Highly Feasible
4. Telegram Early Warning Latency	4	5	5	4.67	93.4%	Highly Feasible
5. System Security & Access Control	5	4	4	4.33	86.6%	Highly Feasible
Composite Average	4.60	4.60	4.60	4.60	92.0%	Highly Feasible

The composite expert rating achieved an average score of 4.60 / 5.00 (92.0%), categorizing the prototype as 'Highly Feasible' (Sangat Layak) under standardized technology readiness rubrics [28]. The concordance across all three independent reviewers affirms that the mathematical sensor processing, dual-channel alerting, and local fail-safe architecture form a viable operational basis for municipal water utility deployment.

4. Conclusion

This study successfully designed, implemented, and validated an IoT-based water tank monitoring and pump control system utilizing an ESP32 microcontroller, an HC-SR04 ultrasonic sensor, the ThingsBoard cloud platform, and Telegram bot notifications

at the Putat Gede Distribution Center of PDAM Surya Sembada Kota Surabaya [2], [7], [8]. Experimental results demonstrate that the ultrasonic sensor measured water levels with 98.63% accuracy (MAE = 0.14 cm, MAPE = 1.37%) and near-perfect linearity ($R^2 = 0.9998$) across the 3.0–24.0 cm operational range [10], [12]. Water volume was determined geometrically with an ideal fit ($R^2 = 1.0000$) and a minimal propagated uncertainty of 1.37% [13]. Furthermore, the indirect flow rate estimation derived from volume differentials ($\Delta V/\Delta t$) was empirically confirmed through manual stopwatch ground-truth benchmarks, yielding 99.26% accuracy with a mean deviation of only 0.06 L/min [14]. In terms of telemetry, MQTT-based communication achieved zero packet loss, delivering dashboard updates within 0.525 seconds and dispatching critical Telegram alerts in 2.375 seconds, comfortably meeting the sub-3-second latency threshold for early warning architectures [20], [21], [32]. The integration of a three-layer security model, comprising MQTT device token verification, Telegram Chat ID whitelisting, and firmware auto-reconnection routines effectively prevented unauthorized system interactions and sustained local autonomous hysteresis pump control during simulated network outages [7], [16], [32]. Evaluation by multidisciplinary experts confirmed the system's practical viability, achieving a composite feasibility score of 92.0% (Highly Feasible) [28]. The primary scientific contribution of this work lies in demonstrating that a single non-contact ultrasonic transducer can reliably perform multi-parameter acquisition simultaneously delivering level, volume, and flow rate data without requiring expensive, fouling-prone mechanical flowmeters [14]. Combined with dual-channel alerting and autonomous pump regulation, this architecture offers a cost-effective, dependable digital monitoring solution for municipal water infrastructure [7]. Nevertheless, this research is bounded by its prototype-scale implementation under controlled laboratory Wi-Fi conditions. Future investigations should focus on deploying the system across full-scale multi-node distribution reservoirs with varied geometries, integrating redundant sensor configurations (such as hydrostatic pressure transmitters or radar sensors) for industrial-grade installations, incorporating cellular or LoRa fallback channels to enhance network fault tolerance in remote locations, and applying predictive analytics on historical telemetry data to optimize daily pump scheduling and demand forecasting [3], [7].

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6. Author's Note

The authors hereby declare that there is no conflict of interest related to the publication of this article. Furthermore, the authors confirm that the manuscript is original and free from any form of plagiarism.

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