Estimate of Power Output from Hydraulic Jumps Generated Downstream from Barrages

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Abstract

Hydropower is an affordable, sustainable way to generate electricity. Research on hydraulic jumps focuses only on determining head loss across the jump, but there are no studies on generating power from the jump. This research aims to utilize energy dissipated from hydraulic jumps for power-generating purposes and further use this power in real-life applications. This research simulates ideal hydraulic conditions to identify the most stable hydraulic jumps, which will be used to generate power. The Seriakos barrage in Egypt was taken as a case study to simulate energy dissipated/power generated from hydraulic jumps generated downstream. This power is then used to simulate lighting up some streets in Egypt according to Egyptian power consumption standards. An Excel spreadsheet was used to mathematically model generated hydraulic jump types, energy dissipated, and generated power. The study found that submerged flow generates maximum power values from hydraulic jumps as opposed to free flow. The research concluded that energy produced by hydraulic jumps at the Seriakos barrage could light up 78 street light bulbs. Although this is a small amount of power, Egypt could meet a significant portion of its energy needs if hydraulic jumps from all its hydraulic structures were utilized for power generation.

Keywords: Hydropower; Hydraulic Jump; Energy Dissipated; Seriakos Barrage; Mathematical Modelling; Hydraulic Operating Conditions.

1. Introduction

Rapid population growth and innovations in technology have resulted in a rapid rise in energy demand [1]. Energies can fall under many different categories; namely, renewable and non-renewable energies; as well as, green and non-green energies. Renewable energy is produced continuously from renewable natural resources or natural processes. Examples of natural resources are the sun, wind, and tides. Renewable energy is expected to become the key means of addressing climate change [2]. Consequently, the majority of governments are making significant investments in a variety of renewable energy sources and are attempting to move away from nonrenewable energy sources as soon as it is feasible from an economic point of view. Contrarily, nuclear, oil, and fossil fuels are limited in supply. On the other hand, 10.9% of the world's energy demand was met by renewable energy in 2002; moreover, this percentage is growing at a rate of 1.5% each year [3]. There are three main categories of renewable energy sources: (1) solar thermal energy conversion and solar photovoltaics, which are direct uses of solar energy; (2) hydropower, wind, wave, and bioenergy or biofuels, which are indirect uses of solar energy; and (3) tidal and geothermal energy, which are sources of renewable energy that are independent of solar radiation [4].

According to the International Energy Agency (IEA), "renewables have grown rapidly in recent years, accompanied by significant cost reductions, particularly for solar PV and wind power." More than 150 countries had renewable energy policies in place for the electricity sector in 2018, and the majority of nations had some sort of renewable energy target in place. More than 45 nations also had policies in place to encourage the use of biofuels in the transportation industry; in 2018, no new nations adopted mandates or regulatory incentives for renewable transportation, although some nations enhanced those that already existed. Additionally, about 45 nations have regulations devoted exclusively to the use of renewable energy for heating and cooling. According to the estimate, by 2050, renewable energy will supply about half of the world's electricity. Figure 1 shows that in 2018, 28% of the world's electricity came from renewable sources, the majority of which (96%) came from hydropower, wind, and solar technologies [5].
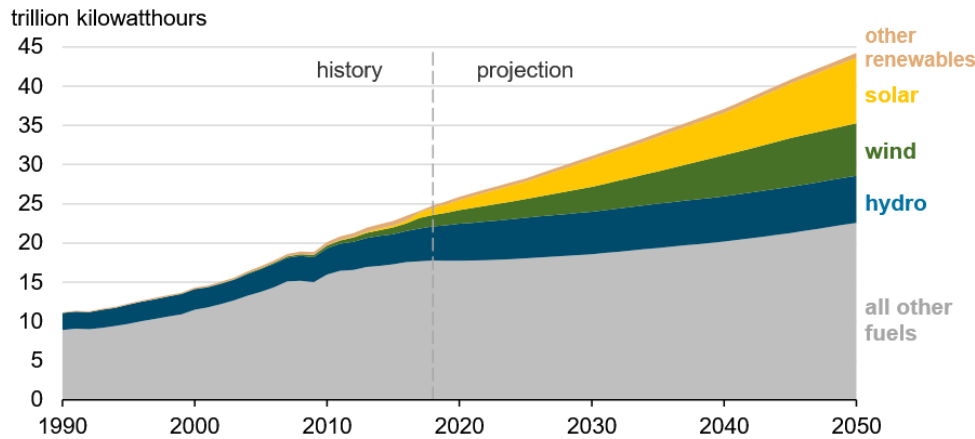
Figure 1. World net electricity generation, IEO reference case (1990–2050) [5]

Power generation is essential in any community to produce light and power that will keep the machinery used in all aspects of life working in a productive manner. Hydropower is another example of an indirect use of solar energy. It is often considered the most developed and beneficial form of renewable energy [6]. When water flows from a high potential to a low potential, a form of renewable energy called hydroelectricity is created. Water turbines are powered by the potential energy of falling water to generate hydroelectricity [7]. Hydropower has long been used by humans, such as wave power, tidal power, etc. Our rivers, streams, and lakes could have been used to generate electricity, but humans hadn't yet begun that.

Hydropower is an economical source of renewable energy since it is less expensive than the majority of other energy sources [8]. Humans can rely on water to flow day and night, all year long, with the exception of severe droughts. And this steadiness is essential if people are to completely rely on purely sustainable energy sources like wind and solar energy. Additionally, new hydropower technologies continue to advance. They facilitate the construction of new facilities without causing too much harm to the environment. Moreover, they aid in lowering building costs, which can make hydropower even more cost-effective and possibly lower energy prices throughout the nation. Some hydropower plants do not simply create power; they also store it in the world's largest "batteries." Pumped storage hydropower, often known as water batteries, has the ability to store massive amounts of renewable energy for months at a time. This is important storage [9].

In the field of hydraulics, a phenomenon known as a "hydraulic jump" is frequently seen in rivers, spillways, barrages, and weirs. In short, there are many hydraulic structures, whether with or without sluice gates. Due to the high flow velocity and supercritical flow regime downstream of sluice gates, hydraulic jumps mainly happen on the downstream side of these structures [10]. The primary function of a hydraulic jump is to dissipate extra kinetic energy from water that flows downstream of hydraulic structures such as spillways, sluice gates, and so on. If left unchecked, this extra energy will damage the banks and the bed of rivers downstream of the existing hydraulic structure [11].

As a result, this research contributes to the understanding of the types of hydraulic jumps that dissipate the most energy, the parameters influencing power dissipation in hydraulic jumps, and most importantly, how much power may be generated from a hydraulic jump and which mechanism can be employed to use this power in an efficient way, like, for example, generating electricity. Furthermore, this research uses a mathematical modeling approach to simulate the optimum hydraulic operation conditions of barrages. The operational conditions, such as the number of gates and gate openings in order to generate power from hydraulic jumps from under sluice gates, are particularly simulated. Many operating scenarios are used, taking into consideration multiple combinations of stream flows, gate openings, and tailwater levels.

In the past few years, there have been many research studies conducted on the hydraulic jump. A study was done by Montes [12] to observe a particular type of hydraulic jump, namely the undular jump, and did some tests on it, measuring velocities, pressure, and energy loss. The experiment was done on a rectangular channel with a width of 0.25 m. The experiment was done on different undular jumps with different Froude number values. Moreover, many experiments were done using different Froude numbers to observe its effects on energy loss. The results showed that energy loss divided by critical depth has a positive relationship with the Froude number.

Another study was done by Kim et al. [13] on hydraulic jumps generated at weirs. The experiment was conducted on different types of weirs, using different values of the Froude number to measure the difference in energy loss generated in each case. Three energy dissipators were installed at different heights: 5mm, 10 mm, and 15mm. The discharge flow was changed during the experiment to measure the difference in energy dissipation. Four scenarios for energy dissipation were used in this study as follows: using no energy dissipator, using the 5mm dissipator, using the 10 mm dissipator, and finally using the 15 mm energy dissipator. The results showed that using a larger energy dissipator resulted in less power dissipation through the hydraulic jump. The conclusion is similar to the previous study, which showed that energy loss has a positive relationship with the Froude number.

Chen et al. (2012) [14] investigated the energy dissipation features of hydraulic jumps following a free fall. The results show that the pre-jump Froude number, the relative height of the weir, the ratio of the widths of the pre-jump and post-jump sections, and other factors all affect the conjugate depth ratio, relative energy loss, and efficiency of energy dissipation. Talib et al. (2019) [15] performed another study on the power generation characteristics of the hydraulic jump downstream of a stepped weir and used it as energy dissipation to reduce the additional power dissipated on the stepped weir. Three various heights, slopes, as well as modified step numbers for 27 stepped weir models, were evaluated. The number of steps, the weir's height, and the weir's slope were found to have a 20%, 20.6%, and 21.8%, respectively, impact on the energy dissipation. It was also found that the energy dissipation increased when the hydraulic jump length increased, although this was found to be uneconomic. The best model for energy dissipation in this study was obtained in the case of a weir with a lower height and a larger slope and number of steps.

Kumar et al. [16] focused on analyzing the hydraulic jump as a method of dissipating energy in various scenarios. To achieve a clear hydraulic jump, a stepped weir is designed and utilized. The energy dissipation achieved through the use of the weir is then compared to the energy dissipated when utilizing a porous obstacle as an energy dissipator. This comparison can be verified using ANSYS software.

The introduction of the incoming Reynolds number (Re) in a sloped channel jump was first explored by Gupta et al. [17]. They developed correlations that considered the influence of Re, inflow Froude number (Fr), and channel slope (θ) in order to gain a better understanding of hydraulic jumps on sloping channels. Their aim was to create new empirical correlations that could accurately assess various jump characteristics, which would be valuable in the design of stilling basins and mitigating the adverse environmental impacts of hydraulic jumps. In their experimental study, Zhou et al. [18] focused on analyzing the uniform flow behavior and energy dissipation capabilities of the hydraulic-jump-stepped spillway in comparison to the traditional stepped spillway. Their findings highlight the numerous benefits offered by the hydraulic-jump-stepped spillway when it comes to effectively dissipating the flow's energy.

Sayyadei et al. [19] conducted experiments to study how bed roughness and abrupt negative drops affect hydraulic jumps. They also examined how geometric and hydraulic parameters impact energy dissipation and the location of the hydraulic jump. They varied the height of the abrupt drop and the roughness for different flow rates (between 30 and 50 L/s) and Froude numbers (ranging from 4.9 to 9.5). The results showed that increasing bed roughness led to a decrease in the subsequent depth ratio and the relative length of the jump by 16.6% and 20.7%, respectively. Additionally, it caused an increase in the relative energy loss and the bed shear force coefficient by 10% and 31%, respectively.

Maryami et al. [20] used a numerical method to estimate the characteristics of hydraulic jumps in a closed conduit with different positive slopes. They compared their results to an analytical method and found that the numerical method was more accurate, with an error of less than 5% compared to the analytical method's error of less than 10%. They also observed that at a slope of 0.00, the energy loss increased by 16% as the Froude number increased from 4.617 to 5.562. This increase was higher, at 23% and 22%, for slopes of 0.01 and 0.02, respectively. Finally, they developed equations to predict hydraulic jump characteristics based on the Froude number, slope, and conduit depth.

Based on the extensive review of existing literature, it is evident that a significant amount of research has been conducted on various aspects related to the hydraulic jump phenomenon. These studies have primarily focused on areas such as the behavior of hydraulic jumps in abruptly expanding stilling basins, the effectiveness of energy dissipators, the energy dissipated downstream of stepped weirs, the characteristics exhibited by hydraulic jumps generated from weirs, and the impact of bed depth and roughness on hydraulic jumps. However, it is noteworthy that no studies have been found that specifically investigate the conversion of the head loss/energy dissipated resulting from hydraulic jumps into power and the potential benefits that can be derived from this generated power.

Accordingly, the primary objective of this research is to use the power generated from hydraulic jumps and utilize it in a manner that maximizes its efficiency and potential benefits for the community living around the area where the hydraulic jump together with the power coming out of it are generated. To further investigate this concept, the renowned Seriakos barrage in Egypt has been selected as a prominent case study in generating hydraulic jumps at its downstream side.

The simulation of the hydraulic optimum operation conditions for the Seriakos barrage taken as a case study of this research barrage involved calculating the amount of energy dissipated by each type of hydraulic jump that occurs after the sluice gate. This was done to determine which hydraulic jump produces the highest levels of dissipated energy, which can then be used to generate power. Power generation is crucial in any community, as it provides the necessary light and power to keep machinery functioning efficiently in all aspects of life. By utilizing the hydropower generated through hydraulic jumps, a renewable and eco-friendly source of power will be created. This will not only enhance our current power generation methods but also introduce a new green energy option. Furthermore, countries with abundant water resources but limited power production capabilities can benefit from this renewable energy source, thereby boosting their economies. Additionally, this research contributes to finding the most efficient and optimal ways to utilize the energy from hydraulic jumps, specifically by identifying the most favorable hydraulic operating conditions for barrages.

2. Research Methodology

The mathematical model was carried out by constructing an Excel spreadsheet to mathematically model and assess the optimum operating scenarios of the Seriakos barrage in Egypt and hence its influence on power generation from the hydraulic jump formed at the sluice gates of the barrage. Mathematical modeling is the process of representing real-world situations using various mathematical structures such as graphs, equations, diagrams, scatterplots, tree diagrams, and so on [21].

The equations used to construct the mathematical model for this research are described in the following section.

The hydraulic operating condition of the Seriakos barrage was thoroughly investigated and mathematically modeled in this research because barrage gate openings and the number of gates to be opened affect the upstream water level, which should remain constant, so the number of gates and their openings that will render a constant upstream water level were investigated. Also, not all hydraulic operating conditions are accepted, so the best operating conditions were chosen to be described in the following paragraphs. For example, the submergence factor of the generated hydraulic jumps was calculated and evaluated, as it should be within specific limits, so that the water released is appropriately balanced and does not harm the downstream side of the barrage. Figure 1 shows the flowchart of the research methodology through which the objectives of this study were achieved.
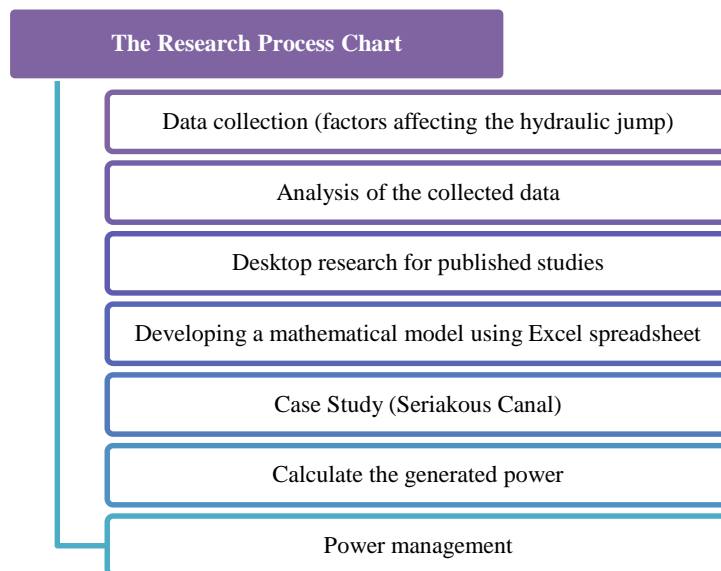

Figure 1. The research process flowchart

2.1. Hydraulic Jump Governing Equations and Factors

The two depths corresponding to the depth of flow before and after a hydraulic jump having the same momentum flux are termed conjugate depths, as shown in Figure 3 [22]. A hydraulic jump always has a depth upstream that is supercritical and a depth downstream that is subcritical.
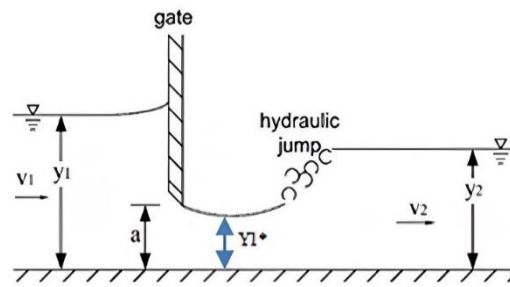
Figure 2. Conjugate depths (Y₁* and y₂) of hydraulic jump

$$\frac{Y_1 *}{y_2} = \frac{\sqrt{1 + 8Fr^2} - 1}{2} \tag{1}$$

where, Y_1* is the depth at the beginning of the jump, y_2 is the depth at the end of the jump, and Fr is the Froude number.

The Froude number (Fr), a dimensionless parameter, is used to quantify how gravity affects fluid motion. In this research, after simulating the hydraulic operating conditions of the Seriakos barrage, the best operating conditions will be chosen, i.e., the numbers of gates to be opened and their optimum gate openings. The best operating conditions will depend on the type of the generated jump and on the value/sign of its submergence factor. When the hydrological tailwater depth in a channel is greater than the jump's subcritical subsequent depth, submergence occurs [23]. So, a negative submergence factor is rejected. For the accepted operating conditions, energy dissipated from the generated hydraulic jumps is simulated. After calculating this dissipated energy, the corresponding generated power is then calculated. Table 1 shows the types of hydraulic jumps based on the Froude number.

Table 1. Types of Hydraulic Jump [24]

Froude Number	Hydraulic jump types	Description
1	No jump	Flow so critical
1 to 1.7	Undular jump	The water surface shows undulations
1.7 to 2.5	Weak jump	A series of small rollers form on the surface of the jump, but downstream water surface remains smooth. Velocity is uniform and energy loss is low.
2.5 to 4.5	Oscillating jump	Causes unlimited damage to the earth banks of the rivers. Not recommended
4.5 to 9	Steady jump	The jump is well balanced, and the performance is at its best.
> 9.0	Strong jump	The jump action is rough.

Froude number is determined through the following calculation steps:

$$Q_g = \frac{Q_{out}}{no.\ of\ opened\ gates} \tag{2}$$

where, Q_g is the discharge passing through one gate, Q_{out} is the total discharge going through all gates.

$$V_j = \frac{Q_g}{W_g * C_c * b} \tag{3}$$

where, V_j is the velocity at the beginning of the jump, W_g is the gate width, C_c is the contraction coefficient, and b is the gate opening as shown in Figure 4 [25].
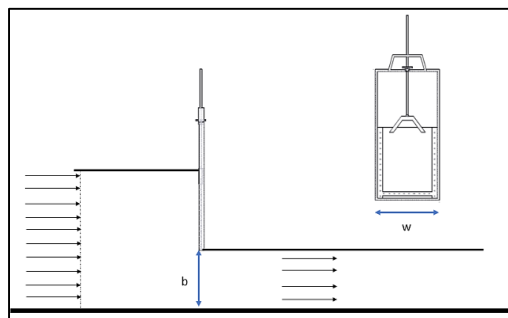

Figure 4. Sluice gate opening and width [25]

$$F_r = \frac{v}{\sqrt{g * D}} \tag{4}$$

where v is the velocity at the beginning of the jump, g is the gravitational acceleration, and D is the water depth at the beginning of the jump.

There are two types of flow below sluice gates, namely, free flow and submerged flow. Free flow occurs when the water surface downstream is not high enough to reduce the velocity of the upstream. Because of their applications in energy dissipation downstream of hydraulic structures such as spillways, barrages, and weirs, free and submerged jumps are essential phenomena in open channel flow [26].

The following equation is applied when the type of flow is a free flow:

$$y_1 \geq 0.81 \, y_2 \, (\frac{y_2}{a})^{1.72} \tag{5}$$

Where y_1 is the upstream water level and y_2 is the downstream level.

On the other hand, if flow is submerged, then the following equation is applied [27]:

$$y_2 < \, y_1 < 0.81 y_2 \, (\frac{y_2}{a})^{1.72} \tag{6}$$

To calculate the submergence factor:

$$s = \frac{y_2 - y_1^*}{y_1^*} \tag{7}$$

Where y_2 is the downstream depth and y_1^* is the depth at the beginning of the jump.

To calculate the flow rate in a channel, first the velocity and cross-section area of the channel are determined, and then the following equation is used to compute the flow rate:

$$q = Av \tag{8}$$

$$v = \frac{1}{n} \, R_h^{\frac{2}{3}} \sqrt{S_o} \tag{9}$$

where R_h is the hydraulic radius which depends on the channel geometry; n is the manning coefficient, and depends on the type and material of canal lining; and S_o is the channel longitudinal slope – bed slope-and is calculated as follows:

$$S_o = \frac{Z_1 - Z_2}{\Delta x} \tag{10}$$

Figure 5 shows a channel selection illustrating bed slopes, different water levels and energy levels.
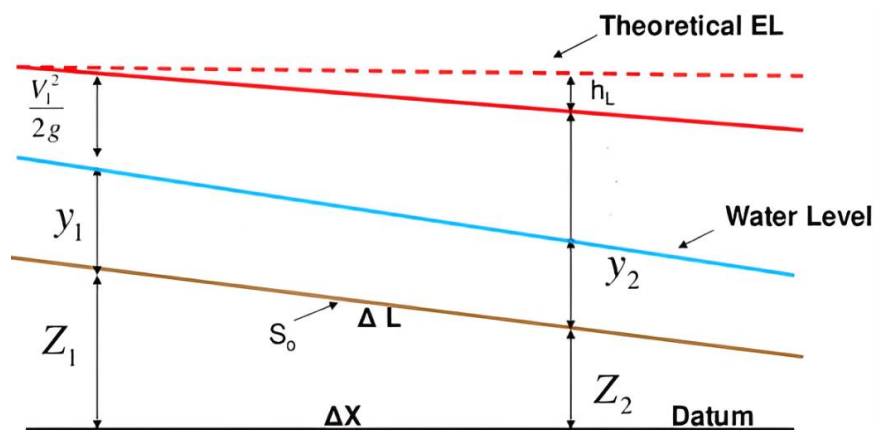

Figure 3. Channel bed slopes, different water levels and energy levels

2.1.1. Sluice Gates

A sluice gate is one of several types of control gates. Its primary function is to regulate the flow level between two zones. Sluice gates are typically built of steel, wood, or a variety of other materials. It works by lowering the gate from the top, and water flows through the gate hole.

The following equation can be used to compute the flow rate for free and submerged flow under a sluice gate:

$$q_s = C_d \, ab_s\sqrt{2gy_1} \qquad\qquad (11)$$

where a, is the sluice gate opening; b, is the sluice gate width; and y_1, is the upstream water depth. The discharge coefficient is determined from the variation of C_d under free and submerged flow conditions as obtained by Henry (1950) [27].

2.1.2. Radial Gates

The radial gate, as shown in Figure 6, is another type of gate. A structure, where a small part of a cylindrical surface serves as the gate, is supported by radial constructions going through the cylinder's radius [24].
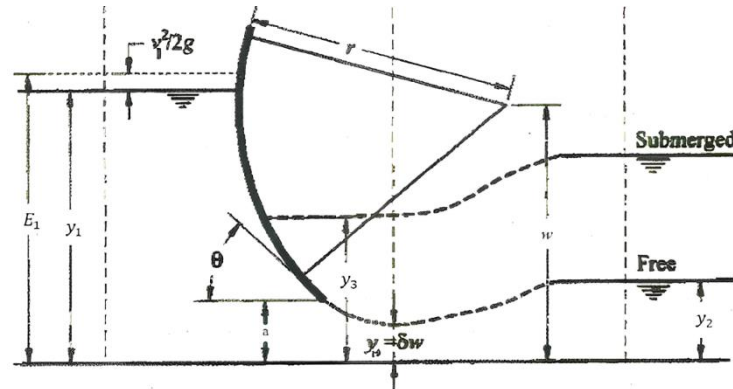

Figure 4. Radial Gates

2.1.3. Types of Flow

There are several types of flow: (1) Subcritical flow usually means the flow has a low velocity. Subcritical flow can be determined using the Froude number (if the flow's Froude number <1). The main reason for slow velocity is the dominating gravitational force; (2) Supercritical flow is a rapid and unstable flow moving at high velocity. When a hydraulic jump occurs, the supercritical flow transfers into subcritical flow because of the decrease in kinetic energy. In supercritical flow, the Froude number is greater than one; and (3) Critical flow where the flow velocity equals the wave velocity (Froude number = 1).

Moreover, critical velocity is one of the factors that affects the hydraulic jump. This velocity occurs in cases with normal depths. Here, both gravity and drag forces are equalized. This velocity results in non-turbulent flows in the water channels.

2.1.4. Calculation Steps for the Estimated Power Generated by Hydraulic Jump

The conversion of potential energy into kinetic energy gives water entering a spillway a significant rise in kinetic energy [16]. If flow with this high velocity was allowed to enter the river at the downstream side of the hydraulic structure directly without any handling of this high velocity, it would cause the riverbed to be scoured. The spillway and the dam may be put in danger by the scouring of the bed [28, 29]. The kinetic energy of the water must be released and dissipated before it is discharged into the channel in order to prevent scouring of the channel bed. The two techniques employed for dissipating the extra kinetic energy are creating a hydraulic jump or utilizing various kinds of buckets [16], like stilling basins. Using the previous equations, the power in watts generated from the hydraulic jump is calculated as follows:

$$P\,(W) = m \times g \times H_{net} \times \eta \qquad\qquad (12)$$

Where m is the mass flow rate (kg/s), g is the acceleration due to gravity, H is the net head, and η is the efficiencies product of all the power components. Since 1 liter of water weighs 1 kilogram, the mass flow rate in kg/s is mathematically equal to the flow rate in liters/second.

The upstream depth is constant because when operating a barrage, it is important to maintain the ideal upstream water level, which is often adjusted to allow for flow diversion to off-takes or to maintain appropriate navigation draughts in the barrage's upstream reach. For obtaining the ideal upstream level for the passing channel flow, the flow rate was divided by the desired number of gates to give the discharge per gate.

3. Case Study

The case study for this research is taken to be the Seriakos barrage to be a real-life case. The Seriakos Barrage is located in Egypt, precisely at the terminus of the Ismailia Canal. This canal serves multiple purposes, including

irrigation, navigation, and domestic water usage. The operating conditions are calculated using Permutations and combinations to generate various ranges of hydraulic jumps for different possible hydraulic conditions that could be generated for barrage (Figures 7 and 8). This barrage is installed in the Ismailia Canal. The barrage consists of 10 gates' openings with a width of 5m each. The canal cross section is a trapezoidal shape and has a bed width of 30 m. The canal has a minimum discharge of 116 m^3/s and a maximum discharge of 347 m^3/s. The upstream water depth is 6 m, whereas the downstream depth is 3.3 m for the minimum discharge and 4.8 m for the maximum discharge case [24].

The generated power from the hydraulic jumps was mathematically modeled using an Excel spreadsheet. For each number of open gates (from 1 to 10 gates), the gate openings are taken at 0.15 m intervals; for example, they are taken to be 0.15 m, 0.3 m, and so on until 5 m.

Figure 5. Seriakos Barrage Location in Egypt

Figure 6. Seriakos Barrage

The downstream depth measures 4.8 m, and the flow rate is recorded at 347 m^3/s. Currently, the canal is carrying the maximum flow, so this analysis has utilized the maximum discharge to represent the potential future expansion of the canal.

4. Results and Discussion

Various forms of hydraulic jumps, including strong, steady, oscillating, undular, and weak jumps, can be observed at the Seriakos barrage. The dissipated energy resulting from these jumps is taken into account when calculating the potential power that can be used under the most favorable and ideal hydraulic operating conditions. The following tables present the outcomes of the power produced by various hydraulic jumps, considering both free jumps and submerged jumps. Tables 2 and 3 summarize the key hydraulic parameters for each operating scenario, including the discharge, number of gates, conjugate depth, gate opening, contraction coefficient, energy loss, upstream water level, efficiency, jump kind, and submergence factor. All these parameters were previously discussed in the above sections. These calculations are utilized to identify the hydraulic jump that dissipates the most energy and can be used for power generation. The first case involves free flow with a discharge rate of 347 m^3/sec. To determine the discharge rate per gate, the total discharge is then divided by the number of gates that are open. Subsequently, the Froude number is determined using equation (4) for each individual gate in every scenario. The results of the study showed that in the case where the flow was free, none of the operating scenarios were deemed suitable as all the submergence factors yielded negative values. In order for these factors to become positive, an excessively large gate opening would be necessary. As a result, these scenarios were excluded from further consideration.

Table 2. Results of free flow at 347 m^3/s

Q (m³/s.)	No. of gates	Froude number (Fr)	Conjugate depth	Gate opening	Gate angle	Contraction coefficient	Energy loss	Y$_1$	Efficiency	Jump kind	V$_1$ (m/s)	S	Comment
34.7	10	13.44	5.57	0.45	0.91	0.67	18.81	0.26	0.21	Strong Jump	23.08	-0.14	Avoid
38.55556	9	9.78	5.32	0.60	0.93	0.66	12.67	0.36	0.28	Strong Jump	19.34	-0.10	Avoid
43.375	8	6.08	4.80	0.90	0.97	0.66	6.57	0.59	0.43	Steady Jump	14.66	0.00	Avoid
49.57143	7	5.56	5.07	1.05	0.99	0.65	5.72	0.65	0.47	Steady Jump	14.43	-0.05	Avoid
57.83333	6	3.88	4.85	1.50	1.05	0.65	3.08	0.96	0.62	Oscillating Jump	11.95	-0.01	Avoid
69.4	5	2.88	4.80	2.10	1.12	0.63	1.63	1.33	0.76	Oscillating Jump	10.41	0.00	Avoid
86.75	4	2.17	4.87	3.00	1.23	0.62	0.73	1.84	0.88	Weak Jump	9.28	-0.01	Avoid
115.6667	3	1.87	5.48	4.05	1.35	0.62	0.43	2.19	0.93	Weak Jump	9.27	-0.12	Avoid
173.5	2	2.81	8.75	4.05	1.35	0.62	1.54	1 .37	0.77	Oscillating Jump	13.91	-0.45	Avoid
347	1	5.62	18.63	4.05	1.35	0.62	5.82	0.64	0.46	Steady Jump	27.81	-0.74	Avoid

Table 3 provides a summary of the operating scenarios for the submerged flow at a rate of 347 m^3/sec, as the free flow scenarios have all been deemed unsuitable and thus excluded. Findings indicate that there is no submerged jump when gates 1, 2, and 3 are opened. However, the most favorable outcomes were observed when gates 10, 9, 8, 7, and 4 were opened, with respective gate openings of 0.6, 0.75, 1.05, 1.2, and 3.15 meters. It is worth noting that there were alternative choices that yielded higher power generation than the selected conditions. Nevertheless, these options were disregarded due to the presence of an unstable hydraulic jump known as an oscillating hydraulic jump.

Table 3. Results of submerged flow at 347 m^3/s

Q (m³/s.)	No. of gates	Froude number (Fr)	Conjugate depth	Gate opening	Gate angle	Contraction coefficient	Energy loss	Y$_1$	Efficiency	Jump kind	V$_1$ (m/s)	S	Comment
34.7	10	8.80	4.77	0.60	0.93	0.66	11.04	0.40	0.31	Steady Jump	17.41	0.01	Best
38.56	9	7.05	4.70	0.75	0.95	0.66	8.15	0.51	0.38	Steady Jump	15.55	0.02	Best
43.37	8	4.86	4.39	1.05	0.99	0.65	4.61	0.75	0.52	Steady Jump	12.63	0.09	Best
49.57	7	4.58	4.69	1.20	1.01	0.65	4.17	0.80	0.55	Steady Jump	12.69	0.02	Best
57.83	6	3.38	4.57	1.65	1.07	0.64	2.34	1.11	0.69	Oscillating Jump	10.91	0.05	Avoid
69.4	5	2.61	4.59	2.25	1.14	0.63	1.27	1.49	0.81	Oscillating Jump	9.75	0.05	Avoid
86.75	4	2.02	4.70	3.15	1.25	0.62	0.57	2.00	0.91	Weak Jump	8.86	0.02	Best

The maximum power that can be generated is 3758.8 watts. This power is produced by each gate when 10 gates are opened, as indicated in Table 4. The study does not include estimations for power generated from free jumps, as these scenarios have been excluded due to their negative submergence factors mentioned earlier. The calculation of generated power follows Equation 12. According to the data presented in Table 4, it can be observed that the generated power increases as the number of gate openings increases. Hence, the correlation between the number of gates that are opened and the amount of power produced is directly proportional, as illustrated in Figure 9. However, it is worth noting that in the scenario where 10 gates are opened, the gate opening is actually lower compared to the scenario where only 4 gates are opened.

Table 4. Power generated from hydraulic jumps

Gates opened	Gate opening	Power from one gate (Watt)	Power from all opened gates (Watt)	Flow rate
10	0.60	3758.8 w	3758.8 w × 10 = 37588 w	34.7 m^3/s
9	0.75	3082.1 w	3082.1 w × 9 = 27738.9 w	38.6 m^3/s
8	1.05	1961.3 w	1961.3 w × 8 = 15690.4 w	43.4 m^3/s
7	1.20	2026.2 w	2026.2 w × 7 = 14183.4 w	49.6 m^3/s
6	1.65	1329 w	1329 w × 6 = 7974 w	57.8 m^3/s
5	2.25	865.1 w	865.1 w × 5 = 4325.5 w	69.4 m^3/s
4	3.15	487.4 w	487.4 w × 4 = 1949.6 w	86.8 m^3/s
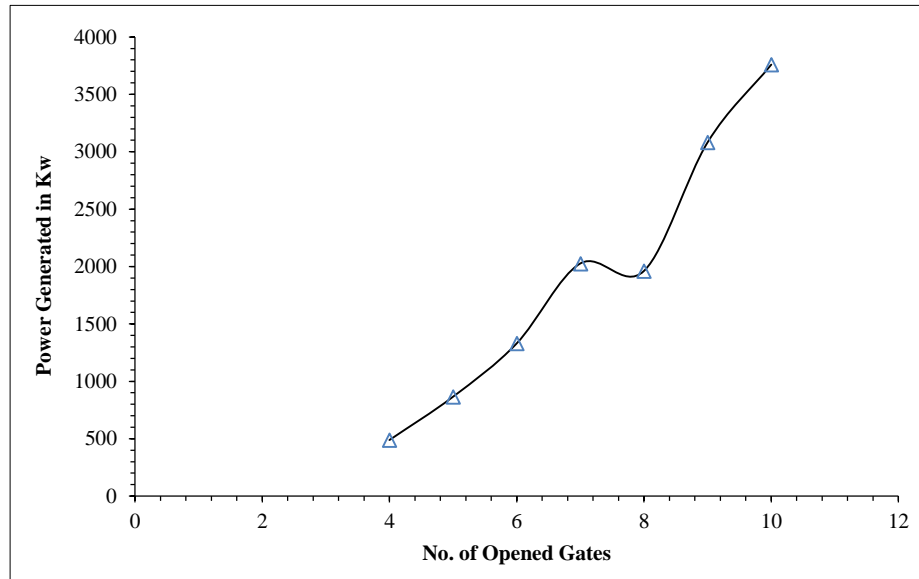
Figure 7. Relation between number of opened gates and power generated.

This estimated generated power has the potential to be utilized in various applications, as will be demonstrated in the upcoming section. As previously mentioned, the majority of research has focused on calculating the hydraulic jump head loss and energy dissipation. However, there is a lack of research exploring the conversion of this head loss into power and the potential benefits it can bring.

5. Estimated Power from Generated Hydraulic Jumps

The maximum power that can be generated from hydraulic jumps created at the Seriakos barrage is 11712.01 W (11.712 MW). This power is generated in the case of opening 10 gates with a 0.6-meter gate opening (the maximum power obtained). This high power can be used in multiple ways to power electric devices and in residential buildings. According to the Egyptian Electric Cooperative Association, an average household will use 1,800 kWh of electric power on a monthly basis [30]. This power is very high compared to the power produced from the Seriakos barrage. As a result, using the power generated from the hydraulic jumps to light up streetlights is the best possible option. The average streetlight lamp consumes 250–400 watts. Now new light bulbs (High Pressure Sodium HPS) are being installed, which will consume 100–150 watts [31].

In order to calculate the number of light bulbs that will use the power generated from hydraulic jumps, the net power (power calculated including efficiency) generated from the opened 10 gates of the Seriakos barrage is calculated according to equation 12 [32, 33]. Then, the power required for the streetlight bulbs is calculated. After that, the power generated from the hydraulic jump is divided by the amount required for one streetlight bulb in order to estimate the number of streetlight bulbs needed.

As per Equation 12: the power generated from hydraulic jump is calculated where the flow rate in m³/s is converted into liters/sec by multiplying it by 1000. The H_{net} is the total head that was measured at the Seriakos barrage, excluding any head losses A turbine should be used to convert head losses and hence, energy dissipated from hydraulic jumps into power. The turbine used in this study is the low-head Kaplan turbine, as the head at the Seriakos barrage is below 4.5 m. The turbine efficiency is assumed to be 87%; according to these turbine standards, efficiency is from 82% to 92%, and the head for this turbine type ranges from 1.8 to 5 m as per Quaranta et al. [34].

H_{net} is the difference between conjugate depths Y_1^* and y_2;

The following calculations represent the power estimates listed in Table 3;

Power = 34.7×1000×9.81× ((4.8-0.4)×0.9)×0.87 = 1171.201 Watts (for one gate);

Note: Q and net head calculations are values taken from Table 2.

$$Net\ Power\ for\ 10\ gates = 1171.201 \times 10 = 11712.01\ Watts \tag{13}$$

- Number of light bulbs using hydraulic jump power (hydropower) = 11712 / 150 = 78 Light bulbs

6. Conclusion

The main objective of this research is to generate power from hydraulic jumps' dissipated energy and to further utilize this power. To reach that, calculations were conducted to determine the amount of energy dissipated through different hydraulic jump types from downstream sluice gates, with the ultimate objective of identifying the hydraulic jump that dissipates the maximum amount of energy. The purpose behind this is to harness this dissipated energy and utilize it to generate power and use this power in generating electricity. There have been no scientific studies conducted that calculate the power generated out of hydraulic jumps and further explore the potential for utilizing this power in practical applications. A mathematical model formulated on an Excel spreadsheet was constructed to simulate hydraulic jumps generated downstream of a real-case study, namely the Seriakos barrage in Egypt. A simulation was conducted to determine the power produced by various types of hydraulic jumps occurring downstream of the barrage. The simulation considered both free and submerged jumps. Free jumps were then disregarded due to negative submergence factors. The findings of the study indicated that the hydraulic jumps generated by the Seriakos barrage have the potential to produce enough power to illuminate a total of 78 street light bulbs. It is recommended to utilize low-head Kaplan turbines for power generation, as they are specifically designed for use with heads that are less than 4.5 meters. Power generated from hydraulic jumps at Seriakos barrage may not be sufficient to power up multiple appliances, yet if the power generated by hydraulic jumps from all hydraulic structures in Egypt were used, then it could significantly contribute to meeting the country's power requirements. This concept is not limited to Egypt alone and can be applied to any other country worldwide.

7. Declarations

7.1. Author Contributions

Conceptualization, S.E.B.; methodology, S.E.B, N.H. and M.E.; software, S.E.B, N.H. and M.E.; validation, S.E.B. and N.H.; formal analysis, S.E.B. and N.H.; investigation, S.E.B.; resources, S.E.B., N.H. and M.E.; data curation, S.E.B. and N.H.; writing—original draft preparation, N.H. and M.E.; writing—review and editing, S.E.B. and N.H.; visualization, S.E.B.; supervision, S.E.B.; project administration, S.E.B. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

7.4. Institutional Review Board Statement

Not applicable.

7.5. Informed Consent Statement

Not applicable.

7.6. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

8. References

[1] Olabi, A. G., & Abdelkareem, M. A. (2022). Renewable energy and climate change. Renewable and Sustainable Energy Reviews, 158, 112111. doi:10.1016/j.rser.2022.112111.

[2] Unacademy. (2023). Use of clean energy sources. Unacademy: India's largest learning platform, Karnataka, India. Available online: https://unacademy.com/content/neet-ug/study-material/biology/use-of-clean-energy-sources/ (accessed on May 2023).

[3] World Bank. (2010). World Bank Annual Report 2010 Year in Review. World Bank Annual Report, 2010. doi:10.1596/978-0-8213-8376-6.

[4] Hersh, M. A. (2006). The Economic and Politics of Energy Generation. In Improving Stability in Developing Nations through Automation, 77–82. doi:10.1016/B978-008045406-1/50011-2.

[5] EIA. (2023). EIA projects that renewables will provide nearly half of world electricity by 2050. U.S. Energy Information Administration (EIA): Today in Energy: Independent Statistics and Analysis, Washington, D.C., United States. Available online: https://www.eia.gov/todayinenergy/detail.php?id=41533 (accessed on May 2023).

[6] Akikur, R. K., Saidur, R., Ping, H. W., & Ullah, K. R. (2013). Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review. Renewable and Sustainable Energy Reviews, 27, 738–752. doi:10.1016/j.rser.2013.06.043.

[7] Bandara, W., & Kowshayini, P. (2018). Evaluation of the Performances of Biomass Briquettes Produced with Invasive Eichornia crassipes (Water hyacinth), Wood Residues and Cow Dung for Small and Medium Scale Industries. Journal of Fundamentals of Renewable Energy and Applications, 8(1), 1000247. doi:10.4172/2090-4541.1000247.

[8] Yah, N. F., Oumer, A. N., & Idris, M. S. (2017). Small scale hydro-power as a source of renewable energy in Malaysia: A review. Renewable and Sustainable Energy Reviews, 72, 228–239. doi:10.1016/j.rser.2017.01.068.

[9] NREL. (2023). Hydropower Basics. National Renewable Energy Laboratory (NREL), Colorado, United States. Available online: https://www.nrel.gov/research/hydropower.html (accessed on May 2023).

[10] Laishram, K., Kumar, P. A., & Devi, T. T. (2022). Effect of channel slope and roughness on hydraulic jump in open channel flow. IOP Conference Series: Earth and Environmental Science, 958(1), 012014. doi:10.1088/1755-1315/958/1/012014.

[11] Gupta, S. K., Mehta, R. C., & Dwivedi, V. K. (2013). Modeling of relative length and relative energy loss of free hydraulic jump in horizontal prismatic channel. Procedia Engineering, 51(NUiCONE), 529–537. doi:10.1016/j.proeng.2013.01.075.

[12] Montes, J. S. (1986). A Study of the Undular Jump Profile. 9th Australasian Fluid Mechanics Conference, Auckland, 8-12 December, 148–151.

[13] Kim, Y., Choi, G., Park, H., & Byeon, S. (2015). Hydraulic jump and energy dissipation with sluice gate. Water (Switzerland), 7(9), 5115–5133. doi:10.3390/w7095115.

[14] Chen, J. Y., Liao, Y. Y., & Liu, S. I. (2013). Energy dissipation of hydraulic jump in gradually expanding channel after free overfall. Journal of the Chinese Institute of Engineers, Transactions of the Chinese Institute of Engineers, Series A, 36(4), 452–457. doi:10.1080/02533839.2012.732263.

[15] Al Talib, A. N., Mohammed, A. Y., & Hayawi, H. A. (2019). Hydraulic jump and energy dissipation downstream stepped weir. Flow Measurement and Instrumentation, 69(July), 101616. doi:10.1016/j.flowmeasinst.2019.101616.

[16] Kumar, T.V., Bais, V., Sihag, S., & Singhal, S. (2022). Methods to Increase Energy Dissipation in Hydraulic Jump. International Journal of Engineering Research & Technology, 10(5), 137–141.

[17] Gupta, S. K., & Dwivedi, V. K. (2023). Prediction of Depth Ratio, Jump Length and Energy Loss in Sloped Channel Hydraulic Jump for Environmental Sustainability. Evergreen, 10(2), 942–952. doi:10.5109/6792889.

[18] Zhou, Y., Wu, J., Ma, F., & Hu, J. (2020). Uniform flow and energy dissipation of hydraulic-jump-stepped spillways. Water Science and Technology: Water Supply, 20(4), 1546–1553. doi:10.2166/ws.2020.056.

[19] Sayyadi, K., Heidarpour, M., & Ghadampour, Z. (2022). Effect of Bed Roughness and Negative Step on Characteristics of Hydraulic Jump in Rectangular Stilling Basin. Shock and Vibration, 1722065. doi:10.1155/2022/1722065.

[20] Maryami, E., Mohammadpour, R., Beirami, M. K., & Haghighi, A. T. (2021). Prediction of hydraulic jump characteristics in a closed conduit using numerical and analytical methods. Flow Measurement and Instrumentation, 82(October), 102071. doi:10.1016/j.flowmeasinst.2021.102071.

[21] Annenberg Learner (2023). Insights into algebra 1 Episodes 1-8: teaching for learning. California, United States. Available online: https://www.learner.org/series/insights-into-algebra-1-teaching-for-learning-2/mathematical-modeling/ (accessed on May 2023).

[22] Zhao, Y., Liu, J., & Wang, Z. (2016). Calculation method for conjugate depths in quadratic parabolic channels. Flow Measurement and Instrumentation, 50, 197–200. doi:10.1016/j.flowmeasinst.2016.06.007.

[23] Leutheusser, H. J., & Fan, J. J. (2001). Backward Flow Velocities of Submerged Hydraulic Jumps. Journal of Hydraulic Engineering, 127(6), 514–517. doi:10.1061/(asce)0733-9429(2001)127:6(514).

[24] Imam, E. H., & El Brardei, S. A. (2011). Optimum Operation of Canal Barrages. International Conference on Water, Energy and Environment, November 14–17, Sharjah, United Arab Emirates (UAE).

[25] El Baradei, S. A., Abodonya, A., Hazem, N., Ahmed, Z., El Sharawy, M., Abdelghaly, M., & Nabil, H. (2022). Ethiopian Dam Optimum Hydraulic Operating Conditions to Reduce Unfavorable Impacts on Downstream Countries. Civil Engineering Journal (Iran), 8(9), 1906–1919. doi:10.28991/CEJ-2022-08-09-011.

[26] Dey, S. (2008). Errata for "Characteristics of Turbulent Flow in Submerged Jumps on Rough Beds" by Subhasish Dey and Arindam Sarkar. Journal of Engineering Mechanics, 134(7), 599–599. doi:10.1061/(asce)0733-9399(2008)134:7(599).

[27] Swamee, P. K. (1992). Sluice- Gate Discharge Equations. Journal of Irrigation and Drainage Engineering, 118(1), 56–60. doi:10.1061/(asce)0733-9437(1992)118:1(56).

[28] Hoffmans, G. J. C. M., & Pilarczyk, K. W. (1995). Local Scour Downstream of Hydraulic Structures. Journal of Hydraulic Engineering, 121(4), 326–340. doi:10.1061/(asce)0733-9429(1995)121:4(326).

[29] Aamir, M., Ahmad, Z., Pandey, M., Khan, M. A., Aldrees, A., & Mohamed, A. (2022). The Effect of Rough Rigid Apron on Scour Downstream of Sluice Gates. Water (Switzerland), 14(14), 2223. doi:10.3390/w14142223.

[30] EECA. (2023). Usage Concerns | Egyptian Electric Cooperative. Egyptian Electric Cooperative Association, Illinois, United States. Available online: https://eeca.coop/energy-efficiency/usage-concerns/ (accessed May 14, 2023).

[31] Mklights. (2023). Does LED street lamps better than high-pressure sodium lamps?. Hangzhou Mklights Technology Co., Zhejiang, China. Available online: https://www.mklights.com/BLOGS/does-led-street-lamps-better-than-high-pressure-sodium-lamps.html (accessed on May 2023).

[32] Majumder, P., & Saha, A. K. (2019). Identification of Most Significant Parameter of Impact of Climate Change and Urbanization on Operational Efficiency of Hydropower Plant. International Journal of Energy Optimization and Engineering, 8(3), 43–68. doi:10.4018/ijeoe.2019070103.

[33] Renewables First. (2023). How much hydropower power can I get. Renewables First, Brimscombe, England. Available online https://www.renewablesfirst.co.uk/renewable-energy-technologies/hydropower/hydropower-learning-centre/how-much-power-could-i-generate-from-a-hydro-turbine/ (accessed on August 2023).

[34] Quaranta, E., Bahreini, A., Riasi, A., & Revelli, R. (2022). The Very Low Head Turbine for hydropower generation in existing hydraulic infrastructures: State of the art and future challenges. Sustainable Energy Technologies and Assessments, 51, 101924. doi:10.1016/j.seta.2021.101924.