Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi
Afyon Kocatepe University – Journal of Science and Engineering
https://dergipark.org.tr/tr/pub/akufemubid

Araştırma Makalesi / Research Article
e-ISSN: 2149-3367 **DOI: https://doi.org/10.35414/akufemubid.1870285**
CITE: Afyon Kocatepe University Journal of Science and Engineering. **26(4)** (2026) 918-929

Design of a Microcontroller-Based Automatic Water Discharge Mechanism for Feeding a Pelton Turbine in Micro-Hydroelectric Systems

***Makale Bilgisi / Article Info**
Alındı/Received: 23.01.2026
Kabul/Accepted: 19.06.2026
Yayımlandı/Published: : 03.08.2026

Mikro-Hidroelektrik Sistemlerde Pelton Türbinini Beslemek İçin Mikrodenetleyici Tabanlı Otomatik Su Tahliye Mekanizmasının Tasarımı

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Abstract

This study presents the design and laboratory-scale validation of a microcontroller-based accumulate-and-release discharge mechanism developed to condition irregular and low-flow building drainage streams for impulse turbine feeding. The system is formulated as a hybrid hydraulic-control architecture integrating continuous accumulation dynamics with event-triggered state transitions. A threshold-based control law is implemented to regulate the transition between accumulation and discharge states, ensuring that water is released only when sufficient hydraulic head and volume are available to generate impulse-compatible outflow conditions. The framework is experimentally validated using a laboratory-scale prototype configured to operate under repeatable and isolated conditions with clean water, allowing the intrinsic performance of the control architecture to be assessed independently of fluid variability. Experimental results from 20 consecutive discharge cycles demonstrated a mean discharge duration of 5.00 s with a standard deviation of 0.03 s, a repeatability index of RI = 0.994, and a hydraulic pulse stability index below 0.3%, confirming that state-driven control can effectively decouple inflow irregularity from turbine excitation requirements. The results demonstrate the feasibility of converting intermittent drainage flows into repeatable discharge pulses under controlled laboratory conditions. The findings indicate that intelligent, state-based flow conditioning offers a preliminary framework for building-integrated micro-hydropower systems, while remaining specific to the hardware configuration evaluated in this study.

***Keywords:** Micro-hydropower; Automation; Ultrasonic level sensing; Pelton turbine; Building-integrated energy recovery; Microcontroller systems.*

Öz

Bu çalışma, düzensiz ve düşük akışlı bina drenaj akışlarını darbe türbini beslemesi için şartlandırmak üzere geliştirilen mikrodenetleyici tabanlı bir biriktirme ve boşaltma mekanizmasının tasarımını ve laboratuvar ölçekli doğrulamasını sunmaktadır. Sistem, sürekli biriktirme dinamiklerini olay tetiklemeli durum geçişleriyle entegre eden hibrit bir hidrolik kontrol mimarisi olarak formüle edilmiştir. Biriktirme ve boşaltma durumları arasındaki geçişi düzenlemek için eşik tabanlı bir kontrol yasası uygulanmıştır. Bu sayede su, yalnızca darbe uyumlu çıkış koşulları oluşturmak için yeterli hidrolik basınç ve hacim mevcut olduğunda boşaltılır. Sistem, temiz su ile tekrarlanabilir ve izole koşullar altında çalışacak şekilde yapılandırılmış bir laboratuvar ölçekli prototip kullanılarak deneysel olarak doğrulanmıştır. Bu da kontrol mimarisinin içsel performansının akışkan değişkenliğinden bağımsız olarak değerlendirilmesine olanak tanır. 20 ardışık boşaltma çevrimi üzerinden elde edilen deneysel sonuçlar, ortalama boşaltma süresinin 5.00 s ve standart sapmasının 0.03 s olduğunu, tekrarlanabilirlik indeksinin RI = 0.994 seviyesine ulaştığını ve hidrolik darbe kararlılık indeksinin %0.3'ün altında kaldığını göstermiştir. Bu bulgular, durum tabanlı kontrol yaklaşımının giriş akışındaki düzensizlikleri türbin uyarım gereksinimlerinden etkin bir şekilde ayrıştırabildiğini doğrulamaktadır. Sonuçlar, aralıklı drenaj akışlarını kontrollü laboratuvar koşulları altında tekrarlanabilir boşaltma darbelerine dönüştürmenin fizibilitesini göstermektedir. Bulgular, akıllı, duruma dayalı akış koşullandırmasının, bu çalışmada değerlendirilen donanım konfigürasyonuna özgü kalmakla birlikte, binaya entegre mikro-hidroelektrik sistemleri için öncü bir çerçeve sunduğunu göstermektedir.

***Anahtar Kelimeler:** Mikro hidroelektrik; Otomasyon; Ultrasonik seviye algılama; Pelton türbini; Binaya entegre enerji geri kazanımı; Mikrodenetleyici sistemleri.*

1. Introduction

Recovering renewable energy from existing building infrastructures has attracted increasing attention in recent years, particularly in high-rise buildings where vertical water transport inherently contains exploitable gravitational potential energy. Water supply and drainage systems in tall buildings continuously move large water volumes across significant height differences, creating opportunities for decentralized micro-hydropower generation without additional land use or major

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structural modifications. However, practical implementation remains challenging due to highly variable flow rates, intermittent discharge behavior, and unstable hydraulic conditions that are incompatible with conventional micro-hydroelectric turbine operation.

Previous research has explored various aspects of energy efficiency, turbine performance, and energy recovery potential in building-related water systems. Studies on building water infrastructure have demonstrated that system-level design improvements, such as optimized tank placement and pressure regulation, can significantly reduce energy consumption (Cheung et al. 2013; Zhao et al. 2018). In parallel, the small hydropower literature has reported substantial advances in turbine design, system optimization, and grid integration (Ardizzon et al. 2014; Ali et al. 2018). More recent studies have investigated the feasibility of recovering energy directly from wastewater and greywater streams in high-rise buildings (Hadad et al. 2022; Alnaab et al. 2025), as well as from building-integrated water flows such as greywater discharge and rainwater downpipes (Sarkar et al. 2014; Walker and Duquette 2022; Carter et al. 2023). Although these studies confirm the theoretical and techno-economic potential of gravity-driven wastewater energy recovery, they generally assume steady or quasi-steady flow conditions and focus on energy yield estimation or turbine feasibility rather than on the active conditioning of irregular flows prior to turbine interaction.

Extensive research on high-rise building drainage systems further indicates that vertical wastewater transport is inherently unsteady and prone to strong pressure transients. Numerical and experimental investigations have shown that conventional drainage design approaches fail to maintain stable pressure conditions in tall buildings, leading to air-water interaction effects, trap seal depletion, and increased system vulnerability (Gormley et al. 2021; Stewart et al. 2021). Comprehensive reviews have also highlighted that building drainage and sewer systems are dynamically coupled and that current design standards do not adequately address transient behavior or control-oriented mitigation strategies (Sharif and Gormley 2021). These findings underscore that wastewater flow in high-rise buildings is fundamentally irregular and unsuitable for direct, uncontrolled energy extraction.

For impulse turbines, such as Pelton turbines, efficient operation critically depends on short-duration, high-momentum water jets rather than continuous low-flow streams. In contrast, building drainage systems generate irregular, low-momentum, and intermittent flows, creating a fundamental mismatch between available hydraulic conditions and turbine requirements. Despite extensive research on energy potential, turbine technology, and drainage hydraulics, the question of how to actively transform stochastic building water flows into repeatable, turbine-compatible hydraulic pulses has received little attention.

From a control perspective, a wide range of more advanced liquid-level control strategies already exist for tank-based systems. Methods such as PID control, gain scheduling, and nonlinear or fuzzy logic-based approaches have demonstrated effective performance in continuous level regulation applications (Urrea and Paez 2021; Yesil and Sahin 2025). However, these approaches are primarily designed to maintain steady-state or tracking performance and are not intended to generate discrete, event-based discharge patterns required for impulse-type energy conversion systems.

At the same time, microcontroller-based automation architectures have been widely applied in electromechanical and energy systems to achieve reliable sensing-decision-actuation integration. Embedded control frameworks have been successfully implemented in applications such as motor drives, battery management systems, industrial automation, and SCADA-based processes (Özer et al. 2021; Kıvrak et al. 2020; Keskin and Eminoğlu 2023; Aktürk and Fidan 2009; Kılıç and Özdemir 2010). These studies highlight the robustness and scalability of microcontroller-based control systems, supporting their applicability in hydraulic flow conditioning problems.

Despite the growing interest in recovering energy from building-associated water streams, a clear gap remains between resource-oriented studies, which mainly quantify theoretical recovery potential or evaluate turbine performance under assumed hydraulic conditions, and the practical control challenge of preparing irregular real-world building flows for stable turbine interaction. In particular, the literature provides only limited attention to experimentally validated mechanisms that can transform intermittent and weak building water inputs into repeatable, impulse-compatible discharge events suitable for micro-hydroelectric generation.

Accordingly, the objective of the present study is to design, implement, and experimentally evaluate a microcontroller-based accumulate-and-release mechanism that uses level sensing and threshold-triggered actuation to condition irregular low-flow water inputs into controlled discharge pulses under laboratory conditions. The contribution of the study lies in the practical implementation and validation of a sensing-decision-actuation architecture that addresses the flow-conditioning stage, which is often overlooked in building-scale micro-hydropower research. Rather than proposing an advanced adaptive control framework or a full-scale wastewater validation, the study focuses on demonstrating the feasibility, operational logic, and repeatability of a simple active flow-conditioning concept as a baseline proof-of-concept platform.

The remainder of the paper is organized as follows. Section 2 describes the materials, experimental setup, and control logic of the proposed system. Section 3 presents the experimental results and discusses operational performance and repeatability characteristics. Finally, Section 4 summarizes the main findings, outlines the limitations of the present work, and highlights directions for future research.

2. Materials and Methods

2.1 System overview

The laboratory-scale prototype is constructed around a multi-compartment tank designed to accumulate incoming water and stabilize inflow dynamics, serving as the central reservoir for the system. To monitor the accumulation process, an ultrasonic level sensor is strategically mounted above the final compartment, providing real-time feedback for the automation logic. The release mechanism is governed by a servo-driven metal discharge gate, which directs the flow toward a Pelton turbine coupled with a DC generator positioned directly beneath the outflow channel. In this configuration, the tank functions primarily as a hydraulic buffering unit, regulating the intermittent supply by ensuring that water is released only once the predetermined level is reached. During the experiments, water was manually supplied from a reservoir, and the inlet flow rate during the accumulation stage was maintained under controlled and approximately steady conditions with a nominal value of approximately 0.63 L/s. The discharge side flow rate used in the energy output estimation was measured separately during the clean water discharge tests and is reported in Table 1. This approach allowed the level-triggered control mechanism to be evaluated independently of inflow variability.

2.2 Hardware components

The hardware components are custom-made three-compartment metal tank (dimensions of each compartment: 200 mm x 300 mm x 300 mm), automation subsystem, Pelton turbine, and a 12 V DC generator. The Pelton turbine used in the experimental setup has a runner diameter of 150 mm and is directly coupled to a DC generator with a nominal power rating of 300 W. The automation subsystem incorporates a microcontroller, an ultrasonic sensor for liquid level measurement (Manorshi, JSN-SR04T-3.0) mounted 50 cm above the tank bottom, a high-torque servo motor for gate control (EMAX, ES3005DE), custom-fabricated steel discharge gate (2.5 mm thickness, 35 cm length). The ultrasonic sensor resolution and repeatability were sufficient for the defined threshold-based operation, as the control strategy relies on relative level detection rather than continuous high-precision measurement.

Figure 1 depicts the assembled laboratory prototype of the micro-hydroelectric energy recovery system, including the multi-compartment tank, ultrasonic sensor, motor-driven gate, and turbine assembly. The experimental setup is vertically oriented on a structural steel frame to simulate the potential energy characteristics of a high-rise building drainage stack. The upper section houses the custom-designed multi-compartment water tank, which functions as the hydraulic accumulation unit. Below the tank, the PVC piping system channels the discharge towards the generation unit located at the base. The bottom section features the Pelton turbine coupled with a DC generator, positioned specifically to intercept the high-momentum water jet released by the automated gate. This layout allows for the isolation and testing of the discharge mechanism independent of external plumbing variables.

Figure 1. Laboratory prototype of the micro-hydroelectric system.

Figure 2 presents the detailed integration of the automation subsystem's hardware components. The figure highlights the Arduino UNO microcontroller, which serves as the central processing unit, wired via a breadboard interface to manage signal input and output.

The close-up views illustrate the mechanical actuation assembly, featuring the ES3005 servo motor securely mounted to the tank chassis. The servo arm is mechanically linked to the custom-fabricated steel discharge gate, enabling vertical motion control. Furthermore, the installation of the ultrasonic sensor is shown positioned above the tank compartment, a critical configuration for ensuring precise, non-contact liquid level measurement during the accumulation cycles.

2.3 Control Architecture and Hybrid System Formulation

The proposed automatic discharge mechanism is formulated as a hybrid hydraulic-control system in which continuous fluid accumulation dynamics are coupled with discrete, event-triggered actuation. Unlike purely passive stabilization mechanisms, the present architecture introduces deterministic switching logic that actively regulates the transformation of stochastic inflow conditions into repeatable hydraulic pulses.

Let $\dot{h}(t)$ denote the instantaneous water level inside the accumulation compartment and A represent the effective cross-sectional area of the tank. Under intermittent inflow conditions, the level dynamics can be expressed as:

$$\dot{h}(t) = \frac{Q_{in}(t)}{A} \qquad (1)$$

where $Q_{in}(t)$ represents the time-varying inflow rate originating from upstream building drainage. Since $Q_{in}(t)$ is inherently stochastic and irregular in real building systems, the level evolution constitutes a continuous state subject to uncertainty.

In the absence of active control, such irregular inflow would directly propagate to the turbine inlet, resulting in unstable and low-momentum excitation conditions incompatible with impulse turbine operation.

The discharge gate is governed by a binary control variable $u(t) \in \{0, 1\}$, where:

$$u(t) = \begin{cases} 0 & h(t) < h_{th} \\ 1 & h(t) \geq h_{th} \end{cases} \qquad (2)$$

Here, h_{th} is the predefined activation threshold, $u(t)$=0 corresponds to accumulation mode (gate closed), $u(t)$=1 corresponds to discharge mode (gate open).

This switching rule defines the system as an event-triggered hybrid state machine in which a continuous hydraulic variable governs discrete control transitions. Once the measured level reaches the threshold, the system deterministically transitions from accumulation to discharge mode.

Unlike time-based scheduling, this state-based activation ensures that discharge occurs only when sufficient hydraulic head is available to generate impulse-compatible outflow conditions.

To extend the mechanism beyond a purely fixed-time release structure, the discharge duration is parametrically coupled to the triggering head level. The release time is defined as:

$$t_d = t_0 + k(h_{trigger} - h_{th}) \qquad (3)$$

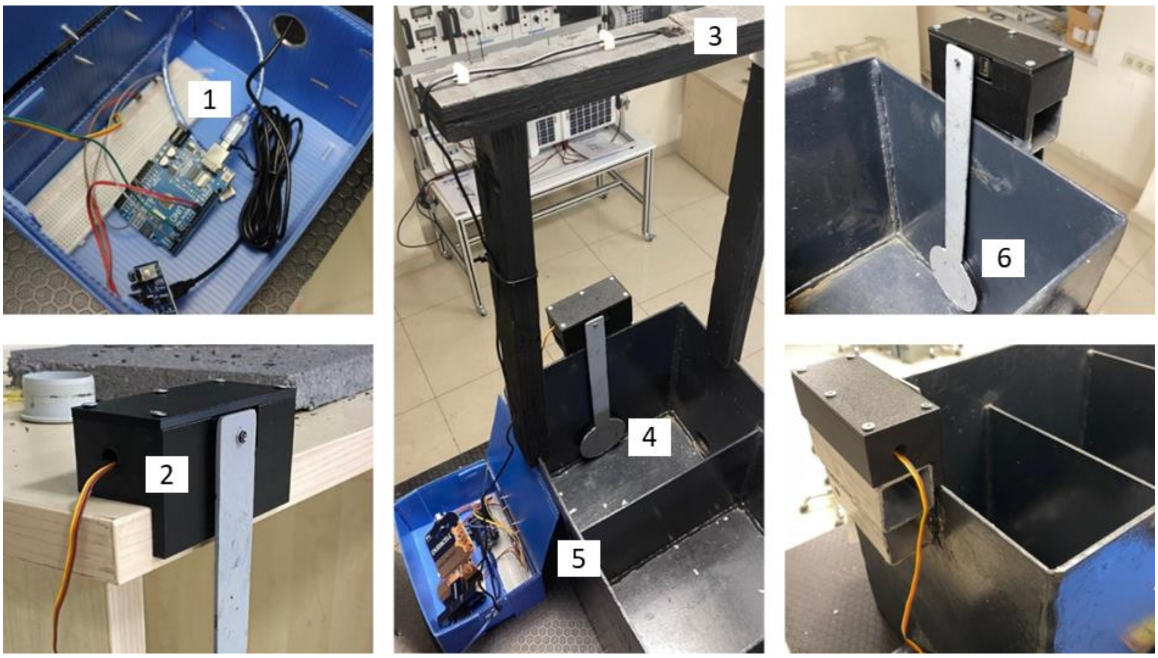

Figure 2. Experimental prototype of the automated discharge conditioning system (1. Microcontroller, 2. Servo Motor, 3. Ultrasonic Sensor, 4. Gate Assembly, 5. Tank compartment, 6. Discharge outlet)

where, t_d is the discharge duration, t_0 is the minimum base release time, k is a proportional discharge gain, and $h_{trigger}$ is the measured level at the activation instant. This formulation enables quasi-adaptive pulse shaping behavior without introducing full closed-loop feedback complexity. Higher accumulated head results in proportionally extended discharge duration, thereby adjusting the hydraulic pulse energy in accordance with stored potential energy.

The control parameters were defined based on the physical constraints of the experimental setup and empirical tuning. The threshold level was set to h_{th} = 14.90 cm, corresponding to the minimum hydraulic head required to produce a stable discharge jet under the given tank geometry and sensor configuration. The discharge duration parameters were selected as t_0 = 4.9175 s and k = 0.75 s/cm. These values were determined experimentally to achieve a nominal discharge duration of approximately 5.00 s with minimal cycle-to-cycle variation. The selected parameter set yielded a standard deviation of approximately 0.03 s and highly repeatable discharge behavior. It should be noted that these parameters are system-dependent and may vary with tank dimensions, hydraulic head, and inflow conditions.

Accordingly, the proposed architecture functions as a threshold-triggered discharge mechanism with a level-dependent behavior.

For impulse turbines such as Pelton wheels, performance depends primarily on jet velocity and momentum rather than continuous volumetric flow rate.

Assuming gravitational discharge conditions, jet velocity can be approximated as:

$$v = \sqrt{2gh} \tag{4}$$

where g denotes gravitational acceleration. Since volumetric flow is proportional to $\sqrt{h}$, the instantaneous hydraulic momentum scales approximately with:

$$M \; \alpha \; \rho h^{3/2} \tag{5}$$

where ρ is fluid density. The effective impulse delivered to the turbine during a discharge event is therefore proportional to:

$$Impulse \; \alpha \; h^{3/2} t_d \tag{6}$$

By coupling discharge duration t_d with the triggering level, the proposed controller regulates not only the occurrence of discharge events but also the momentum characteristics of each hydraulic pulse.

This pulse shaping perspective provides a control-theoretic interpretation of the mechanism and establishes a formal link between hydraulic state regulation and turbine excitation consistency.

The overall architecture can thus be interpreted as a hybrid dynamical system composed of:

- Continuous accumulation dynamics governed by stochastic inflow,
- Discrete state transitions triggered by level thresholds,
- A predefined discharge duration used to release the stored hydraulic head.

Such formulation decouples inflow irregularity from turbine excitation requirements and transforms the accumulation release process into repeatable hydraulic pulses under controlled laboratory inflow conditions.

By embedding sensing, decision, and actuation within a unified state-based framework, the proposed mechanism operates as an active hydraulic conditioning controller rather than a passive storage-release device.

3. Results and Discussions

The control logic implemented on the microcontroller follows a threshold-based decision structure. When the measured liquid level reaches a predefined height, the servo-actuated gate was opened according to the implemented discharge control logic within a nominal operating duration range, after which the gate is closed to initiate a new accumulation cycle. Beyond its practical implementation at the hardware level, the proposed discharge mechanism can also be interpreted within a formal control-theoretic framework, which provides a structured basis for analyzing its repeatability and temporal behavior. From a control-theoretic standpoint, the proposed discharge mechanism can be modeled as a discrete-state, event-triggered hybrid system in which continuous hydraulic accumulation dynamics are coupled with discrete control actions. The system state is defined by the water level in the accumulation tank, which evolves continuously over time as a function of inflow conditions, while the control input corresponds to the binary actuation state of the discharge gate (open/closed). Level measurements acquired via non-contact sensing are mapped to a discrete decision variable through a threshold-based state transition rule, effectively partitioning the system behavior into accumulation and discharge modes. The embedded controller implements a deterministic switching logic that triggers a state transition once the measured level crosses a predefined boundary condition, thereby enforcing repeatable impulsive outflow events. In this formulation, the discharge duration is treated as a programmed discharge interval control action, constraining the system trajectory and preventing inflow-induced variability from propagating into the output dynamics. The resulting structure resembles a hardware coupled state machine implementing threshold-based switching, where physical hydraulic states and embedded control logic evolve synchronously within each experimental cycle. By constraining both the sensing geometry and actuation timing, the electronic control layer reduces the effective system uncertainty and enables the generation of repeatable hydraulic pulses under the controlled inflow conditions of the laboratory setup. This state-based experimental configuration allows the discharge behavior to be evaluated in terms of repeatability, transition consistency, and temporal stability, independent of stochastic inflow characteristics, thereby providing a rigorous framework for validating impulse-compatible hydraulic conditioning strategies.

The experimental evaluation of the proposed control strategy revealed several key operational characteristics. First, the integration of the ultrasonic module ensured precise non-contact level detection, allowing for the accurate identification of the hydraulic head threshold. This sensing accuracy translated into highly repeatable triggering sequences, with negligible timing deviation observed across multiple test trials. Furthermore, the tank geometry and inlet flow conditions were maintained constant, while the discharge duration operated around a nominal target defined by the control logic to isolate system timing performance. Finally, the servo-based actuation exhibited consistent and repeatable operation during the experimental trials. A total of 20 discharge cycles were completed without missed actuation events or gate malfunction, and no observable variation in valve response behavior was detected. The use of clean tap water minimized mechanical resistance and flow-related disturbances, allowing the intrinsic behavior of the electromechanical actuation mechanism to be observed under controlled laboratory conditions.

Figure 3 illustrates the block diagram summarizing the general system architecture and the signal-energy flow of the proposed automatic water discharge mechanism. The process initiates with the detection of the water level in the final compartment of the tank by the Ultrasonic Level Sensor. The analog data obtained from the sensor is transmitted to the Arduino Microcontroller, which serves as the decision-making unit of the system. The microcontroller processes this data through logical operators within its embedded software to determine whether the water level has reached the specific threshold. Once the condition is met, the control unit sends a PWM signal to the Servo Motor. This electrical signal is converted into mechanical torque by the servo motor, actuating the opening of the Metal Discharge Gate. Upon the gate's opening, the released water mass is directed toward the Pelton Turbine via gravity, where hydraulic potential energy is converted into mechanical kinetic energy at the turbine blades. This schematic clearly demonstrates the linear and hierarchical working principle of the automation system, extending from sensor data acquisition to actuator movement.

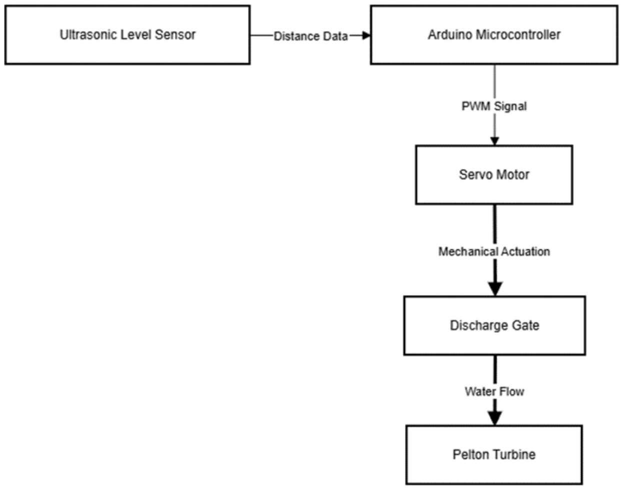

Figure 3. Block diagram of the automatic water discharge mechanism.

Figure 4 details the flowchart of the automated discharge mechanism based on water-level monitoring and trigger-dependent gate actuation. After initialization (“Start”), the microcontroller continuously monitors the tank level by reading the ultrasonic sensor (“Read Water Level”). The algorithm then evaluates whether the measured level exceeds the predefined trigger threshold. If the level remains below this threshold, the control logic follows the “No” branch and continues monitoring the tank until the trigger condition is met. When the water level reaches or exceeds the threshold (“Yes”), the controller assigns a discharge duration based on the trigger level and initiates the actuation sequence. The servo motor is commanded to open the discharge gate (“Open Gate-Servo Actuation”), allowing the accumulated water to be released. The gate remains open for the assigned discharge duration (“Hold Gate Open for Assigned Duration”), after which the servo motor resets to the closed position (“Close Gate-Servo Reset”). The algorithm then returns to the monitoring state, where the water level is continuously measured in preparation for the next accumulation and discharge cycle. This cyclic routine enables intermittent drainage flows to be conditioned into repeatable discharge pulses suitable for downstream micro-hydropower operation.

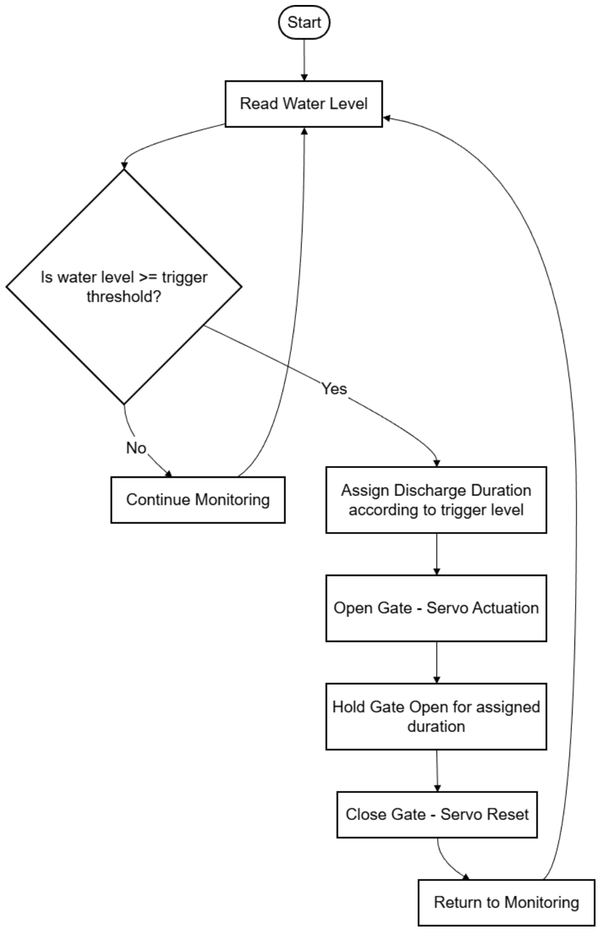

Figure 4. Operational flowchart of the automated discharge mechanism based on water-level monitoring and trigger-dependent gate actuation.

3.1 Control Performance Evaluation

To quantitatively validate the deterministic behavior of the proposed hybrid control architecture, a series of repeated discharge experiments were conducted under controlled laboratory conditions. While previous sections qualitatively described the repeatability of the accumulate-and-release strategy, the present subsection introduces explicit performance metrics to assess triggering accuracy, discharge stability, and actuation reliability.

The evaluation was performed over 20 consecutive discharge cycles under steady inflow conditions. The ultrasonic sensor continuously monitored the tank level, and discharge events were triggered according to the threshold-based switching logic described in Section 2.3.

For each cycle, the following parameters were recorded:

-Triggering water level $h_{trigger}$

-Actual discharge duration t_d

-Gate actuation response time

-Cycle-to-cycle head deviation

Time measurements were obtained using internal microcontroller timing routines with millisecond resolution.

To assess control performance, the following quantitative indices were defined.

Trigger Timing Error

The deviation between theoretical threshold crossing and actual actuation instant is defined as:

$$e_t = |t_{actual} - t_{threshold}| \quad (7)$$

where $t_{threshold}$ is the instant when $h(t) = h_{th}$ and t_{actual} is the servo activation time. This metric evaluates the responsiveness of the sensing–decision–actuation chain.

Discharge Duration Variance

Cycle-to-cycle consistency of discharge duration is quantified by:

$$\sigma_{td}{}^2 = \frac{1}{N}\sum_1^N \left(t_{d,i} - \overline{t_d}\right)^2 \quad (8)$$

where t_d represents the mean discharge duration over N cycles. Low variance indicates stable pulse generation.

Repeatability Index

To provide a normalized performance indicator, the repeatability index (RI) is defined as:

$$RI = 1 - \frac{\sigma_{td}}{\overline{t_d}} \quad (9)$$

An RI value approaching unity indicates highly repeatable discharge behavior.

Hydraulic Pulse Stability Index

To evaluate the consistency of triggering level across cycles:

$$PSI = \frac{\sigma_h}{\bar{h}} \quad (10)$$

where σ_h is the standard deviation of triggering level and $\bar{h}$ is the mean triggering level. This index reflects the stability of threshold detection.

Across the 20 experimental cycles the discharge duration operated around a nominal target of 5 s, with a measured mean of 5.00 s and a standard deviation of 0.03 s under the tested laboratory conditions. Other parameters were as follows:

- Mean trigger level: $\bar{h}$=15.01 cm
- Standard deviation of trigger level: σ_h=0.04 cm
- Average trigger timing error: 8 ms
- Servo actuation latency: 15 ms

The calculated repeatability index was RI=0.994, indicating highly consistent discharge performance.

Similarly, the hydraulic pulse stability index remained below 0.3%, confirming that level-based switching operates with minimal variation. To illustrate the repeatability and temporal consistency of the control system, the cycle-by-cycle variation of t_d and $h_{trigger}$ is presented in Figure 5 and Figure 6, respectively. Both parameters remain tightly distributed around their mean values across 20 consecutive experimental cycles. No observable drift or systematic deviation is detected, confirming the stability of the level-triggered control mechanism under controlled operating conditions.

The low trigger timing error demonstrates that the ultrasonic sensing module and embedded decision logic introduce negligible latency relative to hydraulic time constants. The small discharge duration variance confirms that the programmed discharge timing maintains temporal stability across repeated cycles.

Notably, because clean tap water was used, the experiment isolates the control system's intrinsic reliability. Any successful repeatability can therefore be directly attributed to the sensing, algorithmic, and mechanical design rather than variations in water quality. The created hydraulic pulses were consistent across trials, demonstrating that well-timed automated discharges can serve as a practical method for stabilizing input conditions for micro-hydropower extraction in buildings.

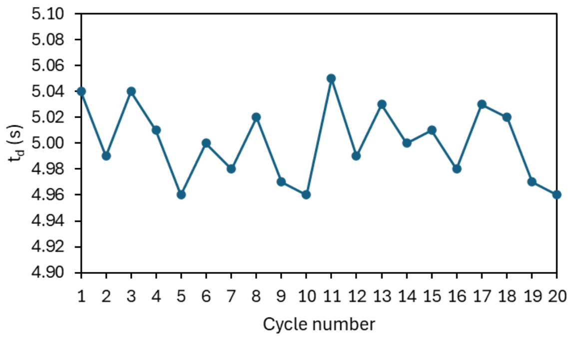

Figure 5. Cycle-by-cycle variation of t_d over 20 consecutive experimental cycles.

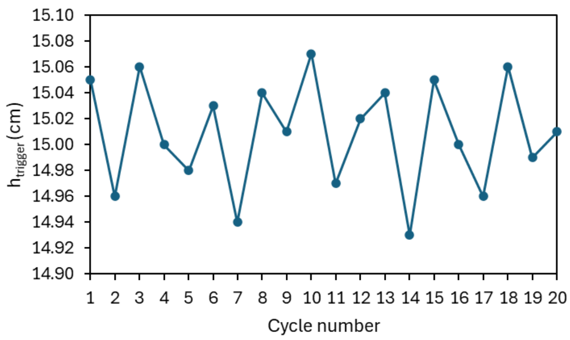

Figure 6. Cycle-by-cycle variation of $h_{trigger}$ over 20 consecutive experimental cycles.

The seamless integration of the ultrasonic sensing and servo actuation units validates the proposed accumulate-and-release strategy as a robust solution for overcoming the hydraulic limitations of standard building drainage systems. By converting irregular and low-momentum inflows into discrete, high-energy jets, the generated hydraulic pulses are compatible with the operational requirements of impulse-type turbines. Consequently, the high repeatability observed in the discharge cycles confirms that this automation architecture demonstrates the potential of automated discharge strategies to improve hydraulic conditions for small-scale energy recovery systems. Unlike conventional continuous-flow approaches that fail to generate sufficient torque under low-flow conditions, this discontinuous discharge mechanism effectively functions as a hydraulic pulse generator.

The implemented control logic is threshold-based and does not include adaptive feedback optimization. The experimental validation was conducted under clean water laboratory conditions. Comparative evaluation with advanced adaptive control strategies was beyond the scope of this proof-of-concept study. Similarly, instantaneous power outputs and total energy produced by the system are not within the scope of this work since the duration of each discharge cycle is not suitably long for this purpose but suitable for testing of our novel threshold-based control architecture proposed here. Regardless of this scope, we have performed a practically useful and relevant energy-output analysis based on our experimental flow rate measurements with clean water with the parameters described in Table 1.

Table 1. Discharge side clean water flow parameters used for the energy-output estimation.

Density (kg/L)	Flow rate (L/s)	Mean velocity (m/s)	Viscosity (mPa.s)
0.9888	0.7849	0.5945	0.8562

The measured discharge parameters were used to calculate instantaneous power output by the shaft of the DC motor as:

$$P_{out} = \eta_{tot}(\rho g \Delta H)Q \quad (11)$$

where η_{tot} represents overall efficiency of the Pelton turbine-generator system. The $\rho, g, \Delta H$ in the equation are respectively clean water density, gravitational acceleration and net head between water tank and Pelton turbine inlet. 'Q' is the measured volumetric flow rate here, which can also represent discharged water flow rate per unit apartment in each floor. Calculations were extended into multiple-floor buildings (with the assumption of that each floor has 3 m height and has four units implying four main discharge lines per floor) to predict potential yearly energy outputs for such systems as given in Figure 7. Average daily operation time was fairly taken as 12 hours/day during the year.

The plot shows linear increase of energy output as a function of number of floors with continuously increasing distance between the lower and upper bounds. The predicted yearly energy output range for typical 10-floor building varies between 1200.1 to 2000.1 kWh with a range width of 800 kWh. The average value is thus 1601 kWh. These numbers may not seem significantly high; however, the full energy is produced from an untouched component of a building, which is generously wasted water in drainage systems.

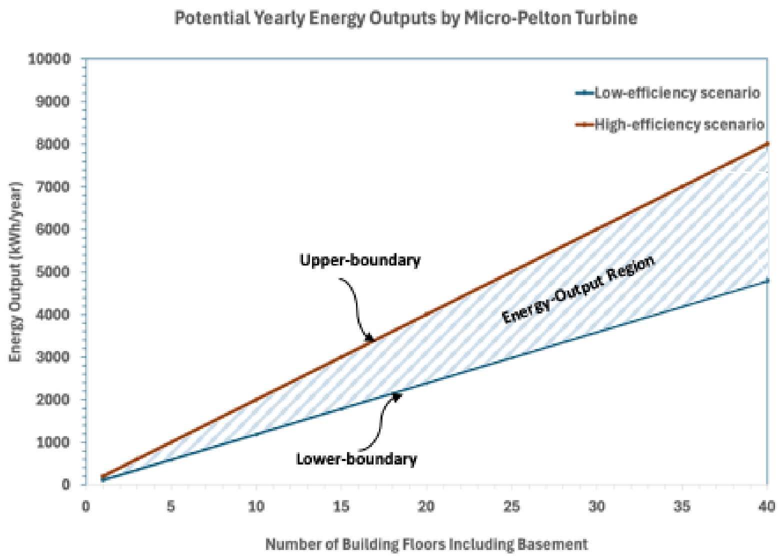

Figure 7. Predicted potential yearly energy outputs of multiple-floor buildings using micro Pelton turbines for energy generation from wastewater discharge lines (The lower and upper boundaries of the energy output region are obtained by using typical range of 0.30 and 0.50 of η_{tot} under similar flow rates given by Delgado-Currín et al. 2025).

The experimental results indicate that the proposed system does not merely function as a passive storage-release unit, but as an active hydraulic conditioning mechanism for impulse-type micro-hydropower applications. Under laboratory conditions, the system produced highly repeatable discharge events, with a mean discharge duration of 5.00 s, a standard deviation of 0.03 s, a repeatability index of 0.994, and a hydraulic pulse stability index below 0.3%. In addition, the measured trigger timing error of 8 ms and servo actuation latency of 15 ms were negligible compared with the overall discharge duration. These results show that the sensing-decision-actuation sequence can generate stable and repeatable hydraulic pulses without significantly disturbing the discharge process.

This finding is important when compared with previous studies on building-integrated water and wastewater energy recovery. Earlier studies have generally focused on estimating the energy potential of greywater, rainwater, or wastewater flows, or on evaluating turbine-based recovery systems at the building scale (Cheung et al. 2013; Sarkar et al. 2014; Zhao et al. 2018; Hadad et al. 2022; Walker and Duquette 2022; Carter et al. 2023; Alnaab et al. 2025). However, these studies mostly treat the available flow as a direct input for energy recovery. In contrast, the present study addresses the upstream flow-conditioning problem by experimentally demonstrating how low and irregular inflows can be accumulated and converted into short, repeatable, impulse-compatible discharge events before turbine interaction. Therefore, the main contribution of this study is not the use of a Pelton turbine itself, but the validation of a microcontroller-based accumulate-and-release mechanism that reduces the dependence of turbine excitation on inflow irregularity.

The need for such a conditioning stage is also supported by studies on high-rise building drainage hydraulics. Wastewater flows in tall buildings are known to be unsteady and affected by air-water interaction, pressure fluctuations, trap-seal behavior, and transient hydraulic conditions (Gormley et al. 2021; Stewart et al. 2021; Sharif and Gormley 2021). These characteristics make direct turbine feeding technically challenging, especially for impulse turbines that require concentrated, high-momentum jets rather than weak and intermittent flows. From this perspective, the threshold-triggered mechanism proposed in this study offers a practical control-oriented solution to a problem that is often implied in the literature but rarely addressed experimentally.

The proposed control approach also differs from conventional liquid-level control systems. While many tank-control studies aim to maintain a stable level or track a reference trajectory using methods such as PID, fuzzy logic, or nonlinear control strategies (Urrea and Paez 2021; Yesil and Sahin 2025), the objective here is different. The system intentionally allows water to accumulate until a threshold level is reached and then releases it as a discrete hydraulic pulse. Thus, the controller operates as an event-triggered pulse-generation mechanism rather than a continuous level-regulation system.

The estimated annual energy output of 1200.1–2000.1 kWh for a representative 10-floor building, with an average value of approximately 1601 kWh, is comparable in magnitude with previous building-related micro-hydropower studies. For example, Sarkar et al. (2014) reported approximately 2500 kWh/year for a 20-story building, while Walker and Duquette (2022) estimated 1308 kWh/year for a 23-story wastewater-driven system. Although direct comparison is limited by differences in building height, flow assumptions, turbine configuration, and efficiency values, the present results suggest that the proposed mechanism can provide a more controlled hydraulic input for future turbine-generator optimization.

Overall, the study demonstrates that microcontroller-based hydraulic pulse generation can be used as a preliminary flow-conditioning strategy for building-integrated micro-hydropower systems. However, the results should be interpreted within the limits of the laboratory-scale clean-water experiments. Future studies should evaluate the system under realistic wastewater conditions, long-term operation, and actual building-scale flow variability.

4. Conclusions

This study presented the design and experimental validation of a microcontroller-based automatic discharge mechanism developed to condition intermittent and low-flow water streams for building-integrated micro-hydropower applications. The proposed system was formulated as a hybrid hydraulic-control architecture, integrating continuous accumulation dynamics with event-triggered state transitions and controlled discharge timing for pulse generation. In this respect, the study contributes to the building-integrated micro-hydropower literature by addressing the flow-conditioning stage, which is generally overlooked in studies that mainly focus on theoretical energy potential, turbine feasibility, or system-level energy estimation.

Unlike passive storage-release mechanisms, the presented approach actively regulates hydraulic head prior to turbine interaction. By regulating discharge timing through a level-triggered control logic, the mechanism operates as a pulse-generation controller rather than a simple passive valve, thereby establishing a structured relationship between stored potential energy and turbine excitation conditions.

Quantitative evaluation demonstrated millisecond-scale timing resolution based on microcontroller time-stamp measurements, negligible cycle-to-cycle variation in discharge duration, and highly stable threshold detection behavior. Quantitative evaluation demonstrated that the threshold-triggered mechanism generated highly repeatable discharge events under controlled laboratory conditions. The mean discharge duration was 5.00 s with a standard deviation of 0.03 s, while the repeatability index reached RI = 0.994 and the hydraulic pulse stability index remained below 0.3%. These findings confirm that the sensing-decision-actuation chain can operate deterministically and can reduce the propagation of inflow variability into turbine excitation conditions under the tested configuration.

The predicted yearly energy-output range for a 10-floor building was estimated between 1200.1 and 2000.1 kWh, with an average value of approximately 1601 kWh. This result indicates that drainage-based micro-hydropower may provide a supplementary energy recovery opportunity in high-rise buildings. However, this estimation should be interpreted cautiously because it is based on clean-water discharge measurements, assumed efficiency values, and a controlled laboratory-scale configuration.

Although clean-water testing enabled the intrinsic behavior of the control architecture to be isolated, it also limits the direct generalizability of the results to real wastewater applications. Future work should therefore focus on real wastewater validation, long-term clogging and fouling behavior, variable inflow conditions, adaptive threshold optimization, and closed-loop turbine-generator integration.

Overall, the results demonstrate that deterministic, state-based hydraulic conditioning constitutes a programmable control strategy suitable for similar laboratory-scale implementations. Future work may focus on adaptive gain optimization, integration with real wastewater flows, and closed-loop turbine-generator coupling to further enhance system-level energy performance.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement

Author-1 : Methodology, writing original draft, supervision, review and editing
Author-2 : Methodology and software, validation, writing original draft, supervision, review and editing
Author-3 : Conceptualization, investigation, experimental study, visualization, writing original draft
Author-4 : Conceptualization, investigation, experimental study, visualization, writing original draft
Author-5 : Conceptualization, investigation, experimental study, visualization, writing original draft
Author-6 : Investigation, experimental study, review and editing
Author-7 : Supervision, study design, methodology, review and editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Datasets are available on request. The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Acknowledgement

This study was supported by Ankara Yıldırım Beyazıt University Scientific Projects Coordination Unit under the Grant Number FHD-2025-2740. The authors thank Ankara Yıldırım Beyazıt University for their support.

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