An Experimental Study of the Hydrodynamic Characteristics of Curved Blade Undershot Water Wheels for Laboratory-Scale Irrigation

Atus Buku
Mechanical Engineering Department, Paulus Christian University of Indonesia, Indonesia
atus@ukipaulus.ac.id. (corresponding author)

Nurul Utami Sri Putri Yandi
Mechanical Engineering Department, Paulus Christian University of Indonesia, Indonesia
nurulputriyandi31@gmail.com

Received: 27 January 2026 | Revised: 18 February 2026 | Accepted: 8 March 2026

ABSTRACT

This study investigates the hydrodynamic and performance characteristics of a laboratory-scale curved-blade undershot water wheel under varying inlet flow velocities, upstream water levels, and bucket configurations (6, 8, 10, and 12 buckets). Experiments were conducted using a recirculating open-channel system to evaluate rotational speed and bucket discharge under steady-state conditions. The results show that rotational speed increases proportionally with flow velocity due to greater kinetic energy transfer. At 0.565 m/s, the 6-bucket configuration achieved the highest angular velocity of 0.665 rad/s, while the 12-bucket configuration produced the lowest velocity of 0.305 rad/s, indicating a torque–speed trade-off associated with increased water mass loading. Increasing the water level from 0.042 m to 0.050 m enhanced bucket discharge from 5.9×10^{-6} m³/s to 7.5×10^{-6} m³/s for 12 buckets; however, it reduced rotational speed due to higher gravitational torque resistance. Bucket discharge was directly proportional to both inlet flow rate and bucket number; however, excessive bucket density introduced hydrodynamic interference, suggesting an optimal configuration. These findings demonstrate that water wheel performance is governed by the interaction between hydraulic input parameters and geometric design, highlighting the importance of optimizing bucket number for low-head irrigation and pico-hydropower applications.

Keywords-undershot water wheels; curved blade; irrigation

I. INTRODUCTION

Energy is crucial for the sustainability of modern human civilization. A reliable and sustainable energy supply not only supports economic growth and social welfare but also plays a significant role in mitigating global climate change challenges. One important research area addressing this issue focuses on the modeling and optimization of hydropower plant operations within power systems to improve energy efficiency, system reliability, and long-term sustainability [1]. Furthermore, performance parameters, such as frequency deviation, settling time, and transient response, are critical factors in the selection of appropriate governor systems. These parameters significantly contribute to enhancing the stability and operational reliability of mini hydropower plants, particularly those operating at low rotational speeds [2].

A type of hydraulic machine that can be utilized as a mini hydropower generator is the water wheel. In general, water wheels are characterized by relatively simple designs, large diameters, low rotational speeds, and the ability to produce high torque [3-5]. Traditionally, rural communities have long employed water wheels to lift and distribute water to agricultural lands located at elevations higher than the water source [6, 7]. However, the application of water wheels as microhydropower systems with smaller diameters and higher rotational speeds still requires further investigation [8-10].

The working principle of a water wheel is based on utilizing the energy of flowing water as a naturally available renewable energy source [11]. In this system, the rotating part is called the rotor or wheel, while the fixed part is called the stator or wheel housing. When the water flow hits the blades, the kinetic energy of the flow is transferred to the rotor, resulting in rotation that can be used for various purposes, one of which is lifting water for agricultural irrigation [12, 13].

A water wheel-based water lifting system consists not only of the wheel itself, but also of several supporting components that function synergistically [14, 15]. These components include a power source in the form of flowing water, bearings to support the rotating shaft, water channels, a drive shaft, and a support frame. The materials used to construct a water wheel vary, depending on local availability. Water wheels can be made from wood, metal plates, split drums, used car rims, and even motor vehicle axles [16].

The use of wood as a water wheel material is generally suitable for areas with abundant wood availability, such as forested areas or remote areas far from welding facilities. Wooden water wheels are relatively inexpensive, easy to build, and can be manufactured directly on site [17]. However, the main drawback of wooden water wheels is their low durability, especially when using low-quality wood or young wood, which can easily rot and be less efficient [18]. Proposed wood types are hardwoods such as ironwood, which are more durable.

Another alternative is a water wheel constructed from used drums. This type of water wheel is simple, easy to fabricate, and utilizes readily available materials [19]. However, its overall dimensions are constrained by the drum size, which limits the generated torque and power output, thereby restricting its application to small-scale operations [5, 20, 21]. In addition, the efficiency of such systems is generally lower due to geometric limitations and suboptimal blade flow interaction.

For larger-scale applications, water wheels fabricated using discarded car axles represent a more advantageous option, as they are capable of producing higher torque and power output and offer a longer operational lifespan [22]. These characteristics contribute to improved mechanical efficiency under higher load conditions. Nevertheless, this type of water wheel involves higher manufacturing costs, requires welding processes, and demands greater technical expertise, making it less suitable for small-scale or individual applications [23].

Therefore, there is a need to develop and evaluate alternative water wheel designs that are simple, cost-effective, and capable of achieving acceptable torque, power, and efficiency levels for small-scale water lifting and energy utilization systems. The present study addresses this need by investigating the performance characteristics of an undershot water wheel with curved blades under varying flow conditions and bucket configurations. In operation, water wheels are typically installed in fast-flowing rivers or in water channels that are deliberately directed to create a stronger current. The flowing water hitting the blades of the wheel creates a thrust that causes the wheel to rotate. In the water-lifting type of wheel, the blades are equipped with small tubes or water pockets that function to collect water when the blades are in the lower position. The collected water then spills out when it reaches the top of the rotation, then flows through gutters to the land requiring irrigation by utilizing gravity.

The operating mechanism of an undershot water wheel is based on the conversion of the kinetic energy of flowing water into rotational mechanical energy as the flow impinges on the lower blades of the wheel. Unlike overshot and breastshot water wheels, which utilize both kinetic and potential energy, the undershot type relies solely on flow velocity and does not benefit from differences in water level (hydraulic head) [3, 24]. Consequently, undershot water wheels are well-suited for shallow water bodies, irrigation channels, and flat terrain, where the available head is minimal. However, this dependence on kinetic energy results in relatively lower torque, rotational speed, and efficiency compared to head-driven water wheels. Therefore, performance improvement of undershot water wheels strongly depends on optimizing blade geometry, wheel diameter, and bucket configuration to enhance momentum transfer between the water flow and the blades. In the literature, the undershot water wheel is also referred to as the Vitruvian wheel, characterized by a water flow direction that is opposite to the direction of blade rotation [25]. This flow–blade interaction directly influences key performance parameters such as rotational speed (rpm), generated torque, output power, and overall efficiency. Accordingly, the present study focuses on evaluating the effects of flow conditions and the number of curved blades on the rotational performance, discharge characteristics, and energy utilization of an undershot water wheel, aiming to identify an optimal configuration for small-scale water lifting and mechanical energy applications.

The undershot water wheel offers several advantages, including simple construction, relatively low manufacturing costs, and ease of relocation according to operational requirements, making it suitable for small-scale and decentralized applications, particularly in rural or remote areas [26]. However, due to its reliance solely on the kinetic energy of flowing water and the absence of hydraulic head, this type of water wheel generally produces lower torque, limited power output, and reduced efficiency compared to head-driven water wheels such as overshot and breastshot types [27]. Consequently, improving the performance of undershot water wheels requires design optimization aimed at enhancing torque generation, increasing usable power output, and improving overall efficiency while maintaining simplicity and cost-effectiveness. In this context, the present study investigates the influence of flow conditions and the number of curved blades on the rotational speed, torque, power output, and efficiency of an undershot water wheel to identify an optimal configuration for small-scale water lifting and mechanical energy utilization.

Water wheel performance has been investigated through blade design optimization, open-channel power generation, breastshot water wheel analysis, hydrodynamic characterization, efficiency comparisons between overshot and undershot configurations, and dimensional effects on flow behavior [3, 28–37]; however, systematic experimental studies focusing on the combined influence of flow conditions and curved-blade number on the rotational performance, discharge characteristics, and energy efficiency of undershot water wheels are limited, thereby motivating the present research.

II. MATERIALS AND METHODS

This laboratory-scale study experimentally investigates the performance characteristics of a curved-blade undershot water wheel under controlled operating conditions. It also systematically examines the effects of inlet flow velocity and blade number as independent variables on key performance indicators, including rotational speed (rpm), generated torque, output power, discharge rate, and overall efficiency. The experimental setup employs a recirculating open-channel flow system, in which flow velocity is regulated and measured to ensure steady-state conditions, while blade configurations are varied in a controlled manner. Performance data are obtained through repeated measurements to ensure reliability and reproducibility. By directly correlating the experimental variables with measurable performance parameters, this study establishes an optimized blade configuration that enhances energy conversion efficiency while preserving the simplicity and cost-effectiveness of undershot water wheel systems for small-scale water lifting and mechanical energy utilization.

A. Research Materials

The materials used in this study are grouped as:

- Structural components: Acrylic sheets, steel plates, 6 mm steel rods, angle steel sections, bolts and nuts, paint, and silicone adhesive.
- Mechanical components: Bearings, shafts, ropes, and drag socks.
- Hydraulic and flow system components: water pump, water circulation reservoir, pipes, pipe fittings and elbows, valves, hose clamps, and pipe insulation.

B. Research Equipment

The equipment used for experimental testing includes a water wheel model, a graduated measuring cylinder, a stopwatch, data recording tools (pen and paper), a small collection tank, and a measuring tape.

C. Experimental Setup and Water Wheel Fabrication

1) Water Wheel Frame Design and Construction

The experimental setup employed a laboratory-scale undershot water wheel designed to operate under controlled open-channel flow conditions. The wheel frame was constructed using 6 mm-thick mild steel to ensure sufficient rigidity and structural stability during operation. Two steel plates were fabricated into circular rings with a diameter of 44 cm, resembling bicycle rims, and subsequently aligned concentrically. These components were welded together to form the main wheel frame, which serves as the structural support for blade installation and torque transmission during experimental testing.

2) Curved-Blade Fabrication and Configuration

The water wheel blades were fabricated from acrylic material to provide a lightweight structure while maintaining geometric precision. Acrylic sheets were cut to the specified dimensions using a grinder, resulting in blades with a height of 4 cm and a width of 8 cm. The blades were mounted onto the wheel frame in a curved configuration, with their angular orientation carefully controlled to ensure consistent interaction with the incoming water flow. A total of twelve blades were installed in the baseline configuration, while variations in blade number were implemented systematically as part of the experimental variables. This configuration allowed the investigation of blade number effects on rotational speed, torque generation, discharge characteristics, and overall energy conversion efficiency.

3) Operating Principle within the Experimental System

Within the experimental setup, the undershot water wheel, as shown in Figure 1, operates by harnessing the kinetic energy of the open-channel water flow. Water impinges directly on the curved blades at the lower portion of the wheel, generating hydrodynamic forces that induce rotational motion. This rotation is transmitted through the shaft to the measurement system, enabling the evaluation of rotational speed, torque, output power, and efficiency under varying inlet flow velocities and blade configurations.

The experimental setup was designed to ensure steady-state flow conditions, allowing direct correlation between controlled input parameters and measured performance outputs.

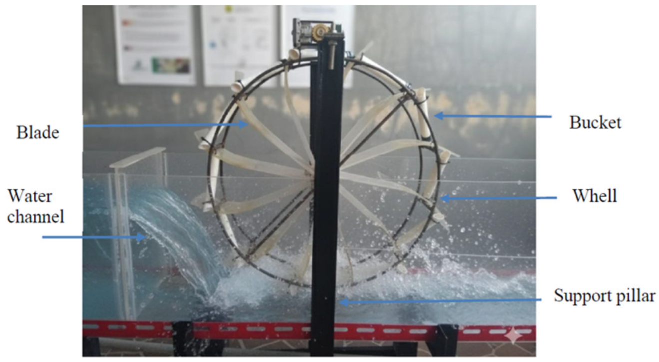

Fig. 1. Curved-blade undershot water wheel.

III. RESULTS AND DISCUSSIONS

The initial results are presented in Table I.

TABLE I. WHEEL ROTATIONAL SPEED AT DIFFERENT WATER VELOCITIES AND NUMBER OF BUCKETS

Water velocity (m/s)	Wheel rotating speed (Rad/s)			
	Buckets 6	Buckets 8	Buckets 10	Buckets 12
0.565	0.665	0.555	0.425	0.305
0.570	0.580	0.500	0.400	0.275
0.575	0.570	0.485	0.395	0.265
0.625	0.520	0.450	0.330	0.255
0.650	0.500	0.420	0.290	0.250

As depicted in Figure 2, the relationship between flow velocity and the rotational speed of the water wheel for different numbers of buckets indicates that the rotational speed obtained with six buckets is higher than that with twelve buckets at the same flow velocity. This behavior can be explained by the following factors.

A. Load Per Revolution

The effect of bucket number on water wheel rotational performance is governed by torque equilibrium and mass distribution principles. Increasing the number of buckets raises the total retained water mass per revolution, thereby increasing the cumulative gravitational load and average resisting torque. Under constant hydraulic input, higher resisting torque shifts the equilibrium condition toward a lower steady-state angular velocity to satisfy torque balance [34]. Experimental studies on overshot, undershot, and breastshot water wheels confirm that greater water retention enhances static torque but reduces rotational speed due to increased gravitational loading and mechanical losses [5, 27].

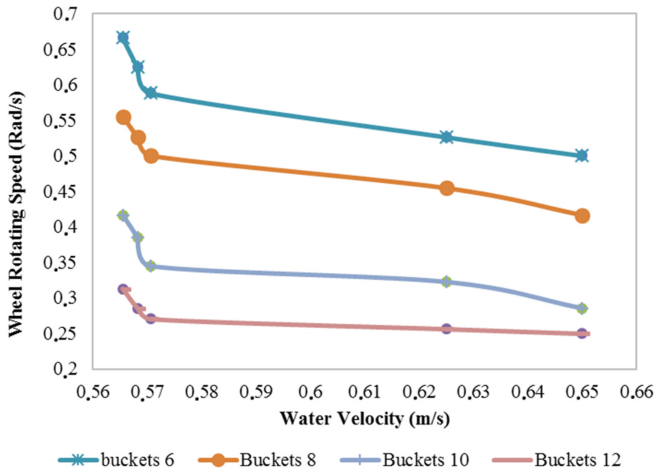

Fig. 2. Relationship between flow velocity and water wheel rotational speed.

Optimization analyses further demonstrate that bucket number represents a trade-off between torque amplification and angular velocity reduction in pico- and micro-hydropower systems [8]. Empirical investigations report that higher bucket loading improves torque output while decreasing rotational speed under identical flow conditions [7, 9]. At steady state ($\alpha = 0$), rotational equilibrium satisfies $T_{hydraulic} = T_{resisting}$. Therefore, increasing the number of filled buckets elevates resisting torque and lowers angular velocity, whereas fewer buckets reduce lifted mass and resisting torque, allowing higher rotational speed. This torque–speed trade-off is consistent with established hydropower performance theory and modern optimization studies of small-scale water wheel systems [5, 7, 8, 27, 34].

B. *Bucket Filling Time Relative to the Rotation Period*

For a fixed flow rate, the total volume of water entering the wheel during one complete revolution remains theoretically constant. However, the distribution of this volume among the buckets significantly influences the loading characteristics of the wheel. When the number of buckets increases, the water volume captured by each individual bucket decreases proportionally. Nevertheless, the filling events occur more frequently and in a sequential manner. This configuration produces a more continuous loading condition compared to a wheel with fewer buckets, where water filling is less frequent, and the loading becomes intermittent.

From a hydraulic performance perspective, the mechanical behavior of water wheels is governed by the interaction between water mass and rotating elements, as demonstrated in classical performance investigations [34]. A more uniform distribution of water around the periphery of the wheel reduces torque fluctuation and enhances the smoothness of mechanical power output. In contrast, wheels with fewer buckets tend to experience larger torque oscillations due to discrete and impulsive loading patterns.

The experimental work reported in [27] confirms that mechanical power estimation and loss mechanisms in breastshot configurations are highly dependent on the filling and emptying dynamics of the buckets. When multiple buckets are simultaneously engaged in the loading phase, the resulting torque becomes more stable and its average value increases. This behavior supports the concept that increasing the bucket number improves torque continuity even though the total hydraulic input energy remains unchanged.

Analyses of water wheel technologies also emphasize that bucket number optimization is a critical parameter in pico- and micro-hydropower systems [8]. An increased number of buckets enhances the continuity of momentum transfer from the flowing water to the rotor, particularly under low-head and low-flow conditions. This design strategy contributes to a higher average resisting torque because a greater portion of the wheel circumference is actively subjected to hydraulic loading at any given time.

Similarly, experimental investigations on micro-hydro water wheel models demonstrated that an optimal bucket configuration balances per-bucket volume and filling frequency to maximize efficiency while minimizing hydraulic losses [7]. Excessively few buckets result in intermittent loading and reduced torque stability, whereas an adequately increased number of buckets promotes smoother rotational motion. From a broader hydropower system perspective, torque continuity at the turbine level is closely related to power output stability and dynamic response characteristics [1]. Although the present study focuses on a water wheel prototype, the principle of load smoothing through distributed hydraulic interaction aligns with system-level requirements for stable energy production.

Therefore, even though increasing the number of buckets does not increase the total hydraulic energy input under constant discharge conditions, it significantly modifies the temporal distribution of loading. The transition from intermittent to continuous loading results in a higher average resisting torque and reduced torque ripple. This mechanical smoothing effect ultimately contributes to improved rotational stability and potentially higher overall efficiency in small-scale hydropower applications.

C. *Capture Efficiency and Flow Resistance*

An excessive number of buckets increases hydraulic interference between adjacent profiles, leading to flow separation, turbulence, and premature spillage, thereby reducing the effective transfer of kinetic energy into shaft torque. This mechanism is consistent with reported hydraulic loss characteristics in water wheels, where internal recirculation and drag significantly diminish mechanical efficiency [27, 34]. Nevertheless, there is optimal bucket number; beyond this optimum, performance declines due to increased hydrodynamic resistance and unstable inflow conditions [5, 7, 22, 29]. Conversely, a smaller bucket number allows the incoming flow to impinge at a more favorable angle and over a more effective contact area, enhancing tangential force generation and improving rotational performance under controlled experimental conditions [19].

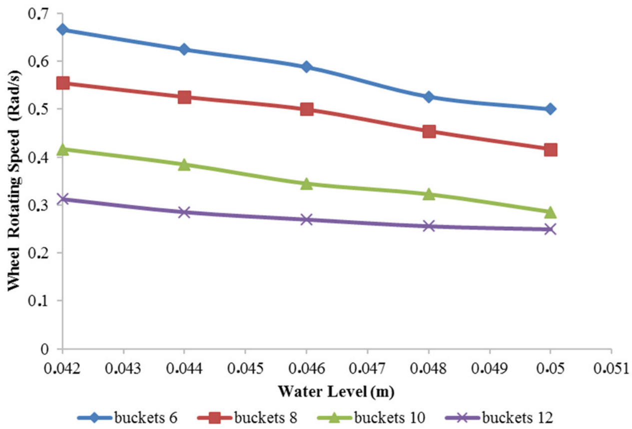

Fig. 3. Relationship between water flow height and water wheel rotational speed for different bucket configurations.

D. Increase in Lifted Water Mass with Rising Water Level

As the upstream water level increases, the volumetric inflow into each bucket rises proportionally, leading to a greater contained water mass ($m = \rho V$). The increased mass amplifies the gravitational force (mg) acting on the wheel, thereby elevating the resisting torque on the shaft and reducing the rotational speed under constant flow conditions. This behavior is consistent with classical performance characteristics of water wheels, where torque is governed by bucket filling ratio and hydrostatic head [5, 34]. Experimental investigations on undershot and breastshot configurations report that excessive bucket loading increases mechanical resistance and decreases angular velocity, particularly beyond the optimal operating point [7, 27, 29]. Parametric optimization studies further confirm that rotational speed is highly sensitive to mass distribution and hydraulic loading, which directly influence shaft torque balance and overall efficiency [19, 22]. Therefore, the observed reduction in rotational speed at higher water levels can be attributed to the dominance of gravitational loading over the driving hydraulic impulse, a phenomenon widely documented in small-scale and pico-hydropower water wheel systems [8, 21, 36].

E. Effect of Bucket Number on Total Load

An increase in the number of buckets enables a greater instantaneous water volume to be captured and lifted during each rotational cycle, thus redistributing the hydraulic load over a larger contact area. This configuration promotes a more continuous and uniform resistive torque acting on the wheel, reducing load fluctuation but increasing the overall effective mass being elevated per revolution. Consequently, the rotational speed tends to decrease due to the higher gravitational and hydraulic loading, although torque stability improves. Conversely, a smaller number of buckets limits the total water mass engaged per cycle, reducing the average resistive torque and allowing the wheel to attain higher angular velocity under identical flow conditions. This behavior is consistent with classical and modern analyses of water wheel performance, where bucket geometry and quantity directly influence torque generation, hydraulic loading distribution, and rotational characteristics [5, 27, 34]. Experimental investigations on undershot and breastshot configurations further confirm that increasing the effective water interception area enhances load uniformity but may reduce rotational speed due to increased lifting mass [7, 21, 22]. Parametric optimization studies also demonstrate that bucket number significantly affects the balance between torque production and angular velocity, thereby influencing overall efficiency and power output [8, 19, 36]. From a hydraulic–mechanical interaction perspective, the distributed loading mechanism aligns with theoretical formulations of water wheel power transfer, where mechanical output depends on the product of torque and angular velocity. Increasing bucket count primarily augments torque while potentially reducing rotational speed, illustrating the significant trade-off between rotational dynamics and hydraulic loading in small-scale hydropower systems [33, 34, 37].

F. Relationship Between Flow Energy and Work Against Gravity

The conversion of hydraulic energy in water wheel systems inherently involves an energy redistribution mechanism between kinetic and potential components. As the incoming flow interacts with the buckets, a portion of its kinetic energy is transformed into gravitational potential energy as the entrapped water mass is elevated against gravity, particularly in overshot and breastshot configurations [5, 34]. This energy conversion mechanism has been experimentally and analytically demonstrated with the lifting process significantly influencing torque generation and rotational characteristics [27, 33].

At higher upstream water levels, the increased water volume captured per bucket amplifies the gravitational load, thereby increasing the required potential energy component. Consequently, a larger fraction of the available hydraulic energy is consumed in lifting the water mass rather than sustaining angular acceleration. This results in a measurable reduction in rotational speed, despite the higher head, due to increased resistive torque and energy redistribution within the system [8, 22, 27]. Similar observations in undershot and low-head pico-hydro systems confirm that excessive water loading may decrease rotational velocity when the gravitational component dominates the energy balance [21, 36]. Therefore, the observed decrease in water wheel rotational speed at elevated water levels can be physically interpreted as a shift in energy partitioning: the enhancement of potential energy storage within the buckets reduces the net kinetic energy available for rotational motion. This behavior is consistent with established hydropower performance theory and empirical investigations of traditional and optimized water wheel technologies [5, 8, 34].

G. Additional Energy Losses

At elevated water levels, the inflow entering the buckets becomes increasingly turbulent, characterized by intensified splashing, overflow, and wall friction, which collectively reduce the effective conversion of hydraulic input into mechanical rotation. Such behavior is consistent with the hydraulic loss mechanisms identified in breastshot and undershot water wheels, where turbulence and impact losses increase significantly under higher head and discharge conditions [27, 34]. Experimental investigations further confirm that excessive inflow velocity induces partial filling, jet deflection, and flow separation inside the buckets, thereby diminishing torque generation and overall efficiency [5, 7, 22]. Moreover, increasing the number of buckets amplifies hydrodynamic interactions between adjacent compartments. Closely spaced buckets promote flow interference, stream splitting, and elevated hydraulic resistance, resulting in additional energy dissipation before complete momentum transfer occurs. Similar interference effects have been reported with blade or bucket density directly influencing internal flow structure and mechanical losses [19, 28, 29]. Analyses of water wheel technologies also emphasize that geometric configuration and bucket spacing determine turbulence intensity and power loss characteristics [8, 34]. Therefore, although higher water levels theoretically provide greater hydraulic potential, practical performance is constrained by turbulence-induced losses and inter-bucket flow interference, leading to a non-linear relationship between head, bucket number, and rotational efficiency, as also observed in experimental and optimization-based hydropower studies [7, 22, 27]. The bucket discharge is highly influenced by the inlet flow rate and the number of buckets. As the inlet flow rate increases, a larger volume of water is available to fill the buckets, resulting in a higher discharge per unit time. Similarly, an increase in the number of buckets leads to a greater total volume of water collected and discharged, as illustrated in Figure 4.

H. Effect of Inlet Flow Rate (Q_{in})

The inlet flow rate Q_{in} represents the primary water supply entering the system. A higher Q_{in} provides a larger volume of water per unit time that can be captured by the buckets. Consequently, the bucket discharge increases because a greater amount of water is filled and released during each rotational cycle. The Q_{in} also represents the primary hydraulic input governing the energy conversion process in water wheel-based hydropower systems. An increase in Q_{in} supplies a larger water volume per unit time, thereby enhancing the mass flow rate interacting with the buckets and increasing the available hydraulic power ($p = \rho g Q H$) [37]. As a consequence, a greater quantity of water is captured and discharged during each rotational cycle, leading to a proportional rise in bucket discharge and torque generation, particularly in undershot and breastshot configurations [34, 27].

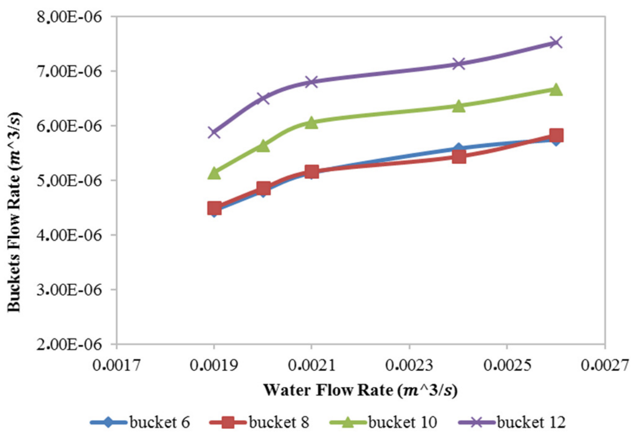

Fig. 4. Relationship between flow rate and bucket discharge.

Higher inflow rates directly improve the filling ratio and effective momentum transfer to the wheel blades, which subsequently increases rotational speed and mechanical output within the optimal operating range [7, 22]. Similar performance trends have been reported in pico-hydro and open-channel applications, with discharge variation significantly affecting wheel efficiency and power characteristics [21, 31]. Furthermore, analyses of water wheel technologies emphasize that flow rate is a dominant parameter affecting hydrodynamic loading, rotational stability, and overall system performance [8]. Therefore, the relationship between Q_{in} and bucket discharge can be interpreted as a direct hydraulic response, where increased volumetric inflow enhances water capture per cycle and strengthens the mechanical energy extraction capability of the system, consistent with established hydropower performance theory and experimental findings [34, 37].

I. Effect of Bucket Number

An increase in the number of buckets allows more containers to interact with the incoming flow within a single rotational cycle, thereby enlarging the effective water–structure contact area. Although the inflow distributed to each bucket may decrease proportionally, the aggregate discharge collected by all buckets increases, leading to a higher cumulative water volume processed by the system. This phenomenon is consistent with the hydraulic performance characteristics of traditional and modern water wheels, where geometric parameters such as bucket number, blade configuration, and filling ratio significantly influence torque generation and volumetric efficiency [5, 7, 36]. Optimizing structural parameters enhances energy conversion capability and flow utilization effectiveness [8, 22, 27]. In particular, studies on undershot and breastshot configurations demonstrate that increasing the number of interacting blades or buckets improves the continuity of momentum transfer and stabilizes rotational motion under steady flow conditions [21, 33]. Furthermore, parametric optimization approaches in pico-hydro water wheels highlight that geometric refinement, including bucket distribution and spacing, directly affects total discharge handling and mechanical output [19, 29]. From a broader hydropower system perspective, improving local flow capture efficiency contributes to overall system optimization and operational stability, which are essential for sustainable small-scale hydropower deployment [36]. Therefore, a higher number of buckets not only increases the total collected and discharged water volume but also enhances the hydraulic–mechanical energy transfer process in small and pico-hydropower applications.

J. Combined Influence of Flow Rate and Bucket Number

The trend observed in Figure 4 confirms that higher inlet flow rates accelerate bucket filling and increase the discharged volume, while a greater number of buckets enlarges the effective storage capacity per rotational cycle, thereby enhancing total discharge. This behavior is consistent with [5, 27, 34], which demonstrate that discharge and power output are governed by flow rate and geometric configuration parameters. Experimental investigations on undershot and breastshot water wheels further indicate that increasing inflow velocity improves torque generation and volumetric transfer, provided that hydraulic interaction remains uniform [7, 21, 22].

From a hydrodynamic perspective, the direct proportionality between inlet flow rate and bucket discharge aligns with pico-hydro optimization principles, where flow availability determines energy conversion capacity [8, 19, 36]. Similar findings have been reported in experimental prototype studies, showing that bucket volume and inflow conditions directly influence output performance and efficiency [6, 11, 31]. However, as highlighted in channel-flow and blade interaction analyses, an excessive number of buckets may disrupt flow uniformity, leading to incomplete filling and hydraulic losses [28, 29], which consequently reduce overall efficiency. This phenomenon corresponds to the performance limitations identified in detailed power-loss and mechanical estimation studies [27, 34].

Overall, the experimental results presented in Figure 4 are in agreement with established hydropower modeling and optimization frameworks, where discharge performance depends on both hydraulic input and turbine geometry [15, 37]. The proportional relationship between inlet flow rate, bucket number, and discharge, therefore, reflects significant hydrokinetic energy conversion mechanisms and confirms the validity of the observed experimental trends within contemporary small-scale hydropower research.

Figure 5 illustrates the relationship between water level and bucket discharge, indicating a direct proportional correlation. The height of the water surface (hydraulic head) directly governs the hydrostatic pressure and the volumetric inflow into each bucket. As the water level rises from 0.042 m to 0.050 m, the hydrostatic pressure increases, resulting in a higher flow rate per bucket. Quantitatively, for 12 buckets, the flow rate rises from approximately 5.9×10^{-6} m³/s at 0.042 m to 7.4×10^{-6} m³/s at 0.050 m, demonstrating a near-linear increase in discharge with increasing head.

The number of buckets determines the system's total water-holding capacity. For a smaller set of buckets (6–8), the cumulative discharge remains relatively low because limited water is captured per cycle. For example, at 0.050 m water level, buckets 6 and 8 produce flow rates of about 5.7×10^{-6} m³/s and 5.9×10^{-6} m³/s, respectively. In contrast, a higher number of buckets (10–12) significantly increases the total discharge, with 10 buckets yielding about 6.7×10^{-6} m³/s and 12 buckets ~7.4×10^{-6} m³/s at the same water level. This demonstrates that both water height and bucket count play crucial roles in determining the discharge, with higher heads and more buckets resulting in proportionally greater flow rates.

TABLE II. EXPERIMENTAL RESULTS OF BUCKET FLOW RATE AT VARIOUS WATER LEVELS FOR DIFFERENT BUCKET CONFIGURATIONS

Water level (m)	Bucket flow rate (m³/s)			
	Buckets 6	Buckets 8	Buckets 10	Buckets 12
0.042	4.50×10^{-6}	4.40×10^{-6}	5.20×10^{-6}	5.90×10^{-6}
0.044	4.80×10^{-6}	4.80×10^{-6}	5.50×10^{-6}	6.50×10^{-6}
0.046	5.05×10^{-6}	5.05×10^{-6}	6.00×10^{-6}	6.80×10^{-6}
0.048	5.50×10^{-6}	5.40×10^{-6}	6.30×10^{-6}	7.10×10^{-6}
0.050	5.80×10^{-6}	5.80×10^{-6}	6.70×10^{-6}	7.50×10^{-6}

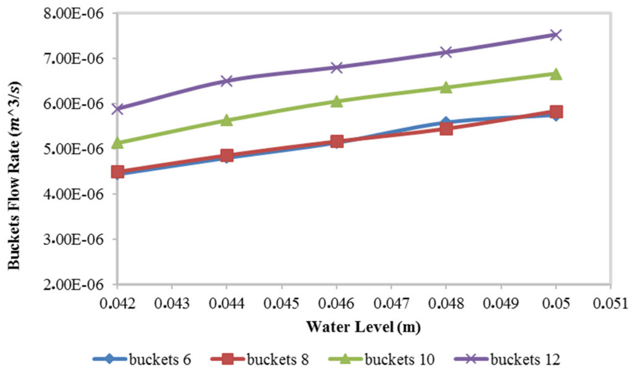

Fig. 5. Relationship between water flow height and bucket discharge for different bucket configurations.

IV. CONCLUSIONS

This study investigated the hydrodynamic and performance characteristics of a small-scale curved-blade undershot water wheel. The wheel was subjected to varying inlet flow velocities and upstream water levels, with various bucket configurations.

The results indicate that the higher speed of the water flow leads to higher kinetic energy, resulting in increased rotation speed. However, the number of buckets significantly affects this response. With 6 buckets, the reduced water load results in a higher rotational speed of the wheel. Conversely, with a higher number of buckets (8, 10, and 12), the wheel speed is slower. A direct correlation between water flow height and the rotation of the water wheel was demonstrated: the higher the water level, the greater the volume of water in the bucket, which significantly increases the lifting load. This results in higher holding torque, which subsequently slows down wheel rotation, especially with a higher number of buckets.

It was also found that the number of buckets significantly affects the flow rate. The bucket flow was proportional to the inflow rate, with a greater flow rate resulting in higher bucket inflow. In addition, the rotational speed of the water wheel increases with increasing water flow velocity due to the higher kinetic energy transferred to the wheel. However, the number of buckets modifies this response. For instance, at a flow velocity of 0.5 m/s, a water wheel with 6 buckets rotates at 18.2 rpm, while wheels with 8, 10, and 12 buckets rotate at 16.7 rpm, 15.3 rpm, and 14.5 rpm, respectively. The reduced rotation speed with more buckets is attributed to the greater water load each bucket lifts per cycle. An increase in water level increases the volume of water captured per bucket, leading to a higher lifting load. For example, at a water height of 0.042 m, the 12-bucket wheel rotates at 15.2 rpm, whereas at 0.050 m, rotation decreases to 14.1 rpm. This trend demonstrates that higher hydraulic heads increase holding torque, slowing the wheel rotation, especially when the number of buckets is high.

The bucket discharge is directly proportional to the inflow rate. For a water inflow of 5.0×10^{-6} m³/s, a 6-bucket wheel produces 5.2×10^{-6} m³/s, whereas a 12-bucket wheel produces 7.1×10^{-6} m³/s. Increasing the number of buckets increases total storage capacity, thereby amplifying the resulting discharge. For 10 buckets, the discharge reaches 6.6 ×

10^{-6} m³/s, confirming the synergistic effect of bucket count and inflow rate on output. A direct relationship between water height and bucket discharge is also revealed. As water height rises from 0.042 m to 0.050 m, the discharge of a 12-bucket wheel increases from 5.9×10^{-6} m³/s to 7.4×10^{-6} m³/s. With a smaller number of buckets (6–8), the limited capacity restricts discharge (e.g., $5.2–5.7 \times 10^{-6}$ m³/s at 0.050 m). In contrast, wheels with 10–12 buckets show significantly higher discharges at the same head, demonstrating that both water height and bucket count significantly influence bucket performance.

ACKNOWLEDGMENT

This work was funded by a research grant from the Ministry of Education, Higher Education, Research, and Technology of the Republic of Indonesia. The authors gratefully acknowledge this financial support.

REFERENCES

[1] D. H. Ngoma, A. Mfangavo, and B. Masenga, "Comparative Control Governor Systems for Power and Frequency Optimization of an Islanding Off-Grid Small Hydropower Plant," *Discover Energy*, vol. 5, no. 1, Feb. 2025, Art. no. 6, https://doi.org/10.1007/s43937-025-00066-8.

[2] W. Guo, L. Wang, and F. Qu, "Optimization of Governor Parameters for Transient Process of Hydropower System with Two Turbine Units Sharing a Super Long Headrace Tunnel," *Energy Science & Engineering*, vol. 12, no. 8, pp. 3505–3523, Aug. 2024, https://doi.org/10.1002/ese3.1832.

[3] M. Masmali, M. I. Elimy, M. Fterich, E. Touti, and G. Abbas, "Comparative Studies on Load Frequency Control with Different Governors Connected to Mini Hydro Power Plant via PSCAD Software," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12975–12983, Feb. 2024, https://doi.org/10.48084/etasr.6722.

[4] F. Chabane, N. Moummi, and S. Benramache, "Experimental Analysis on Thermal Performance of a Solar Air Collector with Longitudinal Fins in a Region of Biskra, Algeria," *Journal of Power Technologies*, vol. 93, no. 1, pp. 52--58, Mar. 2013.

[5] M. Denny, "The Efficiency of Overshot and Undershot Waterwheels," *European Journal of Physics*, vol. 25, no. 2, pp. 193–202, Mar. 2004, https://doi.org/10.1088/0143-0807/25/2/006.

[6] M. D. Irfan, M. Faqrulhadi, and K. Othman, "Prototype Waterwheel Hydro Generator," *Multidisciplinary Applied Research and Innovation*, vol. 5, no. 3, pp. 174–180, 2024.

[7] L. Jasa, A. Priyadi, and M. H. Purnomo, "Experimental Investigation of Micro-Hydro Waterwheel Models to Determine Optimal Efficiency," *Applied Mechanics and Materials*, vol. 776, pp. 413–418, Jul. 2015, https://doi.org/10.4028/www.scientific.net/AMM.776.413.

[8] M. F. Basar, I. A. Zulkarnain, and K. Sopian, "A Comprehensive Analysis of Waterwheel Technologies for Pico Hydropower: Evolution, Performance, and Optimization Strategies," *International Research Journal of Multidisciplinary Scope*, vol. 06, no. 03, pp. 580–599, 2025, https://doi.org/10.47857/irjms.2025.v06i03.05147.

[9] Y. Yassi, "Experimental Study of a High Speed Micro Waterwheel," *Iranian Journal of Mechanical Engineering*, vol. 14, no. 1, pp. 33–47, 2013.

[10] Y. Wu and J. Chen, "Estimating Irrigation Water Demand Using an Improved Method and Optimizing Reservoir Operation for Water Supply and Hydropower Generation: A Case Study of the Xinfengjiang Reservoir in Southern China," *Agricultural Water Management*, vol. 116, pp. 110–121, Jan. 2013, https://doi.org/10.1016/j.agwat.2012.10.016.

[11] I. Imawati *et al.*, "Harnessing Sustainable Energy: Pico-Hydro Power Generation Using an Undershoot Water Wheel Turbine in Irrigation Canals," *Journal of Renewable Energy, Electrical, and Computer Engineering*, vol. 5, no. 2, pp. 130–142, Sep. 2025, https://doi.org/10.29103/jreece.v5i2.18874.

[12] Y. Liu and D. J. Packey, "Combined-Cycle Hydropower Systems – the Potential of Applying Hydrokinetic Turbines in the Tailwaters of Existing Conventional Hydropower Stations," *Renewable Energy*, vol. 66, pp. 228–231, Jun. 2014, https://doi.org/10.1016/j.renene.2013.12.007.

[13] P. N. Bali *et al.*, "Analysis of the Effectiveness of Waterwheels as Water Pump Drivers," *LOGIC: Jurnal Rancang Bangun dan Teknologi*, vol. 25, no. 2, pp. 132–139, Jul. 2025, https://doi.org/10.31940/logic.v25i2.132-139.

[14] F. Chandio, A. R. Junejo, S. F. Shar, K. R. Bhutto, and J. Dahri, "Design and Fabrication of Waterwheel for Lifting of Water," *Indiana Journal of Agriculture and Life Sciences*, vol. 2, no. 5, pp. 49–52, 2022.

[15] I. Butera and R. Balestra, "Estimation of the Hydropower Potential of Irrigation Networks," *Renewable and Sustainable Energy Reviews*, vol. 48, pp. 140–151, Aug. 2015, https://doi.org/10.1016/j.rser.2015.03.046.

[16] M. Saber, G. Abdelall, R. Ezzeldin, A. F. AbdelGawad, and R. Ragab, "Techno-Economic Assessment of the Dethridge Waterwheel Under Sluice Gates in a Novel Design for Pico Hydropower Generation," *Renewable Energy*, vol. 234, Nov. 2024, Art. no. 121206, https://doi.org/10.1016/j.renene.2024.121206.

[17] R. A. Yusra, A. S. Rohendi, R. R. Aiys, and F. H. Kusumah, "Comparative Study of Materials to Improve the Performance of Simple Water Wheels in the Utilization of Hydro Energy," *Jurnal Energi dan Ketenagalistrikan*, vol. 1, no. 2, pp. 197–204, Dec. 2023, https://doi.org/10.33322/juke.v1i2.37.

[18] A. Asral, M. Akbar, and S. Syafri, "The Performance of Undershot Water Turbine Combined with Spiral Tube Pump on Empowerment of Energy Resources Local Contiguous Small River," *The Journal of Ocean, Mechanical and Aerospace -Science and Engineering*, vol. 42, no. 1, pp. 19–23, Apr. 2017, https://doi.org/10.36842/jomase.v42i1.186.

[19] M. Asim *et al.*, "Design and Parametric Optimization of the High-Speed Pico Waterwheel for Rural Electrification of Pakistan," *Sustainability*, vol. 14, no. 11, Jun. 2022, Art. no. 6930, https://doi.org/10.3390/su14116930.

[20] W. Lahamornchaiyakul and N. Kasayapanand, "The Design and Analysis of a Novel Vertical Axis Small Water Turbine Generator for Installation in Drainage Lines," *International Journal of Renewable Energy Development*, vol. 12, no. 2, pp. 235–246, Mar. 2023, https://doi.org/10.14710/ijred.2023.48388.

[21] A. Buku, B. Tangaran, and C. P. Tiwouy, "Performance of Undershot Water Wheel as Mini Hydro Power Plant for Agricultural Road," *International Journal of Mechanical Engineering and Technology*, vol. 12, no. 11, pp. 21–30, Nov. 2021.

[22] P. K. Sanjeevaiah, R. K. Donga, and A. Karn, "Performance Analysis and Optimization of Undershot Water Wheel for Small-Scale Hydropower Applications," *International Journal of Mechanical Engineering*, vol. 12, no. 9, Sep. 2025, https://doi.org/10.14445/23488360/IJME-V12I9P102.

[23] F. Arifin, H. Sutanto, I. Iskandar, and R. Sukwadi, "The Design and Fabrication of Waterwheels with System Floating Pontoon," *International Journal of Research in Vocational Studies*, vol. 2, no. 3, pp. 01–06, Dec. 2022, https://doi.org/10.53893/ijrvocas.v2i3.143.

[24] A. K. Dutta, B. Shrestha, J. Shahi, V. K. Chaudhary, and P. L. Shrestha, "Re-design and Optimization of Traditional Undershot Wheel using High Density Polyethylene (HDPE) Blades," in *International Symposium on Current Research in Hydraulic Turbines*, Dhulikhel, Nepal, Mar. 2016, Art. no. CRHT2016-14.

[25] D. Capecchi, "Over and Undershot Waterwheels in the 18th Century. Science-Technology Controversy," *Advances in Historical Studies*, vol. 02, no. 03, pp. 131–139, 2013, https://doi.org/10.4236/ahs.2013.23017.

[26] A. M. M. Kyaw, P. H. K. Kyaw, and N. A. San, "Design and Stress Analysis of Undershot Waterwheel for Water Pumping System," *International Journal of Scientific Engineering and Technology Research*, vol. 3, no. 12, pp. 2600–2605, Jun. 2014.

[27] E. Quaranta and R. Revelli, "Performance Characteristics, Power Losses and Mechanical Power Estimation for a Breastshot Water Wheel,"

Energy, vol. 87, pp. 315–325, Jul. 2015, https://doi.org/10.1016/j.energy.2015.04.079.

[28] L. Sule, I. N. G. Wardana, R. Soenoko, and S. Wahyudi, "Angled and Curved Blades of Deep-Water Wheel Efficiency," *Australian Journal of Basic and Applied Sciences*, vol. 8, no. 6, pp. 186–192, Apr. 2014.

[29] S. Paudel, N. Linton, U. C. E. Zanke, and N. Saenger, "Experimental Investigation on the Effect of Channel Width on Flexible Rubber Blade Water Wheel Performance," *Renewable Energy*, vol. 52, pp. 1–7, Apr. 2013, https://doi.org/10.1016/j.renene.2012.10.014.

[30] H. F. A. Hamed, A. M. Kassem, and M. E. M. Ali, "Hydro Matrix Power Wheels Generate More than 5 GW/h from Main Branch Canals (River Nile) in Egypt," *Journal of Power and Energy Engineering*, vol. 04, no. 03, pp. 71–78, 2016, https://doi.org/10.4236/jpee.2016.43007.

[31] P. Yelguntwar, P. Bhange, and A. Bahadure, "Design, Fabrication and Testing of a Waterwheel for Power Generation in an Open Channel Flow," *International Journal of Analytical, Experimental and Finite Element Analysis*, vol. 3, no. 1, pp. 47–51, Jul. 2014.

[32] I. Vojtko, V. Fecova, M. Kocisko, and J. Novak-Marcincin, "Proposal of Construction and Analysis of Turbine Blades," in *4th IEEE International Symposium on Logistics and Industrial Informatics*, Smolenice, Slovakia, Sep. 2012, pp. 75–80, https://doi.org/10.1109/LINDI.2012.6319465.

[33] G. Müller and C. Wolter, "The Breastshot Waterwheel: Design and Model Tests," *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, vol. 157, no. 4, pp. 203–211, Dec. 2004, https://doi.org/10.1680/ensu.2004.157.4.203.

[34] G. Müller and K. Kauppert, "Performance Characteristics of Water Wheels," *Journal of Hydraulic Research*, vol. 42, no. 5, pp. 451–460, Jan. 2004, https://doi.org/10.1080/00221686.2004.9641215.

[35] G. Ibrahim, C. Haron, and Azhari, "Traditional Water Wheels as a Renewable Rural Energy," *The Online Journal on Power and Energy Engineering*, vol. 1, no. 2, pp. 62–66, 2014.

[36] S. J. Williamson, B. H. Stark, and J. D. Booker, "Low Head Pico Hydro Turbine Selection Using a Multi-Criteria Analysis," *Renewable Energy*, vol. 61, pp. 43–50, Jan. 2014, https://doi.org/10.1016/j.renene.2012.06.020.

[37] O. Paish, "Small Hydro Power: Technology and Current Status," *Renewable and Sustainable Energy Reviews*, vol. 6, no. 6, pp. 537–556, Dec. 2002, https://doi.org/10.1016/S1364-0321(02)00006-0.