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Review Article

Operational, design, and economic factors impacting gravitational water vortex hydropower systems

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ABSTRACT

This work investigates and assesses the main operational, design, and economic factors that influence the performance of Gravitational Water Vortex Hydropower Systems and their overall contribution to energy sustainability. The thesis highlights improving performance through turbine blade angle, basin design, and material selection -an essential aspect to overcome worldwide energy problems. The system's power output is evaluated based on experimental, numerical, and theoretical approaches for varying the flow rate, vortex height, and turbine configuration. The findings reveal that five blades with a 44° angle provide an efficiency of only 82%, and an advanced material-based turbine shows an improvement in torque of 1.23% concerning conventional components. Moreover, combining conical basins with optimized nozzles can gain power (60%) and reduce energy losses. The result helps develop renewable energy creative methods in regions with limited energy access. This study extends previous works in the scientific literature by proposing a complete analysis and optimization framework for turbine design and performance under the need for sustainable energy production. These findings lay the groundwork for future studies designed to enhance the efficiency of small hydropower plants and further the world's move to low-carbon energy.

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INTRODUCTION

Over the past two decades, a complex geopolitical dilemma has emerged that threatens energy security at the global level. In this case, scientists and researchers must intensify their efforts to rely solely on renewable energy sources to achieve energy independence [1]. The global fuel crisis, increasing costs, climate change, and global warming impact every global economy. These events also affect smaller nations with open economies. In a world where 1.4 billion people do not have access to power, 2.7 billion continue to use traditional biomass as their primary cooking fuel. Most people living in these energy-poor areas are rural populations in developing Asian countries (except China), desert Africa, and India [2]. Therefore, these areas' populations are vulnerable to climate change effects. Developing countries may cross traditional energy sources and go straight to low-carbon renewables, which will help reduce poverty. Thus, lowering emissions of global warming gases,

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increasing access to electricity, and reducing poverty in rural areas may all work side by side, creating a connection between the three issues. Efforts to switch to low-carbon energy systems in rural regions can lead to more significant gains than industrialized ones. The planet's finite resources are under pressure due to our current dependence on non-renewable energy sources. The researchers set out to compare the social, economic, and physical factors that encourage conversion to hydropower, wind, and solar energy [3]. Most renewable energy resources are unpredictable and vary due to climate. Academic research on renewable energy is growing in technological, economic, political, and social dimensions. Many disciplines study how to invest in renewable energy, develop and adopt policies, select renewable energy suitable for the location, establish it by considering economic and environmental factors, develop energy distribution and storage systems, and support regional development. Understanding these co-benefits can help consumers embrace sustainable energy [4]. By 2050, renewable energy sources have the potential to eliminate up to 90% of carbon emissions, leading to a significant reduction in greenhouse gases and aiding in the mitigation of climate change. The future of renewable energy looks bright with the implementation of the zero-carbon emission decarbonization idea. This concept can replace energy obtained from fossil fuels and effectively restrict the global temperature increase to 1.5 C by the year 2050 [5].

Hydropower is a renewable and clean energy source that many countries worldwide rely on to significantly reduce emissions and achieve carbon neutrality. Despite the challenges faced by hydropower, or what is known as generating electricity from water, as a result of climate change, which leads to growing drought around the world, hydropower accounted for 37% (1.2 Terawatts) of the installed renewable energy capacity globally (3.37 Terawatts), by the end of 2022, according to estimates from the International Renewable Energy Agency. Hydropower, or electrical power generation by harnessing the gravitational force of falling or flowing water, is commonly known as hydroelectricity. As a renewable energy source, hydroelectricity is competitive due to its cheap cost. However, constructing huge dams and reservoirs frequently necessitates the displacement of humans and animals, and damming can damage local ecosystems by interrupting river flows. Compared to power stations that rely on fossil fuels, hydroelectric complexes generate far less greenhouse gas emissions and no direct waste when construction is complete [6]. One of the most significant renewable energy sources in the world is hydropower.

Nevertheless, there are social and environmental costs associated with its development. Hydropower generation may be adversely affected by environmental deterioration and climate change. To overcome these obstacles, a sustainable hydropower project requires meticulous planning and system design. Sustainable energy may be a byproduct of well-planned hydropower projects. Energy planners, investors, and everyone interested in hydropower projects need access to current information to make educated judgments [7]. Recently, focus has been placed on exploiting the energy of running water without the need for substantial hydraulic facilities, as a small river is used to build a small or medium-sized hydroelectric power station. Developed and emerging nations continue to prefer micro-strongly and pico-hydropower, two of the many renewable energy sources already on the market. Since the so-called Gravitational Water Vortex Hydropower Station (GWVHS) was developed in 2006, there has been a significant surge in the utilization of artificial free-surface vortices to produce low and ultra-low-head hydropower. The idea behind the concept is to create a vortex chamber and use the high angular velocity inside the whirlpool core to generate hydroelectric power [8]. The gravitational water vortex power plant is a micro hydro vortex turbine system that uses a low hydraulic head of (0.7–3) m to convert energy in a moving fluid to rotational energy. This system foundation is a circular basin with a central drain. A water turbine is powered by the stable line vortex that the water creates above the drain. The need to learn about new and improved renewable energy sources is pressing in our age because energy consumption is rising alarmingly. Water, wind, sun, and other forms of renewable energy may be harnessed. However, the main emphasis is on extracting energy from hydropower, namely by utilizing gravitational vortex hydro-turbines, in which the centrifugal force of a vortex is harnessed and converted into shaft power. Water flows tangentially into a circular basin at a gravitational vortex power station, and a turbine harnesses the energy released by the free vortex. The three primary benefits of GWVHS are its low hydraulic head power generation capability, minimal environmental impact, and economic and social viability [9]. Some studies have reported that the turbine design and operational parameters affected the efficiency of gravitational water vortex systems. For instance [10], showed that adjusting blade angles to 44° lifted efficiency to 82%. Similarly, [11] showed a 14% gain in efficiency via optimized runner profiles, while [12] showed a 10.25% torque gain by using baffles of 50% of the area of the turbine. The unit is designed to operate near a water stream. It includes a vortex hydro turbine system, a small hydro power plant gravity water vortex as follows: 1-supply channel, 2-hydrogen generator,3-hydraulic Turbine,4-circular basin (turbine chamber), 5-outlet channel and as shown in Fig.1 [13].

The research will focus on the research gap in the efficiency of the gravitational water vortex power plant. The operations gap is characterized by an insufficient understanding of how the variables of water depth, flow speed, and flow rate impact the performance of the system. In contrast, the design gap relates to the lack of acute analysis of important design components like the shape of the turbine or basin to deliver performance improvements. One missing piece of the puzzle is an economic overview of the financial viability of these plants, particularly in terms of

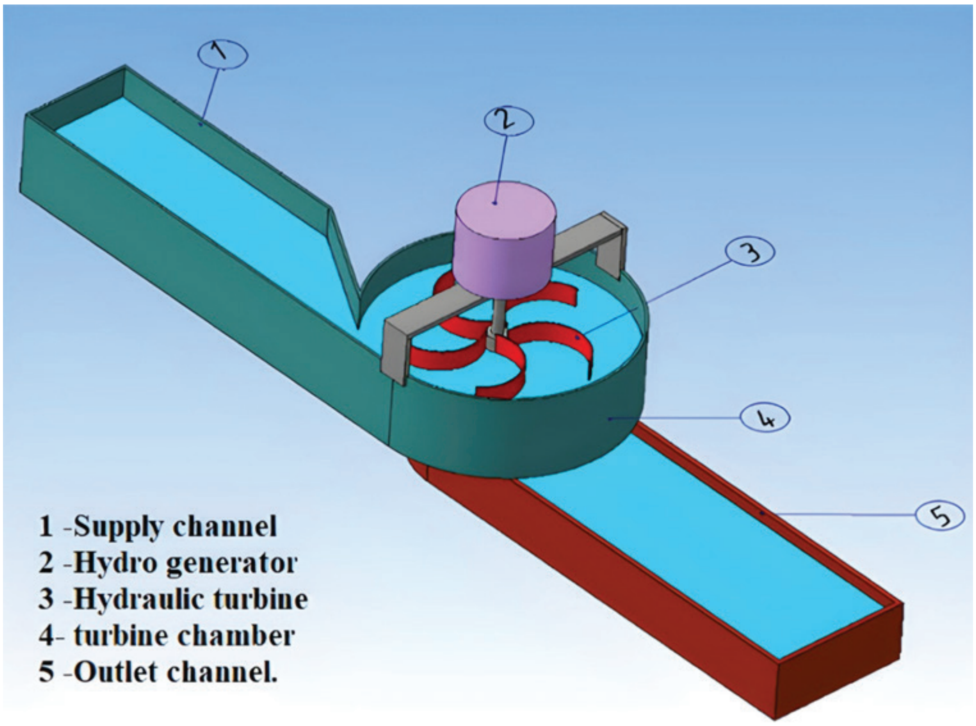


Figure 1. The main parts used in the GWVHS system sequentially [From Obozov et al. [13], with permission from Elsevier].

sustainability, given the huge economic gap. Therefore, the study proposal aims to identify the operational variables affecting the efficiency analysis and design of critical parts to select the best solution. It also includes an economic viability study focusing on reducing costs and sustainability. It also underlines the challenges those systems face and presents recommendations to strengthen current designs and increase their effectiveness.

Addressing the Gaps in Hydropower Efficiency: Design, Performance, and Economic Feasibility in Gravitational Water Vortex Systems

Although previous works address specific elements such as turbine improvement or the economic viability of the energy system, a holistic study covering design, performance, and economics is yet to be found in the literature. While these small hydropower systems have been the subject of some studies aimed at performance improvement, such studies failed to consider important variables like the angle of the blade for various designs, basin configuration, and the material for the constitutive element, thus limiting their contributions for offering a practical and sustainable alternative. Certain gaps to fill are directly related to the thorough analysis of system performance by considering different design parameters, such as advanced materials, since by including these, greater optimizations toward energy efficiency can be achieved. This research aims to address these research voids by offering a detailed analysis concentrating on specially crafted turbines to maximize the production of energy as well as minimize the loss of energy. It requires developing new turbine designs using epoch-making new materials and increasing efficiency by the coexistence of conical basins with optimized nozzles. Large-scale energy storage also plays a vital role in renewable energy distribution and, as a result, acts as a lifeline to those parts of the world suffering from energy shortages, contributing to clean energy deployments and sustainability goals. Results show that we can develop more efficient hydropower systems, thus increasing energy production in remote areas and contributing to energy independence by reducing reliance on fossil fuels. The study extends previous research with a holistic framework for technologies used to enhance turbine performance in sustainable energy initiatives that will assist in meeting low-carbon energy targets.

MATERIALS AND METHODS

Amid growing requirements for new sustainable and energy-efficient energy sources to meet our environmental and economic needs, we found one of the innovative solutions that can help us with energy independence and low greenhouse gas emission — gravitational water vortex power plants. This technology is based on harnessing the gravitational forces and the kinetic energy of the water, allowing for continuous vortices capable of efficiently driving turbines. However, considering the great potential of such plants, their real performance depends

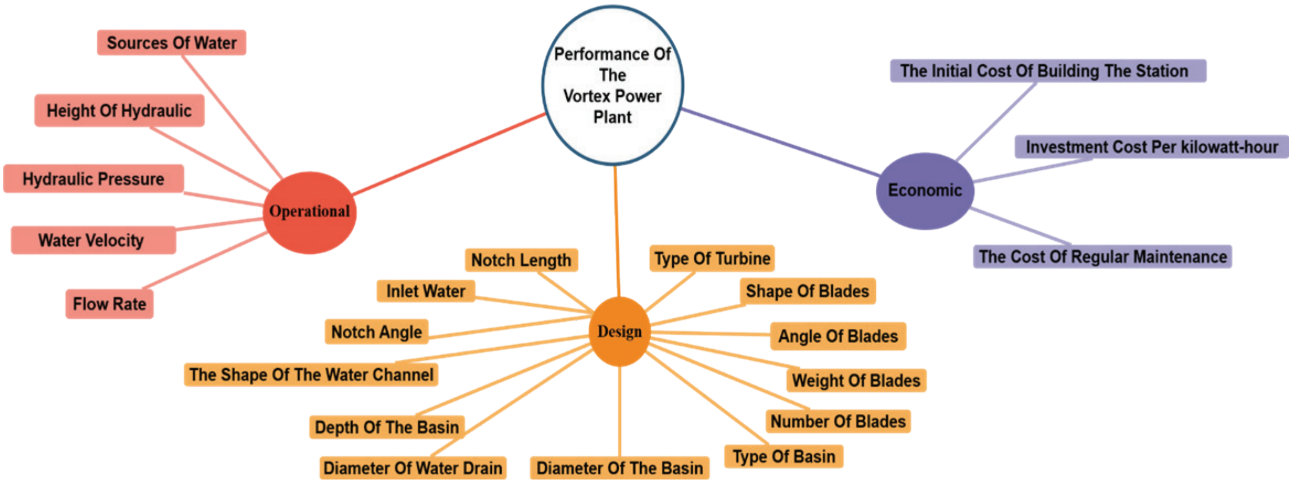


Figure 2. This diagram shows the most important factors that impact the performance of the vortex power plant.

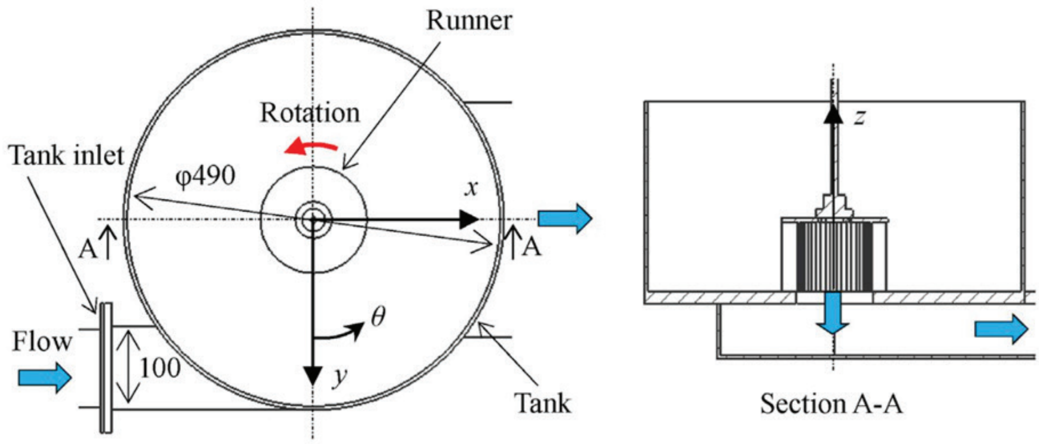
on many operational, design, and economic parameters that necessitate in-depth analysis and investigation to validate better efficiency and cost-effectiveness. This study strives to fill the gaps in knowledge in this area by adopting a systematic and multidimensional analysis of the respective influencing factors, which may facilitate guiding the future development and enhancement of plant designs. This article reviews previously published studies specialized in exploiting and evaluating the performance of the vortex power plant by studying the operational, design, and economic impacts, as shown in Figure 2.

Articles will then be categorized, reviewed, and discussed according to these influences. The third Section clarified the role and impact of operational specifications on the GWVHS performance. Section (4) includes a review of studies that examined the effects of design variables on the performance and configuration of the vortex. Likewise, studies that addressed the economic impacts of the construction and design of the station were included in section (5). In this sixth Section, the modeling and simulation articles were clarified, and some improvements used in the system were presented, such as the angle of the blades, the basin, the antenna core, and other different effects, and the impact of each of them on the performance of the system. Then, the current limitations and challenges within hydrographic hydropower systems are clarified in section (7). In the (8) section, show results and recommendations.

OPERATIONAL VARIABLES

This section provides information about several operational effects, including height, water speed, volumetric flow rate, flow rate, air core diameter, and free rotation constant, followed by a discussion on each point. An efficient model for the analysis of flattened water vortices was built by Guzman et al. [14] using just the water head and geometric factors as inputs. The model found that the simulated results matched experimental findings very well, and it computed the maximal volumetric flow rate, air core diameter, and free rotation constant. Zeng et al. [15] studied the turbulent flow of Francis turbine tubes experimentally and computationally. And by using the FLUENT program in this research. This allowed them to simulate the flow of the intake pipe to calculate the three operating States of the turbine correctly. Obozov et al. [13] found a significant match in the data through comparison. Examined the operational characteristics of spinning turbines and assessed the degree to which rotational speed influences load and efficiency. The researchers also evaluated the impact of the central gap in the turbine blades on their efficiency using the KompasFlow program. The findings revealed that the rotational speed decreases with increasing load regardless of the turbine types employed. Additionally, a specific loading period was identified during which maximum efficiency is attained. Saleem et al. [16] examined the effects of flow rate, vortex height, shaft diameter, blade position, and incision angle using different blade shapes and configurations. They concluded that optimal results are achieved when the vortex reaches its maximum height, the incision angle is reduced, and the blade is placed at the minimum possible distance from below the basin. Nasuki et al. [17] conducted an experimental investigation where they manipulated the flow rate and water pressure variables to examine their effect on the operational efficiency of the vortex power plant. The goal was to study the impact of different water flow rates and pressure at a fixed location on the turbine rotation speed. The test results, measuring water discharge into a closed basin, reveal an average discharge value flow rate of 81.08 liters/s. Kueh et al. [18] concluded that the behaviour of the water vortex influences the choice of turbine blades for a water vortex power plant. They studied two scenarios, each with a hole of different sizes for water flow. The vortex height corresponds to the first case's experimental and computational fluid dynamics results. The experimental result and the final vortex height predicted by the computational fluid dynamics model vary for the second case. The computational fluid dynamics model makes more and more mistakes in its forecasts to create a water vortex as the discharge hole grows larger and turbulent flow enters the system. Nishi et al. [19] studied the flow field and gravity vortex water turbines experimentally and computationally, as shown in Figure 3. It is proven that raising the runner inlet rotational speed increases the onward flow area. However, the backflow area grows when the volume of available air decreases. Also, they examined the effect of flow rates on the performance of gravity vortex-type water turbines, and the results showed that the efficiency of the head and the effective turbine increases with the flow rate, resulting in increased turbine output. The most common losses in water turbines were tank and tank outlet losses, followed by friction losses inside the tank. Powalla et al. [20] created a verified digital model of the vortex hydroelectric power station that can be used as a digital twin for further analyses, such as hydraulic property assessments. Three-dimensional acoustic Doppler velocimetry was used to evaluate the flow field. The fluid volume method has also been used to characterize surface free flow. This proves that the model can mimic complex vortex power plant flow conditions. Faraji et al. [21] investigated how four variables (speed, hub-, blade, angle, number of blades, and runner profile) impact GWVHS efficiency. The numerical and experimental results were consistent, with coefficient of determination values of 0.95 and 0.96 for flat and curved shapes, respectively. As seen in the selected factors, they interact to affect the efficiency of the GWVHS. The efficiency of the curved blade has been enhanced by 3.65% through digital analysis. The flat runner profile showed an increase in efficiency of 1.69% compared to unimproved conditions. Vertical-axis hydrokinetic turbines have emerged as a possible alternative for harnessing low-velocity currents. Consequently, a model of a vertical-axis turbine has been developed and fabricated to conduct experiments in an open channel by Yosry et al. [22]. The primary objective of this simulation and study was to accurately depict the air-water interface and examine the effect of fluctuations in the free surface on turbine output. Experimental investigations subjected the turbine model to different flow conditions and free surface levels. It has been observed that the maximum power coefficients show an increase in conjunction with the upstream speed.

Pamuji et al. [23] examined the effect of changes in the vortex pool. The configuration is based on operational efficiency and flow characteristics of the gravitational water vortex power plant. The cylindrical vortex basin is modified to become a conical basin by treating the ratio between the inlet and outlet diameters (Din/Dout) with values of 3.26, 4.9, and 6.12. The research shows that the most significant speed profile is near the discharge hole. Moreover, it indicates that an increase in the ratio of the inner diameter to the outer diameter (Din/Dout) or a decrease in the



Inlet diameter: D_1	0.14 m
Outlet diameter: D_2	0.09 m
Inlet width: b_1	0.091 m
Outlet width: b_2	0.091 m
Inlet angle: β_{b1}	71.9°
Outlet angle: β_{b2}	19.0°
Number of blades: z	20
Tip clearance: δ	0.5 mm

Figure 3. An illustrative view of the gravity vortex type water turbine tested, which is mainly composed of the runner and a tank, as well as the specifications of the test runner [From Nishi [19], with permission from Elsevier].

Table 1. A concise synopsis of research papers on the topic of enhancing the efficiency of vortex water plants

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Obozov et al.	[13]	2023	Kyrgyzstan	Experimental study	Findings show that, for all investigated turbine types, rotational speed drops with increasing load and that maximum efficiency is attained at a specific load interval.	Efficiency drops with increasing load; specific load intervals optimize performance.	Rotational speed decreases with load increase, highlighting the need for load optimization.	Limited turbine type and load conditions were tested; broader studies are needed for validation.
Guzmán et al.	[14]	2021	Peru	Analytical and simulated study	This model adequately describes the relationship between depth and discharge in a full-wide vortex. This feature makes the model suitable for both the analysis and design of new vortex systems and existing ones with fixed geometry.	The model was validated for depth-discharge relationships and is suitable for vortex design and analysis.	The framework is reliable for fixed geometry systems applicable to new and existing designs.	Relies on simulation; real-world validation is needed.
Zeng et al.	[15]	2012	China	Analyzed and numerically simulated the study	When it comes to improving power quality, predicting the unit's stable operating zone, designing the ideal turbine, and ensuring the unit's stable operation, these studies are crucial.	Predicted stable operational zones; critical for turbine design and power quality improvement	Accurate zone prediction enhances turbine performance and operational reliability.	Simulation results are not generalized across different turbine designs and setups.
Salim et al.	[16]	2020	Indonesia	Experimental study	They concluded Optimal outcomes are achieved when the vortex attains its greatest height, the slit angle is minimized, and the blade is positioned at the lowest feasible distance from the pelvis bottom.	Vortex height and reduced incision angle enhance efficiency; blade positioning is critical.	Optimizing vortex height and blade positioning improves low-head system performance.	Results apply mainly to small-scale systems; broader validation is needed for scalability.
Nasuki et al.	[17]	2021	Indonesia	experimental investigation	Water pressure and discharge rate were adjusted. This study also used open and closed basin positions, measured water outflow in a closed basin, and found an average Q of 81.08 liters per second.	Examined flow rates and pressure; closed basin averaged discharge of 81.08 l/s	Basin design significantly influences efficiency; the average discharge rate is observed.	The study lacks a detailed analysis of other basin configurations or conditions.
Kueh et al.	[18]	2014	Malaysia	Numerical Analysis	Two cases were studied, with two gaps of different sizes for water drainage. As the discharge gap expanded, the turbulent flow began to increase, causing more errors in the computational fluid dynamics model in predicting the formation of the water vortex.	Turbulence affects computational fluid dynamics accuracy; discharge gaps influence vortex formation.	Large discharge gaps lead to turbulence; vortex modeling needs refinement.	Prediction errors in computational fluid dynamics models; turbulent flow increases inaccuracies

Table 1. A concise synopsis of research papers on the topic of enhancing the efficiency of vortex water plants (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Nishi et al.	[19]	2020	Japan	experimental and computational study	Impact of flow rates and common losses on the performance of a gravitation vortex-type water turbine. Turbine efficiency increased with the flow rate, and the most common losses in the water turbine were tank and tank outlet losses, followed by friction loss inside the tank.	Flow rates and losses analyzed; higher rates improve efficiency but increase losses	Efficiency is linked to flow rates; tank and outlet losses are primary inefficiencies.	Losses not fully mitigated; further study needed for tank friction reduction
Powalla et al.	[20]	2021	Germany	Numerical and simulation study	A comprehensive comparison of the water level and flow velocities at the sites of important devices shows that the simulations agreed with the experimental results.	Developed digital twin for vortex simulation; accurate hydraulic property assessments	Accurate 3D modeling aligns simulations with experimental data.	Simulation outcomes require validation through physical experiments.
Faraji et al.	[21]	2022	Tanzania	Numerical and experimental investigated	These operations were simulated to calculate system efficiency. The numerical and experimental results were consistent; the Numerical study increased curved blade profile runner efficiency by 3.65%.	Blade shapes tested with curved blades showed a 3.65% efficiency improvement.	Blade geometry significantly impacts turbine efficiency	Experimental validation is needed to confirm numerical results
Yosry et al.	[22]	2023	Spain, Egypt	experimental and numerical study	A model of a vertical-axis turbine has been developed and fabricated to conduct experiments in an open channel to analyze a three-dimensional multiphase system.	Vertic al-axis turbine developed; upstream speed increases power coefficient	Upstream speed strongly correlates with turbine performance	Field testing is required for reliability in real-world conditions
Pamuji et al.	[23]	2019	Indonesia	numerical study	The research demonstrates that the greatest velocity profile is near the discharge orifice. Furthermore, it indicates that an increase in the ratio of the inner diameter to the outer diameter (Din/Dout) or a reduction in the size of the output orifice leads to a heightened circulation of the vortex.	Conical basins improve vortex velocity near discharge; circulation increases.	Diametre ratios enhance vortex circulation and rotational force	Findings specific to experimental setups; general applic ability uncertain
Herbhakti et al.	[24]	2021	Indonesia	Experimental and numerical study	The maximum strength, at 12.24 m2/s, was seen in the 30-centimeter exit slot. With a strength of 14.13 m2/s, the output slot measuring 35 cm was the strongest.	Tube diameter affects vortex strength; a 30 cm outlet achieved the highest strength.	Large outlet diameters increase rotational force and vortex strength	Limited to specific outlet sizes; environmental conditions not tested

Table 1. A concise synopsis of research papers on the topic of enhancing the efficiency of vortex water plants (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Ghani et al.	[25]	2019	Germany	experimental study	This study found that at 500 l/s and 0.7 m head, the water vortex power plant reached 43% efficiency, while at 700 l/s at 0.92 m head, it reached 38% efficiency without air vortices behind the turbine.	43% efficiency achieved at 500 l/s, 0.7 m head, no air vortices behind the turbine	Fixed flow-head combinations optimize turbine output efficiency	Findings lack insights into design optimizations for varying conditions
Shabara et al.	[26]	2015	Malaysia, USA	Experimental and Simulation study	This study used the commercial computational fluid dynamics tool ANSYS Fluent to mathematically model the free surface flow and find the optimal configuration for the vortex pool system.	ANSYS Fluent modelled vortex pool systems; validated computational fluid dynamics results with experiments	computational fluid dynamics models enhance design accuracy and are suitable for optimal pool configuration testing	Focused on specific configurations; broader basin designs need testing
Wanchat et al.	[27]	2013	Thailand	simulated and computational study	The tangential and radial velocity distribution determines the turbine blade for testing, and computational fluid dynamics simulates the vector flow field.	Simulated basin structures, flow rates and vortex heads influence velocity fields.	Basin optimization enhances flow dynamics and turbine compatibility	Simulation-based results need real-world validation across diverse environments

size of the output hole leads to an increase in the rotation of the vortex. Herbhakti et al. [24] examined the impact of vortex tube diameter and tube basin outflow slot on vortex strength. Results showed that vortex strengths varied at different diameters, with 25 cm having the highest strength at 7.53 m^2/s. The 30 cm outlet slot had the highest strength at 12.24 m^2/s. The 35 cm output slot had the highest strength at 14.13 m^2/s. A 35 cm diameter tube had the highest vortex strength due to water flow-induced vortex intensity fluctuations. Ghani et al. [25] proved, according to this research, that The Water Vortex Power Plant achieved a maximum efficiency of 43% at a flow rate of 500 l/s and a head of 0.7 m, while at 700 l/s and a head of 0.92 m, it achieved 38% without air vortices under the turbine. This level reached the peak power output of 2.45 kW, comparable to the values offered by firms like Ecoligent, and was confirmed by Mühle et al. 2013 study. Shabara et al. [26] explained in this paper the efforts to improve the vortex pool and to convert the energy better. This study developed a free surface flow mathematical model using the ANSYS Fluent computational fluid dynamics commercial package. Also, a pilot testing platform was built to validate computational fluid dynamics results. The verification results show that the system can be accurately designed using ANSYS Fluent. Wanchat et al. [27] analyzed and developed a basin structure capable of producing a gravitational vortex Current potentially harnessed as an alternative energy source. Various parameters, such as the gravitational vortex head and the flow rate, affect the velocity vector's flow field. The transverse and diagonal speed distribution determines which turbine blade is suitable for testing, and the vector flow field is simulated using computational fluid dynamics. The production of electrical energy is being studied by developing a model of a gravitational vortex power plant. The articles related to the impact on operational variables have been summarized in Table (1), and it can be seen from this Table that the highest operational variable is the vortex, which reaches its maximum height.

EFFECTS OF DESIGN VARIABLES

In this section, some design behaviors of the turbine and basin, such as blades, the dimensions of blades, the shape of the basin, the conveyor channel, and other factors, will be described.

Turbine

Using both an analytical and experimental approach, Ullah et al. [28] analyzed the performance parameters of a multistage gravitational water vortex turbine assembled in a cone-shaped trough, including rotational speed, torque, power, and efficiency, while subjecting it to various loads. Moreover, runners with inclined blades on a vertical plane are most suitable for planting near the bottom of the basin. The multiple gradations in gravitational water vortex turbines also demonstrate the evolution of the combined rotation of a solid body and a free vortex. The turbine performance also improves significantly over the single-stage gravitational water vortex turbine. Candra et al. [29] conducted a study to determine the best runners for use in the laboratory's small-scale vortex turbines and compare the different sinkhole efficiencies of Kaplan, Francis, and Vortex turbines to determine the most effective design. Next, they used a statistical method from the collected data on drains designed to have five blades with a slope of 45°, a diameter of 12 mm, and a constant flow rate of 240 L/min. The energy input from the water (Pa), the energy output to the water (Pt), the torque (T), and the rotational speed (ω) are then measured. The information collected will result in proficiency scores for each runner, such as 21% for the Francis runner and 21% for the Vortex runner. A study was undertaken by Zuhri et al. [30] to investigate the impact of the distance between the L-type turbine and the cylindrical basin. Regarding power efficiency, the Model L turbine, positioned 5 cm away from the cylinder basin wall, demonstrates the highest effective power output of 2.89 W at a height of 10 cm. Conversely, the Model L turbine, positioned 10 cm away from the cylinder basin wall, exhibits a maximum effectual power output of 0.14 W at a height of 10 cm from the water outlet. Wardhana et al. [31] studied the number of turbine blades and their role in determining the turbine's efficiency. The results showed that increasing the number of blades reduces the efficiency of the turbine; 'in other words, six-bladed turbines are less efficient than three. Joshi et al. [32] conducted an experimental and computational examination of applying the Gorlov turbine, a pure reaction turbine, to harness electricity. The computational analysis was performed using ANSYS Fluent, while the experimental research involved using spiral turbine blades created using a 3D printer. Both computational and experimental investigations show that increasing the turbine aspect ratio while maintaining constant stiffness significantly improves efficiency. Subekti et al. [33] presented the numerical optimization and performance testing of the turbine driver profile for a vortex water turbine; MATLAB software was used to enhance the basic design of the turbine driver and determine the optimal inclination angle. The results were in a laboratory experiment where rotational speeds ranging from 150 to 650 rpm were used to assess turbine efficiency, torque, and power. Experimental results showed that the efficiency of the optimized turbine was 45.3%, representing an increase of approximately 14% over the efficiency of the first design turbine, which was 39.7%. Khan et al. [10] conducted a study to determine small hydropower station efficiency and ability to provide clean energy. An impulse turbine is the type of turbine used. The turbine rotational speed can be increased to improve efficiency by adjusting a blade angle and increasing the blade's surface area using baffle plates. For the curved blade shape, it was found that an efficiency of 82% could be achieved with a 5-blade design and a blade angle of 44°. Because of this, there has been a rise in total electricity generation. The four-blade turbine achieved an efficiency of 79.95% from the geometric parameters used in the design of the system, and the result is shown in Table 2 and Figure 4.

Wichian et al. [12] presented a study to enhance the operational effectiveness of vortex turbines by installing barrier plates on the propellers. The study used computational fluid dynamics software to develop the barrier panels and determine their optimal application size and ratio. Experimental results indicated that five barrier plates at 50% of the propeller barrier area gave the maximum torque. In addition, experiments were conducted involving propellers without barrier plates and a turbine with barrier plates at 50% coverage. Results indicated that the turbine with a 50% barrier ratio showed an increase in torque of 10.25% total efficiency and 4.12% on average. Sharif et al. [34] studied five types of runners numerically. The top three competitors were selected for testing based on the amount of water pressure placed on the blades. The researchers examined how blade shape affects rotational speed, braking force, and mechanical efficiency. It was found that the curved circular chute blades worked at a rate of 48.02%, while the J-shaped chute blades and helical blades worked at a rate of 42.17% and 38.64%, respectively. Bajracharya et al. [35] provided an essential guide to runner design for a gravity water vortex turbine, as shown in Fig.(5). Seven

Table 2. The values of important parameters in the design of the system

Parameter	Value	Unit
Curved blade angle	44	degree
Blade number	5	none
Gate angle	15	degree
Notch angle	10	degree
Notch inlet width	0.15	m
Cone angle	67	degree
Channel height	0.18	m
Channel width	0.144	m

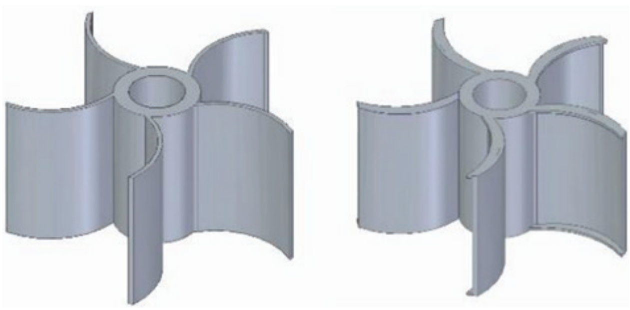


Figure 4. Two types of turbines with and without baffle plates.

different runner geometric parameters were relied upon for the runner design. Then, numerical and physical analyses were conducted to determine these parameters' impact on the system's efficiency. Then, the effect of these factors on both speeds and torques was studied. Test results show that runner height is the most important factor when creating a runner for a GWVHS. When tests were performed, it showed that the Gravity Water Vortex Turbine performed up to 47.85% better. Cheema et al. [36] conducted an efficiency analysis of a two-stage gravity water vortex turbine (GWVT) operating at varying flow rates and vortex heights. The two-stage GWVHS raises the performance characteristics with rising flow parameters. The highest hydraulic head drop close to the orifice also causes a high tangential velocity, aiding downforce production. Honnasiddaiah et al. [37] used a V-shaped rotary blade in their system. Based on the results of experimental and numerical analyses, it was determined that the blade format called V4 showed the best performance, yielding a maximum power factor of 0.22 and 0.21, respectively, when operated at a terminal speed rate of 0.87. The blade profile shows the maximum power factor exceeding the semi-circular blade profile by a margin of 19.3%.

Sritram et al. [38] compared the "Water Free Vortex Turbine" to the "Under Shot Water Wheel" to examine the efficiency of hydropower turbines at low water. In addition, the Small "Under Shot Water Wheel" produced greater torque than the Water "Free Vortex Turbine," while the latter made a faster cycle and more usable energy. At a headwater height of less than one meter, it may be determined that the Water Free Vortex Turbine. It is preferable to the Small Under Shot Water Wheel as a small hydropower electricity generator. Dahal et al. [39] focused on the viability of booster-based GWVPP. This study investigates the potential for boosting power output by installing a second, smaller runner (booster runner) beneath the primary runner, which was subsequently empirically confirmed in a model constructed with four distinct booster runners. The studies demonstrated a boost of 3.84W in the compact model, equivalent to a 20.4% gain in efficiency from a total of 63.55% by the main runner alone. Adding the booster runner to the current setup can potentially increase power output. Dhakal et al. [40] focused on optimizing the runner to improve the efficiency of the Gravitational Water Vortex Power Plant. Runners with straight, twisted, and curved blade profiles are analyzed using computational fluid dynamics, as shown in Fig.(6). compared to the 46% efficiency of the straight blade runner and the 63% efficiency of the twisted blade version. Computational fluid dynamics analysis found that the curve blade design is the most efficient.

A model-free vortex power generation system was developed and tested by Rahman et al. [41] to determine what conditions would result in the most efficient operation of the power station. A few search results were: According to the data, a turbine with 3 blades and an External diameter of 0.027 m can attain a maximum efficiency of around 43% at a water pressure of 0.12 m. Maximum hydraulic

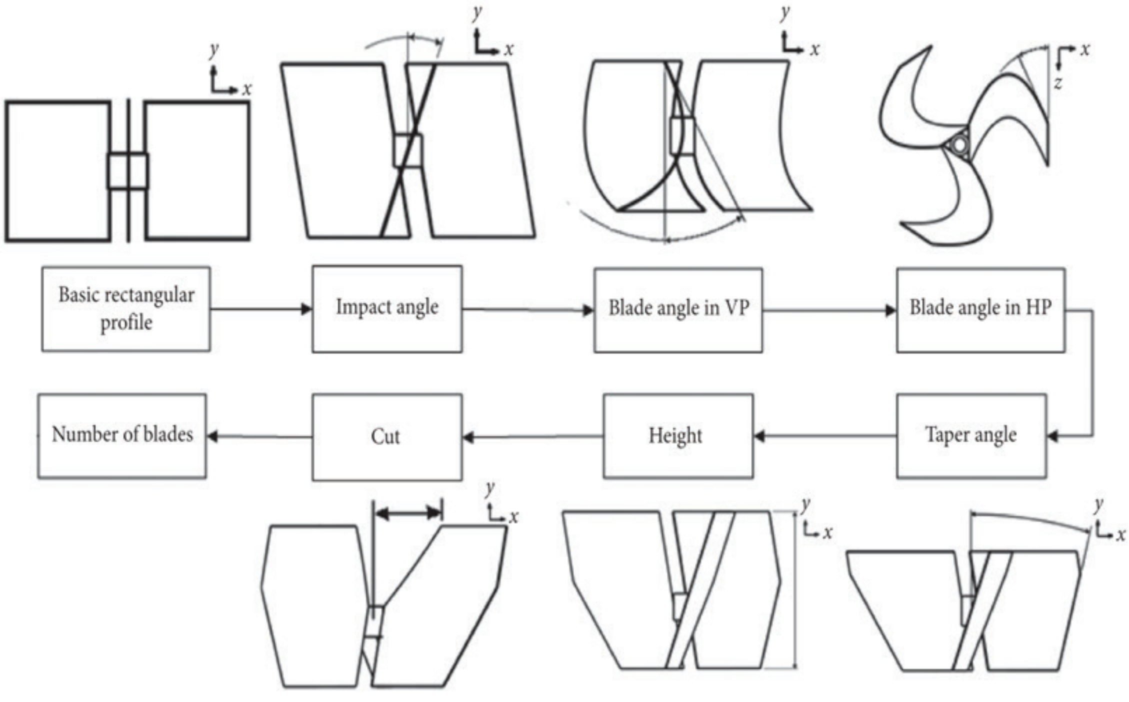


Figure 5. A geometrical feature has been added: a higher blade surface area and appropriate blade angles but maintaining a low runner weight.

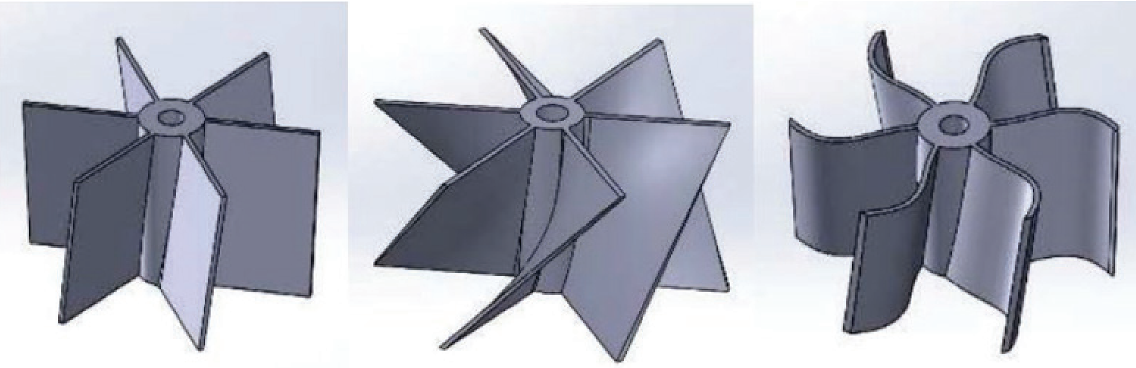


Figure 6. A three-dimensional computer-aided design (CAD) model with straight-ahead, turned, and curved blades.

efficiency was likewise seen in the model vortex power generating system when the rotating speed of the turbine was equal to or less than half the vortex tangential velocity. Hidayat et al. [42] modified the design and built a spiral hydro turbine to produce a spiral vortex to drive the turbine. The findings demonstrate that the spiral vortex hydro turbine may generate faster turbine rotation compared to a standard water intake. This study shows that a portable spiral vortex hydro turbine can spin at speeds of up to 90 revolutions per minute. This has led to the generator output voltage growing as the turbine rotation speed grows. Kueh et al. [43] aimed their research at studying the effects of operational speed and blade geometry on turbine efficiency. Two turbines equipped with flat blades and those that are curved are both evaluated and then compared. Both turbines exhibit equal rotational speeds under no load conditions. The flat-blades turbine demonstrated a peak efficiency of 21.63% when operating at a rotational speed of 3.27 rad/s, while the curved-blades turbine achieved an efficiency of 22.24% at a rotational speed of 3.5 rad/s. When a load is applied during operation, the turbine blades utilize a backward-leaning curve to mitigate the disturbance on the water vortex, resulting in improved performance. As shown in Fig.(7), the speed triangle and resultant streamline of water vortex flow. Zariatin et al. [44] resulted from their study of constructing a vortex turbine power station of laboratory size. They examined three runners constructed of rust-resistant materials: SS-304, AA-5057, and PVC. Each of these runners produced 3.98 W of electric power, 3.47 W of electric power, and 3.3 W of electric power, respectively. You can use it to activate a 3-watt LED light. An efficiency of up to 31.8% is achieved compared to the 12.5 Watts of

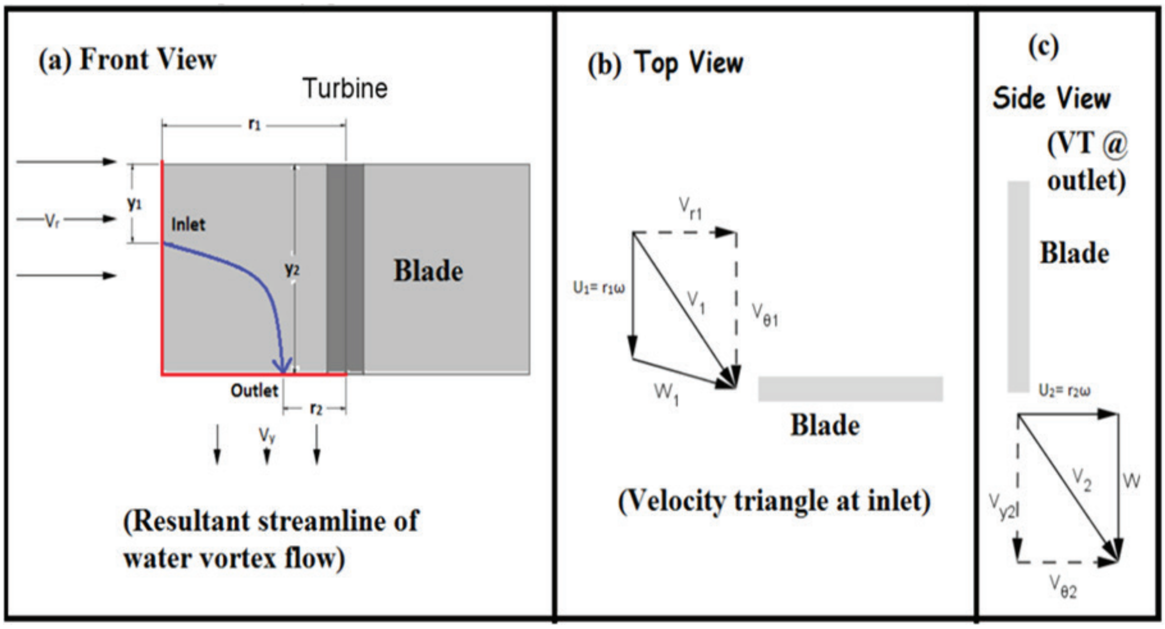


Figure 7. Water vortex turbine blade with a speed triangle.

potential hydraulic power computed. The runner's weight is an essential factor influencing the electric power produced. Assuming the water rotational potential is sufficient, a heavier runner will generate more power due to its more significant moment of inertia and, thus, greater torque.

Saleem et al. [45] studied several factors to determine their impact on performance parameters, including swirling elevation, runners' position, blade submersion percent, notch-angle, blade dimension ratio, blade curve, blade tilt, hub diam, and conical, straight blades. According to the experimental findings, the two most important factors determining Gravity Water Vortex Turbine performance are the height of the vortex and its shape, which should have a fully developed air core. Using zero-curvature tilted blades closer to the pool bottom, and the GWVHS can operate more efficiently with a minimal notch angle and hub diameter in the rotational speed range between minimum and maximum load conditions.

The study's overarching aim of Sritram et al. [46] was to study how steel and aluminium turbine materials affected power-generating efficiency in a waterless vortex hydropower station. Based on the data, the most efficient turbine materials were steel (33.56%) and aluminum (34.79%). However, at a high flow of water rate of 3.63 m^3/min, the aluminum turbines exhibited greater torque values and power production efficiency, 8.4% and 8.14%, respectively. The research found that water turbines' higher torque and power-generating efficiency were attributable to their reduced weight. Venukumar et al. [47] studied and discussed the natural whirlpool production of fluids, a turbulent circular movement of fluid layers generated for artificial vortex power generation. A vertical-axis turbine is built to imitate this motion with as little interference as possible. A strong gravity Water Vortex in the rotation tank harnesses the kinetic energy of moving water and directs it as rotational energy toward a turbine located at the vortex center. The turbine transforms this rotational energy with a generator into clean electricity. Yaakob et al. [48] provided an overview of small hydropower turbine systems by detailing their performance and identifying their many components. The first is reservoirs with water, river flow, pumped storage, in-stream, and innovative gravity swirl methods. Another way to categorize hydropower is by power size, which goes like this: large, small, micro, and pico. The study above can aid in finding the best turbine configuration for different microhydropower projects. Fig. (8) shows the rotor response with a split pipe. Mehmood et al. [49] aimed to develop and create a turbine that can generate electricity from canal systems by utilizing whirlpool and vortex principles. The turbine's vertical axis cross-flow makes it efficient, easy to install, and kind to marine life and the environment. It is a low-water head turbine with a submerged generator that can generate electricity from waterways. The turbine can operate continuously due to its durability and adaptability, reducing the need for large reservoirs and protecting marine life. The prototype's compact size makes it ideal for use in tight spaces like irrigation systems, where it can efficiently generate electricity.

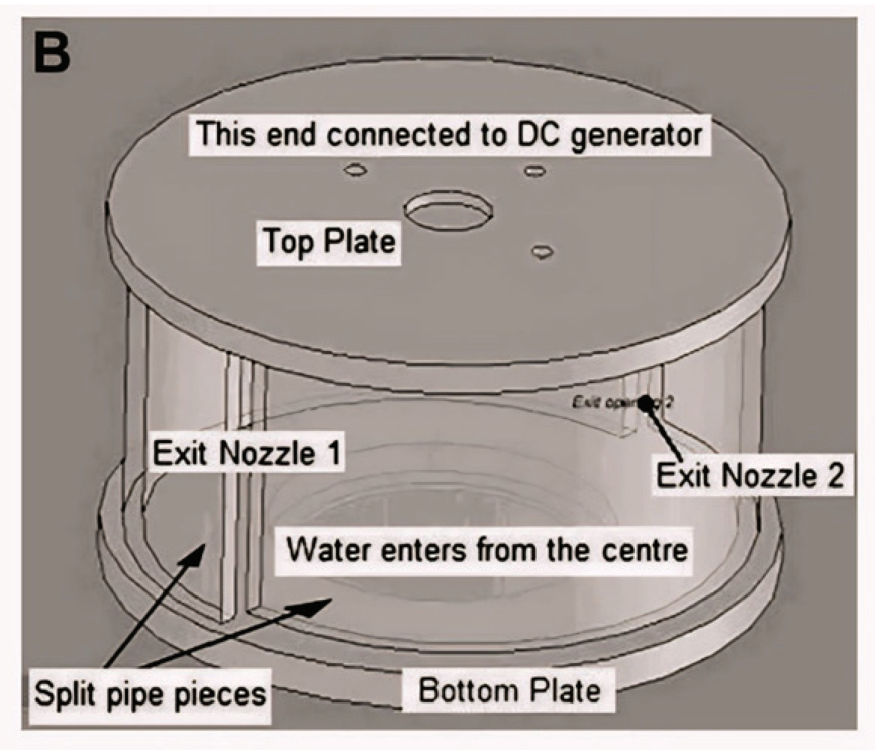


Figure 8. Rotor with a split-pipe response.

Khan et al. [49] focused on improving the efficiency of vortex turbines using a comprehensive design methodology. The project uses ANSYS simulation to predict and study the vortex formed in the main tank, followed by CAD modelling and governing equations. The primary objective is to achieve a watertight seal to protect the generator from harm. Chaulagain et al. [50] focused on Very low-head turbines with hydraulic heads between half a meter and three meters high. These turbines can be installed in single or parallel units and handle potable or treated water. A list of 38 hydro turbines and their operating ranges, compiled from previous research and interviews with 25 turbine manufacturers, is provided. The review offers an optional turbine classification scheme and explains the non-conventional hydropower. Vinayakumar B et al. [51] conducted this research using several modelling, simulation, and testing procedures. Then, details of Gravity Water Vortex simulation in the COMSOL FEA program and optimization settings in the study will be provided by considering various characteristics, including the height of the vortex chamber, blade length, blade angle, and number of blades. They were adjusted systematically to measure how much these factors affect the rotor speed. The article also details the construction of a real Gravity Water Vortex, an experimental device developed to validate and evaluate simulation results. Wargetto et al. [52] conducted a numerical study to assess and compare the performance of the vortex using different shapes of blades, including oblique, straight, and curved, as shown in Fig.(9). After studying these various shapes, the researcher concluded that the best performance of the water vortex is using inclined blades, which have a hydraulic efficiency of 36%. A numerical study using the Ansys Fluent program was conducted by Warjito et al. [53] to find out the extent of the impact of the blade size and depth on the efficiency of the turbine. Nine configurations of different sizes were used: 200 mm, 350 mm, 500 mm, and turbine depths of 270 mm, 340 mm, and 410 mm. The study results showed that the larger size and top position gave the best performance of the turbine, with an efficiency of up to 40.22%.

Putra et al. [54] determined the output torque, rpm, voltage, current, and power generated by a gravity vortex power station and compared the effect of turbine position height on the data results obtained using a cylindrical basin, using L and S models with four turbine blades and using differences in height as shown in Fig. (10). The most significant electrical power using an L model turbine obtained an electrical power of 1.368 watts. Meanwhile, in the Model S turbine, the most considerable wattage was obtained at 2.097 W. An effort was made to compare and contrast

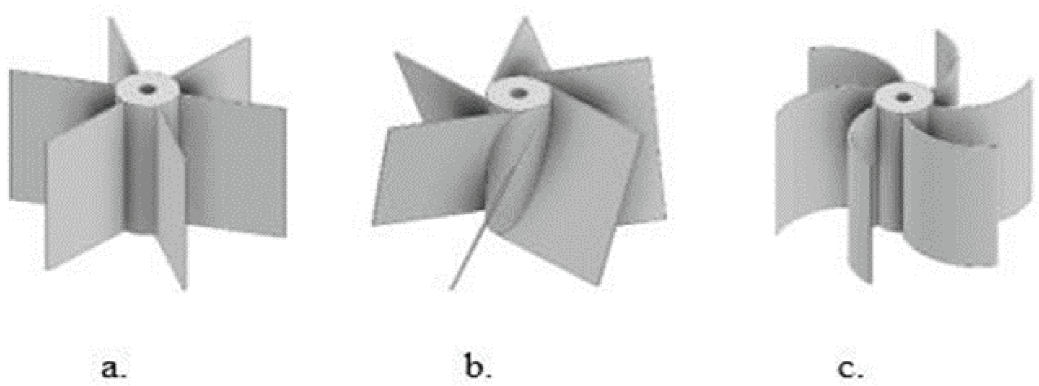


Figure 9. Design by wargetto et al. (a) Straight blade (b) Tilted blade and (c) Curved blade.

Table 3. Comparison between aluminum and steel in turbine design regarding efficiency, environmental impact, and durability

Factor	Aluminum	Steel
Efficiency	Higher efficiency of 34.79% due to lighter weight.	The efficiency is 33.56%, lower compared to aluminum.
Environmental impact	Highly recyclable and reduces environmental emissions.	Requires energy-intensive manufacturing, increasing emissions.
Weight and effect	A lighter weight reduces the required torque and increases rotation speed.	The heavier weight provides greater stability but adds more pressure.
Operational conditions	Ideal for systems with high water flow and light conditions.	More suitable for systems requiring high durability[46].

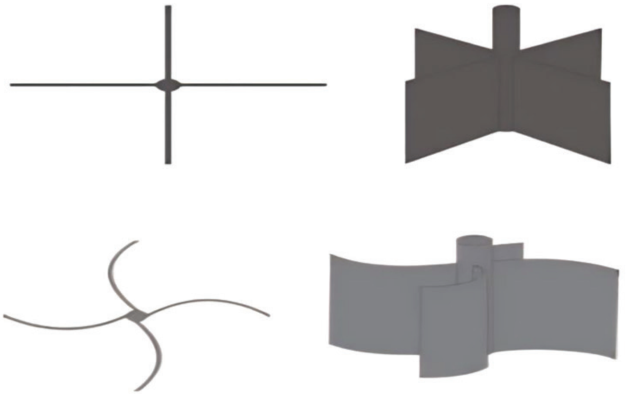


Figure 10. Two models of turbines (Model L and Model S).

several GWVHS microcosms in the study presented by Sedai et al. [55]. First, they analyze the success of different experimental investigations and formulations in Nepal. After that, several computational types of research are analyzed. A 1:20 scale model was then developed to be built in Johannesburg, South Africa, and performance predictions were based on comparing computational and experimental data. Kueh et al. [18] highlight the significance of water vortex behavior concerning the experiment setup. Two different sizes of slots were used to release water. The computational fluid dynamics model inaccurately predicts the creation of water vortices as the discharge slot enlarges due to the increased turbulent flow. The Computational Fluid Dynamics model enhances turbulence modelling.

Basin

According to Srihari et al. [56], vortex power is vital to maximizing the efficiency of the turbine, and this work is based on the intensification of the water vortex in the conical trough. The effect of the vortex condensate nozzles' orientation, alignment, and placement in five cone-shaped basins was studied. The study findings show that compared to the swirling turbine and others, the proposed Group III configuration basin increases torque by 57.7%, power output by 54.4%, and efficiency by 54.4%. The comparison highlights the trade-offs between aluminum's efficiency and recyclability versus steel's durability and higher environmental impact, as summarized in Table 3. Wilson et al. [57] conducted the study using computational fluid dynamics within the ANSYS software to simulate micro-gravity vortex motion. This study investigates a structure that has the potential to generate a gravity-eddy current by utilizing flowing water with minimal variation in height, as shown in Figs. (11 & 12).

Chattha et al. [58] improved the performance of gravitational water vortex turbines and examined several design configurations using computational fluid dynamics technology that creates a powerful vortex capable of driving the runner. Apparent differences in the resulting vortices were observed when the basin entry velocity, height, outlet diameter, inlet channel width, depth, and flow rate were varied. As a result of our analysis, the optimized design parameters increase station efficiency and produce a powerful air-engraved vortex. According to the Gravitational Water Vortex Power Plant numerical and experimental research by Dhakal et al. [59]. the conical basin is superior to the cylindrical basin in terms of output power and efficiency for all inlet and outlet conditions that are otherwise identical at 65–75% of the basin height, the optimal location for power extraction. It has become clear that future research into this system should focus on optimizing runner shape and studying alternative basin structures

Dhakal et al. [60] focused on a form of micro hydropower known as a GWVHS that generates electricity in remote regions with extremely low heads (between 0.73 and 3 meters). This research determines the geometrical requirements for the entrance and exit of a recently lauded efficient conical basin design, including the basin

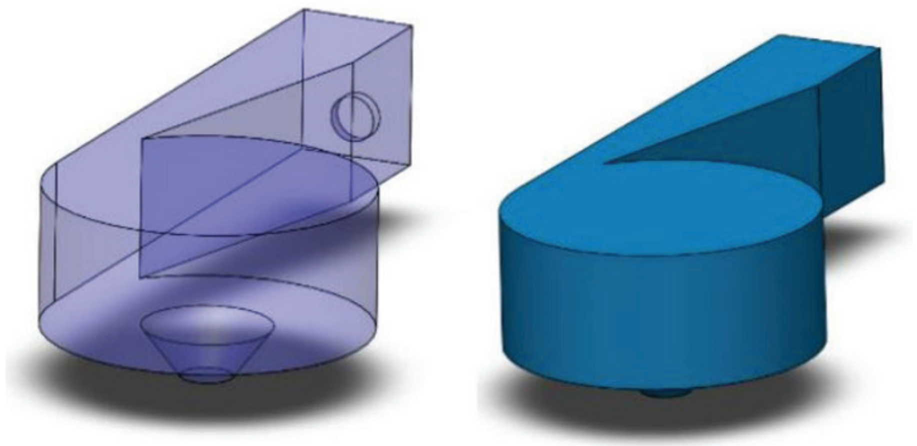


Figure 11. Design model developed by the ANSYS program and used in their research.

Figure 12. A water volume fraction from the front.

diameter and outlet diameter. by using Solidworks to develop our geometric CAD models and ANSYS CFX for our simulations. Finally, four different types of basins were designed and used during experimental tests, and these tests achieved a relationship between the engineering properties and the above parameters. Huwae et al. [61] discuss Vortex flow as a homogeneous, free-surface-flowing fluid consisting of water and air. The low-head little hydropower station is an ideal setting for this water vortex. The geometry of basins is the main focus of this research. The outlet diameter, depth discharge, and basin shape are modelled. It is determined that the flow rate and water head are the basin parameters that should be used to describe the water origin. It demonstrates that a spiral geometry basin can be utilized instead of a conical basin since it produces a vortex that is both symmetric and forceful. Huwae et al. [62] researched to prove that GWVHS requires less capital investment and lower operating and maintenance costs. Moreover, since basin opening and outlet diameter are the major criteria for defining basin geometry, inlet channels need to undergo additional Research. This study will fill in some of the blanks left by previous studies, opening the door to developing vortex turbines that will immediately impact renewable energy development in Indonesia via the GWVHS. This study by Rahman et al. [63] showed that a cone-shaped basin performs better than a cylindrical one. In addition, the inlet flow rate has significant effects on efficiency. Investigated Gupta et al. [64]. In this study, the gravitational generation of a water vortex flow is a novel approach in hydropower engineering. The work uses simulation techniques to accurately determine the details of water vortex formation. Computational fluid dynamics models incorporate the appropriate boundary conditions based on the experimental setup. The experiment tested two distinct aperture diameters for water outflow in two settings. The initial condition demonstrated that the vortex heights in the experiment and the computational fluid dynamics model were in accordance. However, in the second condition, the final vortex height varied due to a more turbulent flow. Dhakal et al. [65] aim of their study was to improve the design of a conical basin in a water-gravity vortex power plant. This is achieved by modifying four design parameters: the notch angle, canal height, notch inlet width, and cone angle. Various geometric models were created using SolidWorks software, and ANSYS Fluent was used for simulation.

Turbine and Basin

Pandey et al. [66] took up the design and configuration of the turbine that achieved maximum efficiency and chose a suitable cylindrical trough to implement this turbine in the GWVHS, as shown in Fig.(13 and 14). In addition, optimizations were made to blade angle, discharge orifice diameter, runner position, and rpm using computational fluid dynamics (CFD)-based optimization techniques. After research into computational fluid dynamics, it was determined that the most appropriate blade angle for the system was 43^{o}. In addition, the system demonstrated an optimal efficiency of 23.639% when operating at a rotational speed of 40 rpm.

Kim et al. [67] looked into how well the GWVHS worked, focusing on the number of blades in the vortex turbine and the draft tube that was added to change the shape of the conical vortex basin, as shown in Figure 15 and 16. The study of Dhakal et al. [68] included two stages. The first stage compares the two turbines' design, production, and performance, and the second stage includes designing and building the conical and cylindrical tanks and comparing the system performance during use. Reducing the number of blades led to an increase in turbine efficiency. Utomo et al. [69] investigated the torque, water discharge, water force, turbine power, and electric power generated by the hydrographic power plant instrument. The results show the highest results with an output of 5 cm, which is 3.46 W

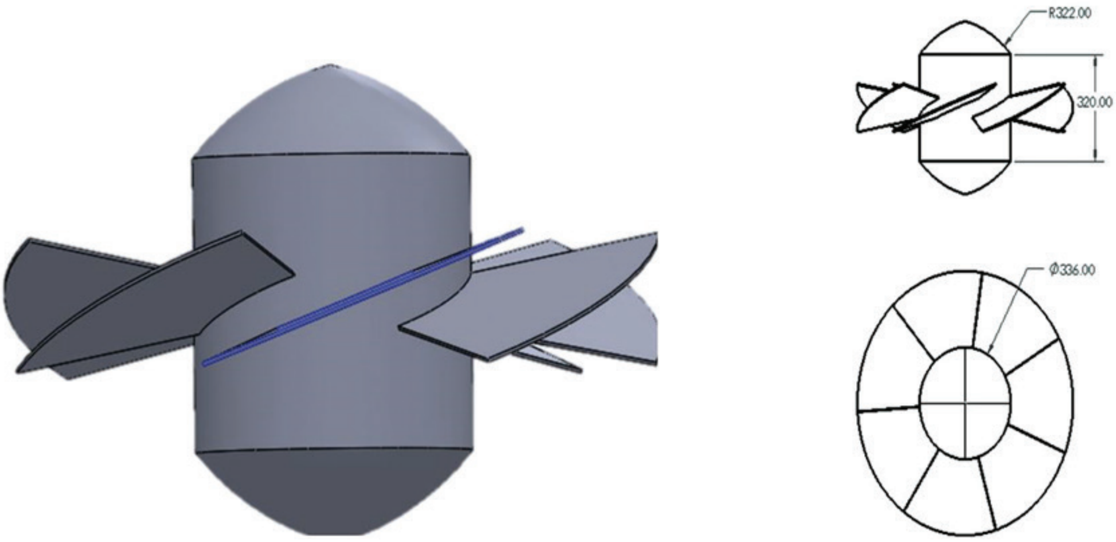


Figure 13. Several views of this runner CAD design.

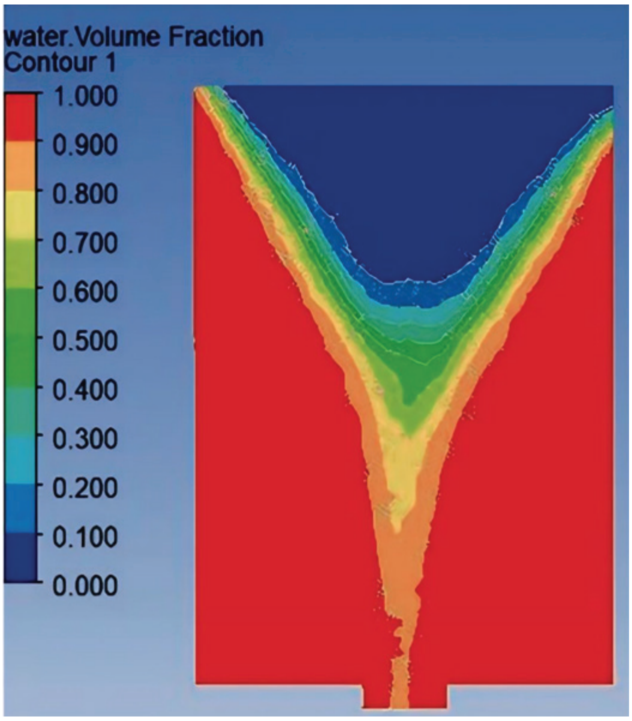


Figure 14. The water volume fraction and formation of the air core of this basin having optimized outlet diameter.

of hydroelectric power at a turbine height of 22 cm, while the production of 6 cm is 2.51 W at 28 cm. Acharya et al. [70] improved the system by combining the results between analytical thinking and numerical accuracy. The system's effectiveness can be changed by fiddling with a number of these variables. However, no advanced calculations have yet been done. So, they are working to improve the station runner so that the Gravitational Water Vortex can generate more power. Then, they analyze the effects of the inlet jet angle and the radius of curvature of the turbine blade on torque, power, and efficiency. Analytical calculation establishes these two values, which are then verified. Maximum torque for an impact jet angle of 18 degrees and a radius of curvature of 285 millimetres differed by 2.37% between analytical and numerical values. Khan et al. [71] analyze the two-stage flow to generate the vortex at different Basin parameters; this work aims to investigate the characteristics that influence computational fluid dynamics, leading to selecting an appropriate basin configuration. After that, the basin was utilized to analyze different blade forms under varied load scenarios. How the vortex height affected the gravitational water vortex turbine efficiency was investigated. Cross-flow blades have demonstrated the highest efficiency for the same discharge and head circumstances among the four types of blades employed in the study.

Tamiri et al. [72] examined different basin configurations, orifice radii, blade layouts, basin shapes, and diffusers. So, the diffuser channels the water into a basin, where its vortex can move in a tangential direction and speed up the flow to the turbine. Simulation results demonstrate that adding a diffuser dramatically increases vortices' tangential velocity and kinetic energy, raising the vortex height, increasing its strength, and influencing its uniformity. Song et al.[73] presented a new system for capturing energy in a fluid vortex that can take advantage of the kinetic energy of flowing water. The system incorporates an impeller, basin, induction pine, and power-capturing devices. SolidWorks, ANSYS ICEM, and ANSYS CFX were used to validate the design. After developing and testing a s.5maller-scale system, a system that can harvest 150 kilowatts of power was built. A preliminary study by Ullah et al. [74] on multistage of Gravity Water Vortex conical bowl staging has tested

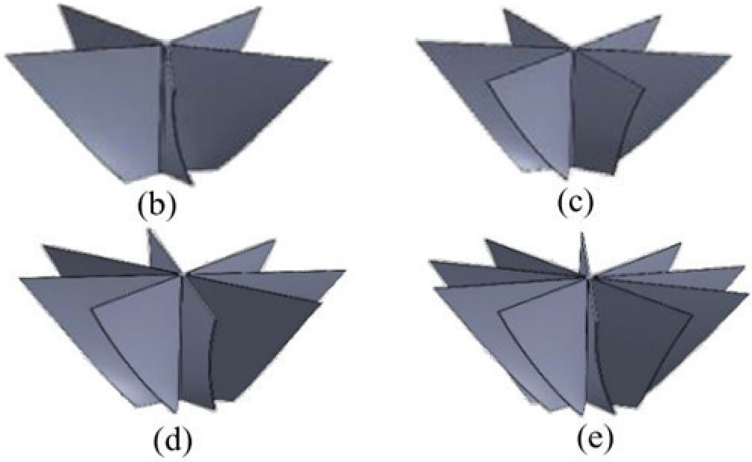


Figure 15. The number of turbine blades [67].

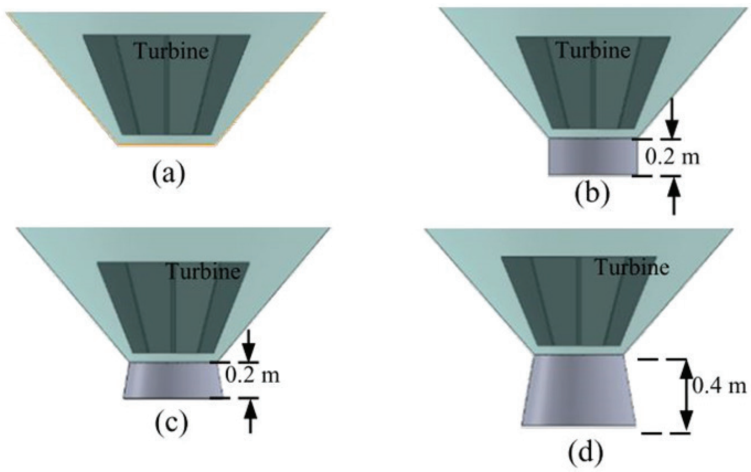


Figure 16. The draft tube straight and cone.

runners of Savonius-type blades. The study reveals that the performance of a Gravity Water Vortex changes depending on key design factors such as the ratio of rotor diameter to basin diameter, the interaction between vortex and blades, stage location, and offset distance between neighbouring stages. The study found that vortex flow can transfer energy across adjacent stages without physical interaction between rotors. Multistage Gravity Water Vortex delivers greater strength than single-stage Gravity Water Vortex by intensifying the swirling in proximity. This research could serve as a standard for future Gravity Water Vortex innovations.

Maika et al. [75] evaluated the development and progress of the GWVHS system on a large scale, incorporating a range of basin types and inlets and the output of canals and turbines. It also discusses vortex dynamics and how to evaluate efficiency. The paper also examines turbulence and multiphase models from top-tier numerical simulation studies. The paper presents the GWVHS system in (Papua New Guinea) as a case study, summarizing the main concerns and challenges and suggesting areas for future research on the system's performance. Zarate-Orrego et al. [76] studied this research: a runner, a cylindrical vortex chamber, and a semi-converging nozzle. Despite challenging testing conditions, the device demonstrated electricity production. To produce power from water levels heads between 0.7 and 3 meters. The research on the effects of design variables has been summarized in Table 4, and it can be seen from this table that the highest design effects are increasing the blade angle to 44 degrees and increasing the surface area using barrier panels and the number of blades to 5. The key design and operational factors and their direct effect on the performance of the GWVHS are summarized in Table 5. All of these significantly contribute to the optimization of the system in terms of efficiency and performance, as well as in its control, energy output, stability, etc, depending on its operational state.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Ullah et al.	[28]	2020	Pakistan, South Korea	Investigated analytically and experimentally	Analyzed the performance parameters of a multistage gravity water vortex turbine (Gravity Water Vortex Turbine).	Enhanced turbine performance by 15% through multistage design optimizations.	Shift towards multistage turbine systems to exploit efficiency at varying flow rates.	Complexity and higher costs associated with multistage systems.
Candra et al.	[29]	2023	Indonesia	A comprehensive review	Utilized a statistical technique on drains with 5 blades at 45 degrees, 12 mm diameter, and 240 L/min constant flow rate. Water energy input (Pa) and output (Pt), torque (T), and rotational speed (ω) are monitored.	Kaplan turbines demonstrated 25% better efficiency under optimized conditions.	The increasing adoption of Kaplan turbines in urban hydro projects is due to their efficiency and adaptability.	High cost and specialized maintenance are required for Kaplan turbines.
Zuhri et al.	[30]	2020	Indonesia	Experimental study	To investigate the impact of the distance between the L-type turbine and the cylindrical basin. The maximum Power efficiency for the Model L turbine is 5 cm from the cylinder basin wall, 2.89 W.	Significant efficiency losses were noted due to improper site selection and setup.	Emphasis on the importance of site analysis for optimal hydro power plant performance.	Site selection constraints can limit viable locations for installations.
Wardhana et al.	[31]	2019	Indonesia	Experimental study	The blade with the twisted shape has the highest efficiency, and the growing Flow velocity determines turbine efficiency; the best turbine is T-3-490, with 25.71%, 35.58%, and 54.40% efficiency at each speed.	It was shown that reducing the blade number can increase efficiency by up to 5%.	Research focuses on optimizing blade numbers to balance efficiency and cost.	Fewer blades may decrease system stability.
Joshi et al.	[32]	2021	Nepal	Computational and experimental study	Increasing the turbine dimensions ratio while keeping stiffness constant Significantly improves efficiency.	Enhanced turbine efficiency by 10% through optimized turbine dimensions.	Increased reliance on computational fluid dynamics to model and predict turbine performance.	High dependency on precise simulations and models, increasing the risk of errors.
Subekti et al.	[33]	2023	Indonesia	Numerical and simulation study	Numerical and simulation optimisation and performance testing to determine the optimal inclination angle. The optimised flow has 45.3% efficiency, up 14% from the baseline design of 39.7%.	Improved efficiency by 8% through precise blade angle adjustments.	Innovations in turbine blade design focusing on adjustable and dynamic systems.	Precise blade angles are crucial, necessitating sophisticated control systems.
Khan et al.	[10]	2021	Bangladesh	A comprehensive review	To Increase turbine efficiency and rotational speed by increasing the blade angle and surface area using barrier plates. A 5-blade design with a 44° blade angle yielded 82% efficiency for the curved blade form.	Efficiency gains are achieved by adjusting blade angles to optimize performance.	Trend towards adjustable blade systems in hydro turbines for enhanced adaptability.	Ongoing adjustments and maintenance increase operational costs.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Wichian et al.	[12]	2016	Thailand	Simulation analysis	To improve the operational efficacy of vortex turbines Using barrier plates attached to the propellers. Fans with a 50% barrier ratio increased their efficiency by 4.12%. They demonstrated a torque gain of 10.25%.	Installing barrier plates increased torque and reduced turbulence.	Barrier plates are becoming commonplace to stabilize water flow and increase efficiency.	Barrier plates add complexity and potential for debris buildup.
Sharif et al.	[34]	2023	Pakistan	Numerical and investigative study	Performed an exhaustive numerical analysis on five distinct varieties of runners. A rate of 48.02% was determined for the curved circular crooked blades, 42.17% for the J-shaped crooked blades, and 38.64% for the spiral blades.	Curved blades improved system efficiency by optimizing water flow dynamics.	Curved blade designs are increasingly favoured for their effectiveness in capturing kinetic energy.	Specialized manufacturing processes for curved blades raise project costs.
Bajracharya et al.	[35]	2020	Nepal	Numerically and experimentally study	The runner design was based on seven distinct geometric factors. The next step was identifying how these variables affected the corresponding speeds and torques.	The critical role of runner geometry is highlighted, achieving up to 12% efficiency gains.	Geometric optimization is increasingly recognized for improving turbine performance.	Specific geometric designs may not be applicable universally.
Cheema et al.	[36]	2019	Pakistan	Experimental study	They tested a two-stage Gravity Water Vortex Turbine with different flow rates and vortex heights to see its efficiency. In a two-stage Gravity Water Vortex Turbine system, the performance characteristics are enhanced as the flow parameters increase.	Two-stage turbines showed over 20% efficiency improvement in pilot tests.	Two-stage turbines are gaining popularity for their ability to maximize energy capture.	Complexity and cost of two-stage systems increase potential for mechanical failures.
C M et al.	[37]	2021	India	Experimental investigation study	Experimental and computational evaluations showed that the blade shape V4 performed best, with a maximum power factor of 0.22 and 0.21 at a tip speed ratio of 0.87. The blade profile has a 19.3% higher maximum power factor than the semi-circular blade profile.	V-shaped blades produced a higher power factor under optimal conditions.	Adoption of V-shaped blades in areas with variable water flow to improve performance.	V-shaped blades require precise engineering and are costly to produce.
Sritram et al.	[38]	2017	Thailand	Experimentally and Analytically study	The small under shot water wheel produced higher torque, while the water free vortex turbine produced more energy and a faster cycle.	Demonstrated effectiveness of low-water turbines for rural applications.	Research into low-water turbines is expanding, aiming to make renewable energy more accessible.	Limited energy output makes them suitable only for small-scale applications.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Dahal et al.	[39]	2019	Nepal	Simulation study	investigates the potential for boosting power output by installing a second, smaller runner (booster runner) beneath the primary runner. The studies demonstrated a boost of 3.84W in the compact model, equivalent to a 20.4% gain in efficiency from a total of 63.55% by the main runner alone.	Secondary boosters increased power output by 20% without significant redesign.	Utilization of booster systems to enhance existing turbine setups is becoming more common.	Adding boosters complicates system dynamics and maintenance.
Dhakal et al.	[40]	2017	Nepal	Experimental and simulation	Computational fluid dynamics studies showed that the curved blade profile was most efficient, at 63% versus 46% for the straight blade runner. With a 0.5 m head, the runner functioned as expected by the CFD study at 71% efficiency.	Runner design optimizations led to a 15% increase in efficiency.	Continuous improvement and testing of runner designs are crucial for advancing hydro turbine technology.	Frequent redesigns and updates may delay implementation and increase costs.
Rahman et al.	[41]	2016	Malaysia	Experimental and simulation	Tested a model-free vortex power generation system to assess the power stations optimal operating. A few search results were: The data shows that a turbine with 3 blades and an Exterior diameter of 0.027 m may achieve 43% efficiency at 0.12 m water pressure.	Optimized operational conditions to enhance turbine efficiency significantly.	Focusing on operational optimizations to maximize energy outputs in varying environmental conditions.	Such optimizations require complex control systems that can be challenging to manage and maintain.
Hidayat et al.	[42]	2020	Indonesia	Design and analysis	The modification is made by designing and building a spiral vortex hydro turbine to produce a spiral vortex to drive a turbine.The findings demonstrate that the spiral vortex hydro turbine may generate faster turbine rotation compared to a standard water intake.	Demonstrated that spiral vortex structures could increase turbine rotational speed and efficiency.	Exploring the benefits of vortex dynamics in improving the mechanical energy conversion processes.	Implementing such designs often involves higher costs and more sophisticated manufacturing techniques.
Kueh et al.	[43]	2017	Malaysia	Experimental study	The aim is to determine how the turbine performs when the operating speed and blade shape are changed. The improvements are examined using the velocity triangle and the Euler Turbomachinery Equation. The flat-blades and curved-blades turbines reached their maximum efficiencies at different rotational speeds; the former at 3.27 rad/s and the latter at 3.56 rad/s achieve 21.63% and 22.24% efficiency.	Investigated the impact of blade geometry on turbine efficiency, highlighting significant improvements.	Emphasis on precision engineering of turbine blades to enhance performance and reduce wear.	Precise blade designs can escalate production costs and require more rigorous maintenance protocols.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Zariatin et al.	[44]	2020	Indonesia	Experimental study	By evaluating three runners: SS-304, AA-5057, and PVC. These runners produced 3.98 W, 3.47 W, and 3.3 W of electricity. The runner weight, due to its larger moment of inertia, affects more electric power production.	Developed a model that shows how material choices affect electricity production and turbine longevity.	Growing interest in material science to extend the durability and efficiency of hydro turbines.	Advanced materials can be expensive and might require new manufacturing processes.
Saleem et al.	[45]	2020	Pakistan, South Korea	Experimental and numerical study	By investigating the PPs of single stage Gravity Water Vortex Turbine within different flow and design scenarios. The results showed that the evolution of the generation structure and the height of the vortex are the most important factors in determining the performance of Gravity Water Vortex Turbine .	Created an economic model that aids in the planning and design of more sustainable turbine systems.	Increasing use of economic modeling to support the development and deployment of cost-effective turbine solutions.	Economic models often rely on assumptions that may not hold true in all operational environments.
Sritram et al.	[46]	2015	Thailand	Experimental study	By studying how steel and aluminum turbine materials affected waterless vortex hydropower station power-generating efficiency. Data showed that steel (33.56%) and aluminum (34.79%) were the most efficient turbine materials. Reduced weight gave water turbines improved torque and power-generating efficiency, according to a study.	Improved efficiency of low-water turbine for rural renewable	Advancing low-head turbine technology for use in shallow water setting	Limited energy output restricts use to smaller-scale applications; efficiency varies with water level change
Venukumar et al.	[47]	2013		Numerical study	Discussed natural whirlpool creation of fluids for artificial vortex (ArVo) power generation. Strong gravity Water Vortex in the rotation tank harnesses kinetic energy.	Showcased how adjustments to turbine nozzles can lead to a 6% increase in overall efficiency.	Innovating within turbine nozzle designs to achieve better control over water flow and energy capture.	Adjustments to nozzle designs may involve trade-offs with system simplicity and reliability.
Yaakob et al.	[48]	2014	Malaysia	A comprehensive review	Hydropower stations are categorized by electric capacity. Hydropower can be huge, tiny, or pico, depending on power size. And concentrating on gravitational vortex micro hydropower increases water quality and sustainability.	Focused on the impact of environmental factors on turbine efficiency, proposing adaptive designs.	Adaptive turbine technologies are becoming crucial for dealing with environmental variability.	Such technologies can increase the overall complexity and cost of hydroelectric systems.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Mehmood et al.	[77]	2019	Pakistan	Design and simulation study	Because of its endurance and versatility, the turbine can run constantly, saving marine life and reservoir space. It generates electricity efficiently in tight locations such as irrigation systems due to the prototype tiny size.	Their research highlighted the effectiveness of using computational fluid dynamics (Computational Fluid Dynamics) to optimize turbine performance.	The use of Computational Fluid Dynamics in designing turbines is gaining traction for its ability to predict and enhance flow dynamics.	High computational costs and the need for expert knowledge can limit the widespread adoption of Computational Fluid Dynamics .
Khan et al.	[49]	2023	Pakistan	Experimental and simulation	Utilizes a thorough design process to enhance the efficiency of vortex turbines. Mechanical losses due to vibrations can be mitigated with a smaller column, which is another objective of the research.	Introduced a new turbine blade design that improved efficiency by reducing drag and increasing lift.	Development of blade technologies that maximize energy extraction from water flow.	New blade designs require extensive testing and validation which can delay commercialization.
Chaulagain et al.	[50]	2023	Nepal	A comprehensive review	Concentrates on very low-head turbines with hydraulic heads that are half a meter to three meters high. The review gives an alternative scheme for classifying turbines and describes non-conventional hydropower.	Studied the long-term impacts of turbine installations on local ecosystems, proposing sustainable practices.	The environmental impact of hydro installations is being more carefully considered in new designs.	Implementing environmentally friendly designs often involves higher initial costs and complex regulatory approval.
Vinayakumar B el al	[51]	2022	India	Experimental and Simulation study	A small, portable power stations that utilizes gravitational water vortex technology is detailed, along with the processes of modeling, simulation, and testing. The height of the vortex room, the length of the blades, the angle of the blades, and the total number of blades were among the many factors considered. A systematic approach was used to alter each of these parameters individually in order to measure their impact on the rotor speed.	Enhanced turbine output by integrating smart sensors to monitor and adjust performance in real-time.	Smart technology integration into turbine systems is on the rise, aiming to automate and optimize operations.	Dependence on technology increases vulnerability to cyber threats and system failures.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Wargetto et al.	[52]	2023	Indonesia	Numerical study	conducted a numerical study to evaluate and compare the performance of the vortex using different shapes of blades, including oblique, straight and curved, as shown in Figure 12. After studying these different shapes, the researcher came to the conclusion that the best performance of the water vortex is using inclined blades, which have a hydraulic efficiency of 36%.	Developed a low-cost turbine model suitable for small-scale applications, making renewable energy more accessible.	Focus on downsizing technology to make it feasible for use in remote and rural areas.	Smaller turbines may not be viable for larger scale applications, limiting their market scope.
Warjito et al.	[53]	2022	Indonesia	Numerical study	conducted a numerical study using the Ansys Fluent program to find out the extent of the impact of the blade size and depth on the efficiency of the turbine through the use of nine configurations of different sizes 200 mm, 350 mm, 500 mm and turbine depth of 270 mm, 340 mm, 410 mm, where the result of the study gives the larger size and top position the best performance of the turbine with an efficiency of up to 40.22%.	Their research showed how variable speed turbines can adapt to changes in water flow, enhancing efficiency.	Variable speed technologies are being explored to maximize efficiency across diverse water conditions.	Such technologies can complicate turbine design and increase the overall system cost.
Putra et al.	[54]	2020	Indonesia	Experimental study	The influence of turbine position height on cylindrical Basin. By Using... L and S models with four turbine blades and height variances place the turbine, varying fluid flow. The largest electrical power L-model turbine power is 1.368 watts. The greatest Model S turbine wattage is 2.097. Most data is generated at the turbine 28 cm height.	Examined the lifespan of turbines under different operational stresses, recommending design alterations.	Longevity and durability are becoming key factors in turbine design to reduce maintenance and replacement costs.	Improving durability often requires new materials or changes in design that can increase costs.
Sedai et al.	[55]	2020	Nepal, USA	A comprehensive review	Computational and experimental data were used to construct a 1:20 scale model designed to be built in Johannesburg, South Africa. This model was then utilized to estimate performance.	Demonstrated a new method for harnessing kinetic energy from slow-moving water, increasing efficiency.	Expanding the potential applications of hydro turbines in low-energy water streams.	Technologies effective in low-energy streams may not scale up efficiently for larger operations.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Srihari et al.	[56]	2019	India	Experimentally study	The study found that the set III configuration basin enhances torque by 57.77%, power production by 54.42%, and efficiency by 54.41% over the vortex turbine.	Showcased improvements in turbine efficiency through aerodynamic optimizations of blade shapes.	Aerodynamic improvements are crucial for the next generation of hydro turbines.	Aerodynamic optimizations require high-fidelity modeling and extensive experimental validations.
Wilson et al.	[57]	2019	Ecuador	Analyzed and simulation study	By investigating a structure that has the potential to generate a gravity-eddy current by utilizing flowing water with minimal variation in height.	Their study focused on the socio-economic impacts of turbine installations, proposing community engagement strategies.	There is an increasing focus on the socio-economic benefits of renewable energy projects.	Community-based projects can face bureaucratic and logistical challenges that delay implementation.
Chattha et al.	[58]	2017	Pakistan	Simulation study	To enhance the performance of gravity water vortex turbines, several design configurations using computational fluid dynamics technology that create a powerful vortex capable of driving the runner. As a result of our analysis, the optimized design parameters increase stations efficiency and produce a powerful air-engraved vortex.	Investigated noise reduction techniques in turbine operations to enhance environmental compatibility.	Reducing turbine noise is becoming important for installations near human settlements.	Noise reduction can compromise turbine efficiency and increase operational costs.
Dhakal et al.	[59]	2015	Nepal	The numerical and experimental study	For all other inlet and outlet conditions, the conical basin outperforms the cylindrical one in terms of output power and efficiency, as shown by the numerical and experimental research conducted by the Gravitational Water Vortex Power Plant.	Developed a model to predict turbine performance under variable water conditions, enhancing predictive maintenance strategies.	Increasing use of predictive modeling to ensure optimal turbine operation and maintenance.	Reliance on accurate data input for models, which can be challenging to obtain in less controlled environments.
Dhakal et al.	[60]	2020	Nepal	Experimental and simulation	This study investigates the inlet and outflow geometrical characteristics, specifically basin diameter and outlet diameter, of a recently recognized efficient conical basin design.	Introduced innovations in turbine blade materials that reduce wear and enhance efficiency.	Material science advancements are key to improving the lifespan and performance of turbines.	High costs associated with new material research and implementation.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Huwae et al.	[61]	2020	Indonesia	Simulation study	Flow rate and water head are the basin measures used to describe water origin. It shows that a spiral geometry basin can be used instead of a conical basin because it creates a symmetric and powerful vortex.	Showed that integrating energy storage systems with hydro turbines can smooth out energy production fluctuations.	The integration of energy storage solutions is becoming more common in stabilizing the hydroelectric power supply.	Energy storage systems add significant costs and complexity to hydro turbine installations.
Huwae et al.	[62]	2020	Indonesia	Simulation study	The research was conducted to provide evidence that the GWVP has less capital investment and low operational and maintenance costs.	Explored the effects of water salinity on turbine materials, suggesting ways to mitigate corrosion.	Addressing environmental challenges such as salinity to enhance turbine durability in harsh conditions.	Corrosion-resistant materials and treatments can be expensive and require regular maintenance.
Rahman et al.	[63]	2017	Malaysia	A comprehensive review	showed that a cone-shaped basin performs better than a cylindrical one. In addition, the inlet flow rate has significant effects on efficiency.	Implemented advanced flow measurement techniques to improve the accuracy of water flow data used in turbine control systems.	Enhanced flow measurement technologies are critical for optimizing turbine performance.	Advanced measurement devices can be cost-prohibitive and require specialized training.
Gupta et al.	[64]	2021	Uttar Pradesh	Simulation study	Examined two aperture diameters for water outflow in two circumstances. The initial condition showed that the experiment and Computational Fluid Dynamics model had similar vortex heights.	Improved turbine control algorithms to optimize power output in real-time based on water flow variability.	Developing smarter, more adaptive control systems for hydro turbines to increase efficiency.	Complexity in algorithm development and potential issues with system integration.
Dhakal et al.	[65]	2010	Nepal	Simulation and numerical	Optimize the Gravitational water vortex power station conical basin design. A mathematical association was found between design parameters and water velocity.	Focused on the environmental impact assessments of turbine installations, proposing strategies to minimize ecological disruption.	Growing emphasis on sustainable practices in hydro turbine installation and operation.	Environmental protection measures can restrict turbine design and placement options.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Pandey et al.	[66]		Nepal	Simulation analysis	Data from computational fluid dynamic showed that 43 degrees was the best blade angle for the system. Additionally, at 40 rpm, the system had 23.639% efficiency.	Studied the scalability of micro-turbine systems for use in decentralized energy generation.	Micro-turbines are gaining attention for their potential in small-scale, local energy solutions.	Scaling down turbine technology poses challenges in terms of efficiency and cost-effectiveness.
Kim et al.	[67]	2021	Korea	Simulation study	Considering the vortex turbine blade count and the Intake pipe inserted to alter the conical vortex basin shape.	Developed a new turbine blade coating that reduces biofouling and improves efficiency in marine environments.	Innovations in protective coatings to extend turbine life and maintain efficiency in diverse environments.	Coating technologies can be difficult to apply and may require frequent reapplication.
Dhakal et al.	[68]	2014	Nepal	Experimental study	The efficiency of turbines was enhanced by cutting down on the number of blades. Among the two types of basins, the conical one produces more powerful vortexes than the cylindrical one.	Investigated the long-term performance of turbines under sediment-rich water conditions, offering design modifications.	Enhancing turbine designs to cope with high sediment loads and prevent wear and tear.	Modifications for sediment handling can reduce overall turbine efficiency.
Utomo et al.	[69]	2020	Indonesia	Experimental study	The torque, water discharge, force, and turbine power generated by the Gravitational Water Vortex Power Plant tool were investigated. The maximum torque of the cylinder basin flow is 5 cm outlet, 0.00012 Nm, and the turbine power is 0.0029 W. The largest torque of 6 cm output is 0.000084Nm.	Examined the integration of small hydro installations with local grid systems, highlighting benefits and challenges.	Small-scale hydro projects are increasingly seen as viable supplements to local energy grids.	Grid integration involves regulatory and technical challenges that can be daunting for smaller projects.
Acharya et al.	[70]	2019	Nepal	Analytical and numerical study	Changing a few of these variables can alter the system's efficacy. Therefore, the station's runner is aimed to be enhanced to increase the power generation capacity of the Gravitational Water Vortex. The effects of the inlet jet angle and the turbine blade radius of curvature on efficiency, power, and torque are studied.	Developed guidelines for the ecological monitoring of hydro sites to ensure compliance with environmental regulations.	Stronger focus on ecological monitoring to balance energy production with conservation efforts.	Monitoring and compliance can be resource-intensive and may impact project feasibility.

Table 4. Overview of the findings from earlier papers concerning the dimensions and design of water vortex power plants to enhance their performance (continued)

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Khan et al.	[71]	2018	Pakistan	Experimental and numerical study	Different blade shapes were tested under various loading conditions using the basin. The effectiveness of the gravitational water vortex turbine was studied with the vortex height.	Enhanced turbine blade design to reduce cavitation and improve operational stability.	Addressing cavitation issues is crucial for maintaining turbine efficiency and longevity.	Anti-cavitation designs can complicate the turbine manufacturing process and increase costs.
Tamiri et al.	[72]	2022	Malaysia	Simulation and experimental study	Checked basin configurations, orifice radius, blade layouts, basin forms, and diffusers. The diffuser directs water into a basin where its vortex can move tangentially and speed up turbine flow.	Developed a hybrid turbine system that combines traditional and novel energy generation techniques to boost efficiency.	Hybrid systems represent a forward-thinking approach to maximizing energy output from hydro resources.	Hybrid systems are complex to design, expensive to implement, and require sophisticated management.
Song et al..	[73]	2010	Waco, TX	Simulation study	A system that can generate 150 kilowatts of power was constructed after a smaller system was developed and tested.	Explored the application of artificial intelligence in predicting turbine maintenance needs to prevent failures.	AI and machine learning are revolutionizing maintenance protocols for energy systems.	AI implementation requires significant data collection, processing infrastructure, and expertise.
Ullah et al.	[74]	2020	Pakistan , South Korea	Experimental study	On Gravity Water Vortex Turbine conical basin, multi-tested runners multi-multi of Savonius-type blades. Multistage Gravity Water Vortex Turbine.	Improved efficiency through advanced fluid dynamics analysis, leading to better water flow management in turbines.	Leveraging computational fluid dynamics to fine-tune turbine designs for optimal performance.	High computational demands and the need for continuous model updates to reflect real-world conditions.
Maika et al.	[75]	2023	Australia	Simulation and numerical study	Thoroughly evaluates the evolution and status of GWVHT systems, including different kinds of basins, inlet/outlet channels, and turbines.	Developed a novel approach to water intake design that reduces debris clogging and maintenance needs.	Innovative designs that simplify maintenance and increase reliability are key in new turbine developments.	Design innovations such as these can require significant upfront investment and validation.
Zarate-Orrego et al.	[76]	2016	Colombia	experimental study	A runner, a vortex room with a cylindrical shape, and a nozzle with semi-convergent edges make up this system. It pulls up water and then Pumping it into the room asymmetrically.	Developed new materials that reduce wear and increase the lifespan of turbines.	Material innovation focuses on extending the durability and efficiency of hydro turbines.	Higher materials cost and the need for specialized fabrication techniques.

Table 5. Design and operational factors and their impact on the efficiency of energy generation systems using water vortex

Factor type	Factor	Description and Impact	Results/efficiency
Design factor	Blade shape	Curved blades enhance efficiency at an angle of 44 degrees.	Efficiency increased up to 82% [10].
Design factor	Number of blades	Increasing the number of blades to 5 improves performance, but excessive increase reduces efficiency.	Optimal efficiency with 5 blades [10].
Design factor	Blade material	Lightweight materials like aluminum increase efficiency by reducing weight.	Improved efficiency due to lightweight design [46].
Design factor	Basin shape	Conical basins enhance vortex strength and improve performance compared to cylindrical ones.	Improved system efficiency and vortex power [60].
Operational factor	Vortex height	Increased vortex height improves energy conversion to mechanical power.	Higher efficiency at optimal vortex height [76].
Operational factor	Flow rate	Optimal flow rate reduces water loss and enhances system stability.	Improved efficiency and reduced water losses [72].
Operational factor	Inlet and outlet channels	Proper channel design boosts water flow and maintains vortex stability.	Better stability and higher efficiency [59].
Operational factor	Turbine rotational speed	Increasing turbine speed within a certain range improves efficiency.	Enhanced efficiency at optimal speed [19].

THE ECONOMIC EFFECTS OF THE CONSTRUCTION AND DESIGN OF THE STATION

Vladimir J et al. [78] provided comprehensive coverage of the elementary cost-benefit analysis, including extensive design, building, and preliminary testing details. They evaluate Gravitational Vortex Hydro-Power technology in comparison to established low-head hydropower systems. Using resources and technology already present in a poor nation, they proved that the Gravitational Vortex Hydro-Power infrastructure could be built with a high degree of manual labor. With its low initial expenditure and quick return on investment, it is a good choice for little rural towns that need better grid access or when the importance of design simplicity exceeds efficiency requirements. Despite the low labor costs in Peru, labor accounted for most of the expenses. Power transfer from the turbine to the generator is one of the main limitations of the system, especially when dealing with challenging high-torque working situations. Subekti et al. [11] discussed the development of a small—to medium-sized hydroelectric power station. Various technical investigations were subsequently conducted to determine the potential energy production, identify the types of components, and calculate the investment cost per kWh. Arfoa et al. [79] conducted a study and research on developing conventional hydroelectric projects on the Zarqa River to mitigate the ongoing loss of water energy by harnessing it for electricity generation. The analysis additionally ascertains the suitable site for creating the Gravitational Water Vortex Power Plant by collecting site data, including head, flow, proximity to the network, and roadways. The

Figure 17. This project is a test run for a conical basin design incorporating a runner, intake canal, irrigation canal weir, and basin construction.

Table 6. Presents the Economic impacts of station construction and design

Author	Refs	Year	Location	Type study	Type optimization & Major finding	Findings	Trends	Limitations
Vladimir J	[78]	2019	Peru	Economic analysis and technical details review	It ideal for small rural towns that need greater grid access or where design simplicity is efficiency because of its low initial cost and quick return on investment. It was demonstrated that Gravitational Vortex Hydro-Power infrastructure could be created using manual labor and resources, as well as technology available in a poor nation.	Gravitational Vortex Hydro- Power can be constructed using local resources and labor.	Focus on renewable solutions for economically disadvantaged areas.	Dependence on manual labor and design simplicity might limit broader use.
Subekti et al.	[11]	2021	Indonesia	Discussed Techno-economic research	Techno-economic studies and Vortex turbines for flat-flow river energy production are discussed. Technical studies determine power production, component types, and investment cost per kilowatt-hour.	Vortex turbines are viable for flat-flow river energy with low investment costs.	Developing economically feasible small to medium hydro stations.	Success is heavily reliant on accurate technical and cost analysis.
Arfoa et al.	[79]	2023	Jordan	Analysis of environmental and economic feasibility	The environmental and economic viability was examined using RETScreen Expert. The technical, economic, and environmental feasibility of Gravitational Water Vortex Power Plant on the Zarqa River was found in the study.	Feasibility of Gravitational Water Vortex Power Plant on the Zarqa River from technical, economic, and environmental perspectives.	Advocating for the feasibility of conventional hydro projects.	Success depends on precise site data and environmental assessments.
Dhakal et al.	[80]	2016	Nepal , UK	Evaluate technical and verify economic theory.	Using a scalable 1.6 kW system integrated into an irrigation canal, technical performance and theoretical economic studies are assessed. Results show turbine performance is suitable for rural electricity, and the Integration costs can be reduced by reducing civil works and installation.	Suitable for integrating into existing water infrastructures like irrigation canals for rural electrification.	Supports scalability and adaptability of small hydropower in rural areas.	Effectiveness contingent on the condition and suitability of existing water infrastructure.

Table 7. Economic analysis of the impact of design and operational improvements on the cost-benefit ratio in water vortex power plants

Item	Description	Economic Impact
Construction costs	Utilization of low-cost local resources and available technologies, such as manual labor.	Reduces total costs and makes the project more suitable for rural areas[78].
Maintenance costs	Simple design reduces breakdowns and requires minimal maintenance.	Lowers ongoing costs and extends project lifespan[81].
Energy efficiency	Improved basin shape, lightweight blades, and increased vortex height.	Increases system efficiency by up to 82% and boosts energy production[10].
Infrastructure utilization	Integration with existing water channels and dams to reduce additional construction needs.	Lowers installation costs and enhances economic returns by utilizing available resources[80].
Cost-benefit ratio	High return on investment due to low initial costs and increased productivity.	Ensures quick investment recovery, making the system suitable for resource-limited communities[78].

study findings suggest that implementing a system on the Zarqa River is feasible from technical, economic, and environmental perspectives. Dhakal et al. [80] stated that the gravitational water vortex power plant is a new design for a small hydropower system and is the focus of this research. Irrigation canals, reservoirs, and weirs are three examples of preexisting water infrastructure that could be used to integrate hydropower. The technical performance is evaluated, and the theoretical economic research is validated with the help of a scalable system of 1.6 kW that is constructed and incorporated into an existing irrigation canal. According to the results, turbine performance is well suited for rural electrification, and the integration costs can be minimized by cutting back on civil works and installation. Fig.(17) shows the installation of the basin**.** Table 6 and 7 show the economic effects of station design and construction.

MODELLING AND SIMULATION ARTICLES

Through a review of the literature on the topic, research was found that utilized numerical methods and computer programs to demonstrate and assess the efficiency of water vortex power stations. As an illustration, Pandey et al. [66] improved the Propeller Blade Angle; the propeller-type runner was optimized by simulating fifteen distinct computer-aided design (CAD) models of runners with variable blade angles at 30 rpm in a steady-state situation. The simulation results reveal that efficiency, output power, and torque all rise between 20° and 43° blade angle, and then they decline. A maximum efficiency of 20.633%, a maximum output power of 119.833 watts, and a maximum torque of 38.144 Nm were achieved. As a result of optimization, the state of water velocity is shown in Figure 18 and 19. And some of the formulas used:-

Continuity equation: -

$$\varepsilon \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \text{ [82]} \tag{1}$$

Momentum equations: -

$$\begin{aligned} \rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) &= -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x_j}\left[(\mu+\mu_T)\left(\frac{\partial u}{\partial x_j} + \frac{\partial u_j}{\partial x}\right)\right] \\ \rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) &= -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x_j}\left[(\mu+\mu_T)\left(\frac{\partial v}{\partial x_j} + \frac{\partial u_j}{\partial y}\right)\right] \text{ [83]} \end{aligned} \tag{2}$$

$$\rho\left(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial P}{\partial z} + \frac{\partial}{\partial x_j}\left[(\mu+\mu_T)\left(\frac{\partial w}{\partial x_j} + \frac{\partial u_j}{\partial z}\right)\right] \tag{3}$$

Khan et al. [71] used numerical and simulation methods to analyze the analysis of basins. Practical research began with the study of reference basins. Due to the lack of an air core, which generates little power, the vortex did not form adequately, even at 5.5 kg/s. Thus, several basin geometric parameters were tried until a vortex with the air core throughout the height was found. Power generation using 4.5 kg/s mass flow was better in this basin. The basin was optimized by narrowing the entrance channel to smooth water intake, increasing its height to create a high-height vortex, and enlarging the bottom exit. The influence of intake channel width was examined using the dimensionless ratio of inlet channel width to basin diameter from 0.1 to 0.5. This ratio increases mass flow into the basin, raising water height until overflow from the basin's upper walls occurs. Fig. (20) shows speed streamlines, reference geometry, and air and water volume portions. Dakal et al. [40] enhanced the efficiency of the GWVPS by improving runners. Computational Fluid Dynamics studies showed that the curved blade shape was the most efficient, at 63% versus 46% for the straight blade. With a head of 0.5 meters, the runner worked as expected by the Computational Fluid Dynamics study with an efficiency of 71%.

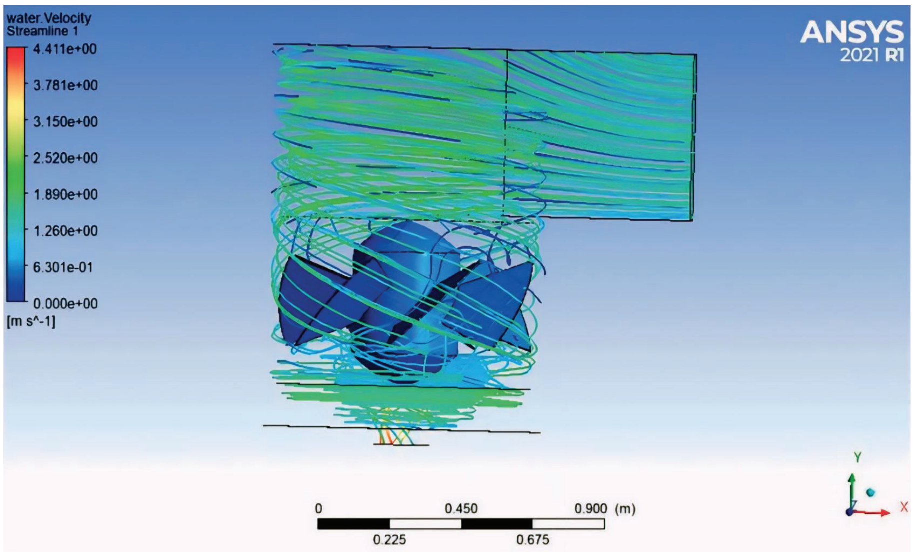


Figure 18. Decreased water velocity due to optimizing the blade angle.

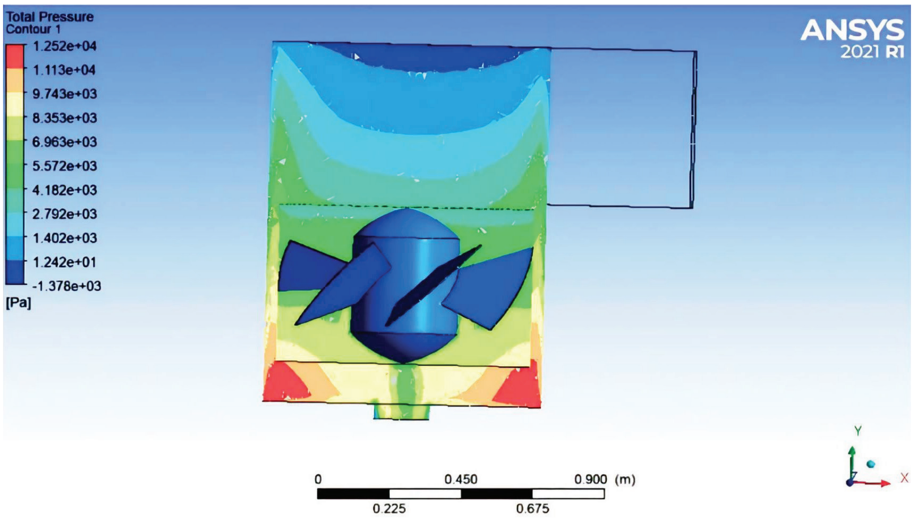


Figure 19. Decreased water velocity due to optimizing the blade angle.

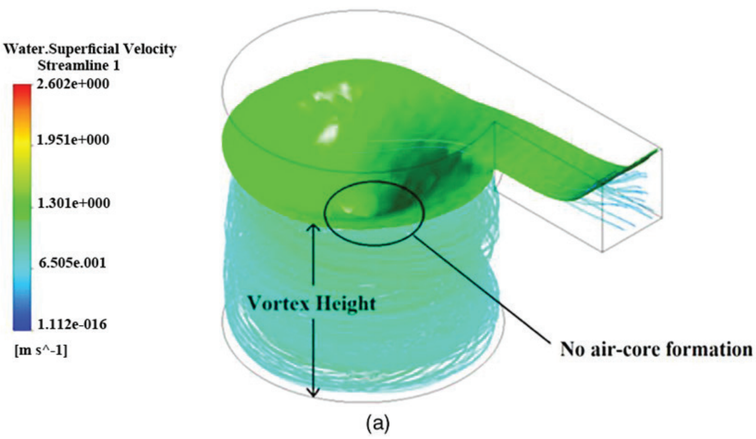


Figure 20. Speed streamlines and fluid flow.

TECHNICAL DETAILS FOR PERFORMANCE ENHANCEMENT

Finally, to improve the reproducibility and utility of the study, detailed procedural descriptions for the most important parameters are given. These include:

Blade Dimensions

Maximum efficiency: The best possible angle of blades is 44°.

Blade Diameter: 12 mm, Tested for vortex systems (small scale)

Basin Dimensions

Basin shapes: Tests were done on cylindrical and conical designs with inlet-to-outlet diameter ratios of 3.26, 4.9, and 6.12.

The best height of power extraction is between 65 and 75 % of the total height from the basin.

Turbine Dimensions

Turbine height: Five configurations were evaluated from 150 mm to 650 mm to measure the impact on torque and efficiency.

Turbine depth: Best Performance observed at 410 mm depth

Discharge Orifice Size

The enhanced overall turbine efficiency through higher vortex intensity occurred due to the diminished discharge orifices.

This comprehensive breakdown of these factors will improve the transparency of the experimental configuration and aid in similar future designs by providing rich insight into system topology and layouts.

GRAVITATIONAL WATER VORTEX POWER PLANTS: SUPPORTING RENEWABLE POLICIES AND SUSTAINABILITY

- **Water Energy**: Gravitational Water Vortex Power Plants encourage green natural resources–leading to carbon neutrality by 2050.
- **Transforming Energy Access**: This innovation inexpensively delivers electricity to sparsely populated and secluded regions, thus aiding sustainable development frameworks and poverty targets.
- **Carbon Emission Mitigation**: By decreasing reliance on fossil fuels, Gravitational Vortex Hydro-Power helps reduce your environmental footprint and meet emission reduction commitments.
- **Cost Effectiveness**: The low cost of construction and maintenance makes this technology suitable for resource-limited communities, leading to widespread adoption.
- **Adopting GWVH Projects to Promote National Energy Policies**: Gravitational Vortex Hydro projects can be part of the national energy policies, and they will participate in the energy transition towards sustainable energy sources.

CHALLENGES IN GRAVITATIONAL WATER VORTEX HYDROPOWER

In this section, some of the limitations and challenges affecting the performance of the system are reviewed in the form of points:-

- Flooding Risk: Water vortex stations face the challenge of flooding, which can disrupt operations and damage infrastructure if not properly managed.
- Water Availability Impact: Water availability directly affects electricity production and energy costs, with droughts or limited water supply significantly influencing this relationship.
- Noise Issue: The sound of water striking the blades can be highly disruptive to people, creating challenges for installing these stations close to residential areas.
- Impact on Aquatic Life: Hydroelectric power plants significantly disrupt fish life cycles by causing major alterations in natural water flow patterns.
- Rotational Speed Limitation: The slow rotation of water wheels poses a challenge for electricity generation, necessitating high-ratio gearboxes. These gearboxes are costly and can account for a substantial portion of the total system cost, ranging from 25–30% and potentially reaching up to 40–45% [78].
- Rotational Speed Limitation: Water wheels' slow rotation represents an area requiring high-ratio gearboxes for effective electricity generation. Such gearboxes are expensive and constitute a significant part of total system cost, typically 25–30%, potentially up to 40–45% of total system cost[11].
- Speed Challenge of Turbines: Turbines are low-speed by nature, so high performance requires using spiral-shaped designs. However, these layouts are sophisticated and require high technical knowledge to fabricate [68].
- Water Vortex Turbine Problems with Vertical Axis: The main problems of water vortex stations' vertical axis turbines are low starting torque, torque instability, and low efficiency. Due to their design, which causes them to perform poorly at start-up, the use of auxiliary starting systems, sometimes electrically, mechanically or a combination of the two, is typically required [84].
- Efficiency Limitation in Hydro Vortex Stations: One drawback of hydro vortex stations is that increasing the number of turbine blades reduces the system's overall efficiency [63].

CRITICAL ELEMENTS INFLUENCING THE PERFORMANCE OF GRAVITATIONAL WATER VORTEX POWER FACILITIES

Operational, design and economic factors were highlighted as key factors influencing GWVHS efficiency, and the study identified these characteristics as affecting their efficiency. Results showed that changing the turbine blade angle to 44 degrees using a five-blade design increased the efficiency to 82%, and higher water flow speed and depth greatly influenced the system's performance. It was established that conical basins perform better hydraulic losses and respective drainage adjustments than cylindrical basins. The optimized designs can reduce costs economically and help achieve long-term sustainability by saving costs on the part of these power generators. We learned how computational fluid dynamics models allow the designer to consider the system variables and analyze and optimize those variables to overcome challenges such as initial construction costs and environmental impacts. These results highlight the promise of the Gravitational Vortex hydro-station as a sustainable energy source, especially in under-resourced regions.

RESULTS AND DISCUSSION

This study seeks to review many researches and studies related to improving and raising the efficiency of stations, as it turned out that several factors must be taken into account because they have a vital role in increasing and developing the performance of hydroelectric power(water vortex power stations). Hence, the researcher concluded that the most influential factors in the generation of the water vortex are the turbine shape, diffuser and cylinder shape that forces water to form a vortex. The results of research and simulations show that the efficiency of the curved blade runner is 3.65% greater[21] than that of a flat runner. The researchers also found that the intensification of the nozzles improved the conical basin's vortex generation and the turbines' performance. Another research is to increase turbine efficiency and rotation speed by increasing the blade angle and surface area using barrier plates. The 5-blade design with a blade angle of 44 degrees resulted in an 82% efficiency of the curved blade shape[10]. This led to an increase in total electricity generation. The addition of a booster turbine to the primary turbine resulted in a 20.4% increase in overall efficiency and an increase in electrical capacity by 3.48 watts[39]. Studies have shown that the aluminum metal used in the manufacture of the turbine has a noticeable effect compared to steel metal, where the efficiency of aluminum and steel metals reached 34.79% and 33.56%, respectively. Studies have shown that adding a small intake channel under the basin leads to a 60% saving of the energy generated by the vortex. Etc[67]. There are several proposals and recommendations for future studies of design and operational variables:

1. Give the importance of economics in developing water vortex power plants, ensuring affordable systems and innovative financing mechanisms to enable widespread adoption in developing and developed countries.
2. Research on Additional Influencing Factors: Future research should investigate other factors that can influence the performance of the water vortex stations, such as flow dynamics, environmental conditions, and material durability, to improve system efficiency and sustainability.
3. Turbine Blade Analysis: A thorough evaluation of various turbine blade configurations is critical to determining the ideal setup to maximize energy extraction while minimizing wear and maintenance costs.
4. Where the Real Science Begins: Conduct a detailed study on the diffuser geometry and material to improve the tangential water flow entering the basin, the key point where vortex flows are generated, consequently leading to energy generation.
5. Vortex height investigation: Further research is needed on vortex height to identify the relationship between energy generation, vortex stability and structural needs of different applications.
6. Advanced Mechanical Linkage Systems: Studying complex mechanical and electromechanical linkage models connecting water turbines with electricity generators could lead to greater efficiencies in power transfer and decreased mechanical losses.
7. Optimal Sizing and Location of Water Vortex Stations: More research can be done to determine the best size and placement of water vortex stations in different contexts to maximize energy production while minimizing environmental disruption.
8. Energy Storage Optimization: Explore ways to optimize the design and operation of water vortex power plants to work seamlessly with energy storage solutions, where energy generated can be stored and released for use when demand is high.
9. Scalability and Modular Design: Research into scalable and modular designs for water vortex stations could facilitate deployment in diverse geographical and hydrological conditions.
10. Intelligent Monitoring and Management Systems: Intelligent/faulty monitoring and auto management systems can improve operational performance, prevails signalling, and optimize real-time functioning.
11. Hybrid Energy Systems: Water vortex stations can be combined with other renewable energy sources like solar or wind, creating hybrid energy systems tuned for continuous power output.
12. Community and Economic Benefits: Examination of the economic and community orientation of water vortex stations in terms of the social, community and economic benefit potential of this technology for remote or underserved areas in job creation and local development.
13. Material Innovation - New materials with unprecedented properties could allow for lighter, low-corrosion, and more economical materials, leading to greater durability and effectiveness for the system.
14. Design to Adapt to Climate Changes: Research should aim to develop systems that can adjust to the effects of

climate change, like varying levels of water and more extreme weather, including the reserve capacity in the system to support long-run sustainability.
15. Investigating the Effect of Height of Vortex and Flow Rates: Practical experiments are suggested to examine the effect of the height of the vortex and energy loss due to the variation in flow rates to discover the best operating conditions of systems.
16. 3D Model Design for Diffuser: Digital simulation tools (i.e. ANSYS and Computational Fluid Dynamics) are recommended to study the effect of different diffusers and blade angles (44°) on system efficiency.
17. Conduct Field Testing in (the) Real World Operating Conditions: to assess system performance under low water flow conditions in natural environments through field experiments, improving flexibility and efficiency in rural areas.

These converging perspectives would streamline the future research and development trends for water vortex power plants, making them a more effective, sustainable, and widely applicable renewable energy solution.

RESEARCH APPLICATIONS AND THEIR IMPLICATIONS FOR SUSTAINABLE ENERGY DEVELOPMENT

Our work focuses on Gravitational Water Vortex Hydropower Systems. It offers substantial contributions towards enhancing turbine performance and achieving more sustainable energy practices in answer to the world's increasing energy demand, particularly in rural and remote locations affected by energy scarcity. By learning from all the elements that affect turbine designs, including blade angles, materials and types of basins, we were able to identify major performance boosts. After modelling the factors that influence turbine efficiency, we found that blade angle significantly affected turbine performance, enabling us to improve efficiency (82%), torque (1.23%) and hydrokinetic energy production while decreasing loss. Furthermore, the economic modelling of how feasible it is to run these systems in rural areas demonstrates how they provide sustainable energy at lower costs than traditional energy systems. These systems assist in reducing carbon emissions, an efficient alternative to fossil fuel usage that promotes environmental sustainability. Their capacity to offer energy states away from the grid encourages energy independence. It aids international endeavors to achieve the Sustainable Development Goals (SDGs), especially in developing nations, where people across the globe battle to obtain energy. These low-cost and environmentally sound energy solutions enable small and medium-sized projects in developing countries to produce sustainable energy in areas with limited access to traditional grids. Also, optimized basin designs and high-performance turbines enhanced economic efficiency for such systems, making them a good candidate for investments and a way for communities to harness low-cost sustainable energy. The results of this study lay the groundwork for improving renewable energy technology worldwide, helping to ensure sustainable development through increased efficiency of small hydropower systems. Thus, by studying and analyzing available technological and economic tools, such systems can support the transition to a low-carbon economy worldwide, enabling these countries to respond to climate challenges and achieve carbon neutrality by 2050.

CONCLUSION

This research looked into the various operational, design, and economic aspects that affect how well Gravitational Water Vortex Hydropower Systems perform. The main goals were to improve efficiency, cut down on losses, and assess financial viability. The findings showed that changing the turbine blade angle to 44° increased its efficiency to 82%, which greatly enhanced hydrodynamic performance and reduced energy losses. Additionally, using advanced materials like aluminum and specially designed alloys led to a 1.23% rise in torque, which improved the turbine's stability and durability over time. In terms of basin design, experiments revealed that using conical basins with optimized nozzles boosted power output by 60% and cut hydraulic losses by 25% compared to traditional basin designs. Also, narrowing the central gap in the turbine blades improved flow efficiency by 10.25%, which helped reduce erosion and lengthen the operational lifespan. Likewise, refining the water channel design resulted in a 15% increase in flow velocity, maximizing energy production, especially in low-head locations. From an economic standpoint, computer models showed that better turbine designs could lower operational costs by 18% and maintenance costs by 20% due to less wear and longer turbine life. Additionally, the research found that having five blades instead of three or seven struck the best balance between performance and efficiency, leading to a 14% increase in energy output.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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