

Experimental Investigation of The Flow Over an Arched Sharp-Crested Weir

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Received: September 1st 2025 Received in revised form: October 21th, 2025 Accepted: December 28th, 2025

ABSTRACT

Weirs are used to raise the water level in the open channels upstream of the weir for many purposes, such as irrigation; however, they cause turbulence and develop a hydraulic jump downstream of the weir. This leads to a process of scouring at the bed of the open channel, which threatens the stability of the weirs. An arched, sharp-crested weir is one of the weirs characterized by its ability to pass high discharges due to its long edge compared to the traditional sharp-crested weir. In this experimental study, four physical models of an arched sharp-crested weir were investigated with different ratios of the radius parallel to the flow (a) to the radius perpendicular to the flow (b) (1, 1.2, 1.4, and 1.6). The results displayed that the arched weir has a higher discharge coefficient (C_d) and energy dissipation ratio ($\eta\%$) than the sharp-crested weir. In addition, increasing the (a/b) ratio led to an increase in (C_d) and a decrease in the turbulent length of the flow downstream of the weir, which significantly determines the length of the stilling basin. A secondary hydraulic jump was also observed in the arched weir, which provides additional energy dissipation. The discharge coefficient (C_d) ranges between 0.8 and 1.17 for different cases of arched weir ratios compared to 0.56 for a sharp-crested weir with the same dimensions and flow conditions. Regarding energy dissipation, it ranges between 56% and 69% for different models' ratios (a/b), and for a certain model, it decreases as the water discharge increases.

Keywords: Arched crested-weir; sharp crested weir; energy dissipations; discharge coefficient; flow measurement.

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1. INTRODUCTION

Hydraulic structures, including weirs, are constructed to control the flow level [1], maximize the benefits of these natural formations, and facilitate the pumping of water to irrigation stations and various irrigation projects [2], [3]. Additionally, it can be used to estimate water discharge in water streams [4], [5].

The difference in water level between upstream and downstream weirs increases due to the location of the weir in the water stream. Falling water from the weir crest causes a change in flow from supercritical to subcritical, generating a hydraulic jump and forming a zone of turbulence. This hydraulic jump is important to reduce the flow energy downstream of the hydraulic structure [6]. This difference in water level leads to an increase in the flow energy of the water falling from the weir, transforming the flow into super-critical flow, which leads to scouring in the channel bed and banks of the watercourse [7] and affects the

shape of the watercourse and the stability of the weir [8]. This water mass then collides with a stationary or low-speed water mass, i.e., in a sub-critical flow state, generating a hydraulic jump [9].

There are three types of weirs based on their width relative to the width of the channel, which are the full-width weir, the partially narrowed weir, and the fully narrowed weir [10]. As for the shape of the weir in general, there are several types. Rectangular weirs with a sharp and broad crest, which are the oldest type, have a lower discharge coefficient than the other types [11]. The piano weir, in all its types, is characterized by a high (C_d) compared to the rectangular weir due to the crest length [9]. The triangular weir with a sharp crested weir has a higher (C_d) value than the rectangular weir [12]. Another type is an arched weir [13], which is used to increase the discharge coefficient because it has a longer crest than other types, allowing it to pass larger discharges during floods. This type also reduces the water height

upstream of the weir for a given discharge compared to a traditional rectangular weir, thereby reducing the severity of the impact of water falling over the rear of the weir mentioned above.

Literature studies have concluded that the head exponent of water over the arched weir (H) depends on the arch length of the weir, in addition to its height, and is equal to 1.5. Experimental and theoretical investigations on weirs have proven that equation (1) can be applicable for use in curved weirs [13], and the effective crest width of the weir (B), which is normally vertical to the flow, will be used instead of the arc length.

$$Q = \frac{2}{3} C_d \sqrt{2g} B H^{1.5} \quad (1)$$

Where the Q is the water discharge passing over the weir, g is the acceleration of gravity, C_d can be estimated based on experimental or field measurements, and H is the total head above the weir.

[14] Conducted an experimental study of sharp-crested arched weirs for different values of curvature angle. The results showed an increase in the weir's ability to pass discharge with increasing curvature angle due to the increase in crest length. [15] Investigated the flow characteristics of flow for arched weirs with sharp or semi-circular crests. They considered different a/b ratios (0.5, 1, 2, and 4). Two cases of the weir curvature direction were also considered, in and opposite to the flow direction. They derived four empirical equations to predict water discharge for different cases, which were adopted in their study. The results showed that curvature ratios of (1 and 2) gave the highest values for C_d when the curvature was in the direction of the flow. [16] Experimentally investigated the arched weirs located in a reservoir to determine the discharge coefficient (C_d). The results indicated that C_d decreases with increasing the H/P ratio and the ratio of weir length to weir width. Compared to a linear weir, they showed that the efficiency of an arched weir can increase up to 50%.

[13] Conducted a study on the hydraulic behavior of arched weirs and compared them with a traditional rectangular weir, where the length of the weir crest was taken into account to determine the C_d value. The results showed an increase in the ability to pass discharge for arched weirs compared to rectangular weirs, despite the decrease in the C_d value.

Despite the benefits of constructing the weirs for irrigation and other purposes, they may increase the flood problem that arises during the flood season. An arched weir can increase the ability of the weir to pass more flow by expanding the crest length and decreasing the adverse effect

of the flood waves. In addition, weirs cause a scour in the bed and banks of the channel downstream of the weir as a result of falling water and generating a hydraulic jump. Therefore, investigating the turbulence length and the distance downstream of the weir at which the flow becomes stable is important, as it determines the stilling basin length, which has received less attention in previous studies for the arched weir. The current study aims to study the discharge coefficient, energy dissipation, and flow stability location of a contracted arched sharp-crested weir with different ratios of curvature diameters. Four different ratios of (a/b) between 1 and 1.6 will be adopted and compared with a rectangular sharp-crested weir with the same contraction ratio and under the same flow conditions.

2. METHODOLOGY

2.1. Experimental Work: The experiments were conducted in the hydraulics laboratory of the Dams and Water Resources Engineering Department at the University of Mosul using a rectangular concrete open channel. The channel has a width of 0.81 m, a depth of 0.76 m, and a length of 24.2 m, with a horizontal bed slope at the section work as shown in Fig. 1 (A).

Clear water was pumped from a 72 m³ underground tank to the channel and recirculated using an electric pump. Four different discharges up to 80 L/sec were considered for the experiments. The discharge was measured using a standard sharp-crested weir at the end of the channel, which was previously calibrated by [17] using the volumetric method, which involves collecting water volume over a specific period of time for several discharges.

A 0.1 cm accuracy point gauge was used to measure water depths along the channel center line upstream and downstream of the weir location. The water head above the weir (h) was measured at a distance of 3-4 times the maximum water head above the weir at the upstream of the weir location. Using the hydraulic jump equation, the water depth after the hydraulic jump (Y_2) was calculated in the case of a rectangular sharp-crested weir, and the water depth before the hydraulic jump (Y_1) in the case of arched sharp-crested weirs [18], [19]. This is because it's impossible to measure it due to the turbulence in the flow and the return of water on both sides of the channel.

Four different models of arched, sharp-crested weirs were fabricated from transparent plastic (acrylic) with a thickness of 8 mm, as shown in Fig. 1B and 1C. All the models have a constant weir curvature axis perpendicular to the direction of the flow (b) equal to 30 cm length; however, four different values of the curvature axis

parallel to the direction of the flow (a) equal to (30, 36, 42, and 48) cm. Therefore, the ratio (a/b) for the different models equals 1, 1.2, 1.4, and 1.6, as shown in Fig. 1(C). For comparison purposes, a 25% contracted sharp-crested rectangular weir was used. The British Standards Weir Specifications (BSI) were also adopted in fabricating this sharp-crested weir [11]. The flow for all the experiments is uniform and subcritical upstream of the weir (Froud number between 0.07 and 0.12). The minimum discharge value (40 L/s) was chosen to ensure that surface tension forces do not affect the flow, especially at an a/b ratio of 1.6. However, the maximum discharge from the pump is 80 L/s. More than this value, the discharge becomes unstable. Table 1 provides the experimental measurements data and calculations.

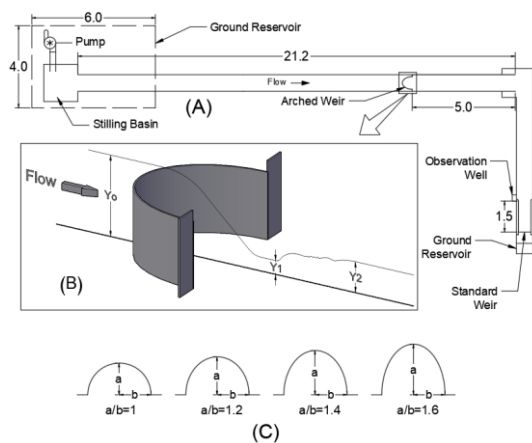


Fig. 1 (A) Sketch of the channel.
(B) Three-dimensional model and water depths.
(C) Curvature ratios

Table 1 experimental measurements data and calculations

NO.	Q L/s	Y ₀ m	Y ₂ m	V ₀ m/s	V ₂ m/s	E ₀ m	E ₂ m	Cd	η _T %	a/b ratio
1	40	0.39	0.11	0.13	0.45	0.39	0.12	0.82	68.91	a/b=1
2	50	0.41	0.13	0.15	0.48	0.41	0.14	0.77	65.88	
3	64	0.42	0.15	0.19	0.54	0.42	0.16	0.82	61.87	
4	77	0.44	0.16	0.22	0.59	0.44	0.18	0.80	59.21	
5	40	0.39	0.11	0.13	0.44	0.39	0.12	0.87	68.16	a/b=1.2
6	55	0.41	0.14	0.17	0.50	0.41	0.15	0.85	63.30	
7	69	0.42	0.15	0.20	0.56	0.42	0.17	0.88	59.86	
8	78	0.43	0.17	0.22	0.58	0.44	0.18	0.86	57.73	
9	42	0.38	0.12	0.14	0.43	0.38	0.13	1.03	65.64	a/b=1.4
10	56	0.40	0.14	0.17	0.49	0.40	0.15	0.98	62.01	
11	69	0.41	0.16	0.21	0.55	0.41	0.17	0.98	58.62	
12	81	0.42	0.17	0.24	0.58	0.43	0.19	0.98	55.63	
13	40	0.37	0.12	0.13	0.41	0.37	0.13	1.15	65.58	a/b=1.6
14	50	0.38	0.13	0.16	0.46	0.39	0.14	1.10	62.39	
15	63	0.40	0.15	0.19	0.52	0.40	0.16	1.07	59.20	
16	77	0.41	0.17	0.23	0.57	0.42	0.18	1.06	55.94	
17	40	0.42	0.15	0.12	0.32	0.42	0.16	0.57	62.27	Rectangular
18	56	0.45	0.18	0.15	0.38	0.45	0.19	0.55	58.49	
19	69	0.47	0.20	0.18	0.43	0.47	0.21	0.57	56.02	
20	81	0.49	0.21	0.21	0.48	0.49	0.22	0.56	54.67	

2.2. Dimensional analysis: Flow over an arched, sharp-crested weir is influenced by many factors as follows:

- Geometric properties: which include effective weir crest width and height, (B) and (P), respectively, weir curvature axis parallel and perpendicular to the direction of the the flow, a and b, respectively.
- Flow properties: flow depth and velocity upstream of the weir, (Y₀) and (V₀), respectively. In addition, the energy dissipation ratio is affected by the flow depths before and after the jump (Y₁) and (Y₂), respectively, and by the flow velocities before and after the jump (V₁) and (V₂), respectively.
- Fluid properties: water viscosity (μ), mass density of the water (ρ), and gravitational acceleration (g).

Using Buckingham’s theory and after determining the variables affecting both (C_d) and (η), which are as follows:

$$C_d = f_1 \left(\frac{H}{P}, \frac{B}{P}, \frac{a}{b}, \frac{V_0^2}{gY_0}, \frac{\mu}{\rho V_0 Y_0}, \frac{\sigma}{P^2 \rho g} \right) \quad (2)$$

$$\eta\% = f_2 \left(\frac{H}{P}, \frac{B}{P}, \frac{a}{b}, \frac{V_0^2}{gY_0}, \frac{\mu}{\rho V_0 Y_0}, \frac{\sigma}{P^2 \rho g}, \frac{Y_2}{Y_1}, \frac{V_2}{V_1} \right) \quad (3)$$

Where H is the total water head above the weir, which is equal to the water head above the weir (h) + V₀²/2g. The energy loss percentage between any two-flow sections can be expressed by the coefficient (η%) [6], [20], where:

$$\eta\% = \frac{E_A - E_B}{E_A} * 100\% \quad (4)$$

Where E_A and E_B are the total energies at sections A and B. In this study, the total energy upstream of the weir (E₀) and the total energy after the jump (E₂) were compared.

The total energy for each section is calculated according to the equations:

$$E_0 = P + h + \frac{V_0^2}{2g} \quad (5)$$

$$E_2 = Y_2 + \frac{V_2^2}{2g} \quad (6)$$

The percentage of total energy dissipated can be expressed as follows:

$$\eta\% = \frac{E_0 - E_2}{E_0} \quad (7)$$

After neglecting both (B/P) as it is a constant value and Weber’s number, given that the water depth above the weir crest is greater than 3cm [21], [22]. The Reynolds number is a large value; it can also be neglected, and neglecting the friction forces between the water and the sides and bottom of the channel, equations (2 & 3) can be expressed as shown in equations (8 & 9)

$$C_d = f_3 \left(\frac{H}{P}, \frac{a}{b}, Fr_0^2 \right) \quad (8)$$

$$\eta\% = f4 \left(\frac{H}{P}, \frac{a}{b}, Fr_o^2, \frac{Y_2}{Y_1}, \frac{V_2}{V_1} \right) \quad (9)$$

Where Fr_o is the Froude number upstream of the weir.

3. RESULTS AND DISCUSSIONS

3.1. Water Surface Profile: Fig. 2 shows the longitudinal section of the water surface profile for a water discharge of 40 L/s and (a/b) equal to 1 and 1.6, respectively. It can be seen from the figure that the Y_o decreases with increasing (a/b) ratio due to an increase in the weir crest length and, consequently, the increase in the weir’s ability to pass a larger amount of water over it. The figure also shows generating a secondary jump in the center of the flow, i.e., in the middle of the channel, as in Fig. 2, where it was in the form of a slice in cases of a/b = 1 and 1.2, as shown in Fig. 3 (a, b). However, it becomes conical for a/b = 1.4 and 1.6, as shown in Fig. 3(c, d). This secondary jump is generated due to the collision of water falling from opposite points on the crest of the weir, as shown in Fig. 4. After colliding with the channel bed, the change in the shape of the jump to a conical shape may be due to the most of collision falling water almost meet at appoint in the center of channel in case of a/b = (1, 1.2), However, with increasing the ratio a/b, this point becomes as aline due to increasing the length of (a) therefor, the secondary hydraulic jump change from slice to conical shape. Because of the water depth upstream, the weir increases as the ratio a/b decreases, as mentioned above. Consequently, the depth decreases as the ratio a/b decreases. Therefore, the highest secondary jump was recorded in the case of a/b =1, and its height decreases as the ratio a/b increases.

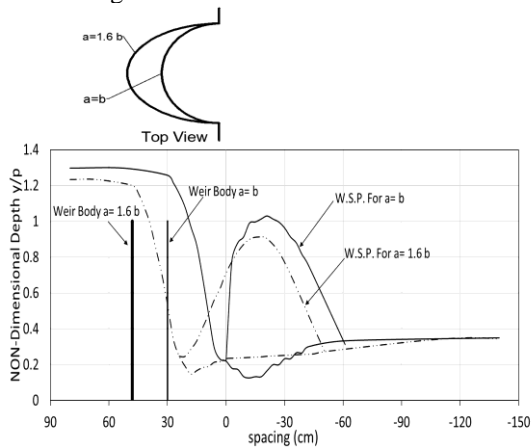


Fig. 2 Water Surface Profile for the smallest and largest values for the ratio a/b

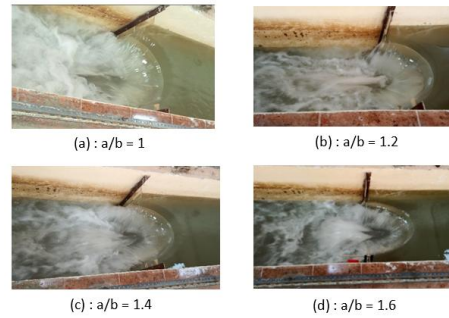


Fig. 3 Arched crested weir models during experiments

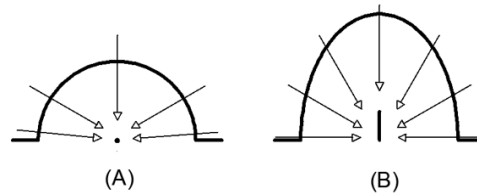


Fig. 4 collision site of falling water

3.2. Discharge coefficient: Discharge coefficient (C_d) is an actual-to-theoretical discharge ratio [23]. The discharge coefficient for different cases was calculated and plotted against (H/P) and (Fr_o), as shown in Figs. 5 and Fig. 6, demonstrating the difference in (C_d) between the arched sharp-crested weir and the rectangular sharp-crested weir. Due to the increased length of the crest of the arched, sharp-crested weir, the ability to pass more discharges is increased. Therefore, all models of the arched sharp-crested weir recorded an increase in (C_d) value. This increase is in direct relation to the (a/b) ratio for the same reason mentioned above. One more observation from Fig. 5 and Fig. 6 is that the discharge coefficient is less sensitive to H/P and Fr_o variations for rectangular and arched sharp-crested weirs with a/b equal to 1 and 1.2. However, in cases of a/b 1.4 and 1.6, the discharge coefficient starts to decrease with increasing H/P and Fr_o . That may be due to increasing the crest length with an increasing a/b ratio, thus the friction loss due to the crest becomes more effective.

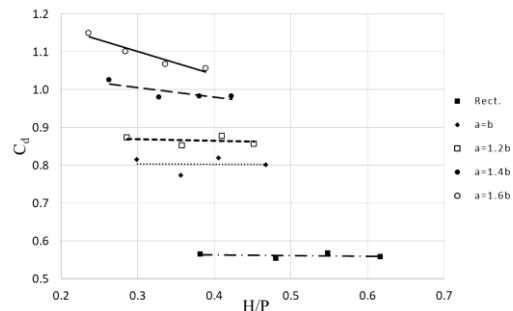


Fig. 5 Relationship between C_d and H/P for different models

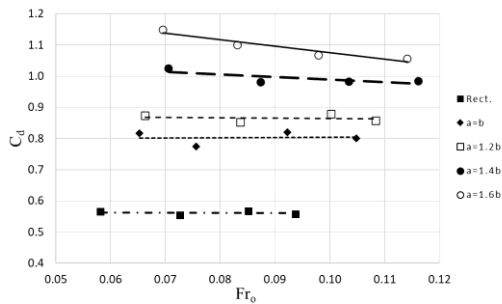


Fig. 6 Relationship between C_d and Fr_0 for different models

3.3. Energy dissipation: Energy dissipation ratio between section (0) (upstream of the weir) and section (2) (after the jump) has been calculated for different cases using equation (7) and drawn in Fig. 7. From this Fig., the main trend of the energy dissipation ratio of the arched sharp-crested weir was the same as that of the sharp-crested weir, where the dissipation ratio decreases with an increase in the Froude number at upstream of the weir (Fr_0). However, the effect of the weir overflow on local flooding [24] is that the amount of water accumulated after the weir increases as discharge increases. In addition, the flow becomes a skimming flow as the H/P value increases due to increased discharge [25], because the point of contact between the falling water and the channel bottom moves farther away, changing the angle of fall from vertical to steep and reducing the impact force. Many researchers have also observed this behavior for different kinds of weirs, such as stepped spillways [26] and labyrinth weirs [25], [27]. It has been observed in all cases of the arched weir with sharp-crest that the total energy dissipation ratio recorded more values compared to that of a conventional weir with sharp-crest. When the flow passes over the weir, the falling water and its impact with the channel bed or tailwater dissipate some of the flow energy. Furthermore, the flow over the arched weir with a sharp crest adds another effective factor for dissipating energy, namely the collision of falling water near the channel center and the generation of a secondary hydraulic jump, as shown in Fig. 4. Fig. 7 and 8 also show that the total energy dissipation ratio is inversely proportional to the a/b ratio. As mentioned above, for the same flow discharge, the height of water above the weir at upstream (h) increases as decreasing a/b ratio led to increase the different water level between upstream and downstream the weir thus, increases the impact effect and energy dissipation, despite the decrease in (h) as a result of the collision of the water nappe flowing down from the weir to the opposite points of the weir, as shown in Fig. 4, This increase is

inversely proportional to the a/b ratio, because the (h) decreases, represented by the ratio H/P , as the a/b ratio increases. Fig. 8 shows a decrease in the percentage of energy dissipated with an increase in the value of H/P . This may be due to several reasons. The first is the effect of the overflow from the weir on the depth of water at the downstream [22]. Increasing H increases water discharge, thereby accumulating water downstream of the weir and reducing the impact on energy dissipation. The second is that the flow becomes skimming flow as the H/P value increases due to increased discharge [23], because the point of contact between the falling water and the channel bottom moves farther away, changing the angle of fall from vertical to steep and reducing the impact force. The third reason is that the percentage of water affected by friction with the edge of the weir decreases as H/P increases.

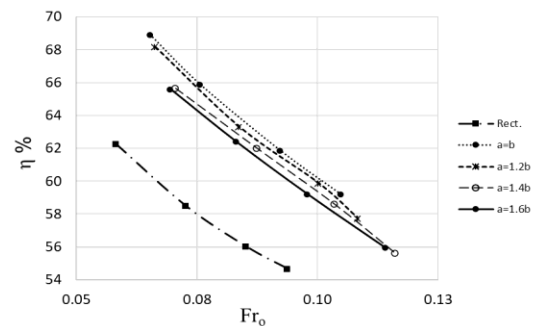


Fig. 7 Relationship $\eta\%$ and Fr_0 for different models

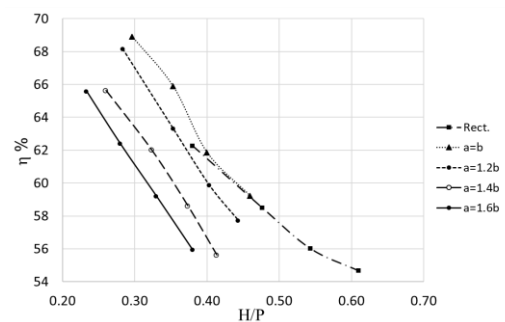


Fig. 8 Relationship between $\eta\%$ and H/P for different models

3.4. Flow Stability location: Based on the dimensional analyses, the $\eta\%$ depends on the hydraulic jump properties ($\frac{Y_2}{Y_1}$ and $\frac{V_2}{V_1}$). The hydraulic jump properties reflect on the length of the turbulence downstream of the weir. Therefore, the flow downstream of the weir needs a distance to stabilize. This distance is very important because it determines the length of the protected

section, measured from the beginning of the weir. The relationship between unit discharge (q) and the flow stability location is shown in Fig. 9. From this figure, for a certain amount of unit discharge, the flow stability point approaches the weir body as the a/b ratio increases. Increasing the water falling angle by increasing the a/b ratio, as shown in Fig. 4. In other words, the falling water almost becomes vertical to the flow direction in the case of $a/b=1.6$, which led to a reduction in the length of turbulence. An increase in the ratio (a/b) also leads to a rise in the discharge passing over the weir, and thus the falling water collides with a larger mass of water, which reduces the length of the jump. This is a good phenomenon in this type of weir from an economic perspective, as the cost of protecting the channel will be reduced. As for the traditional sharp-crested weir, the flow stability point was much further away, and the channel ended before we could measure its distance from the weir.

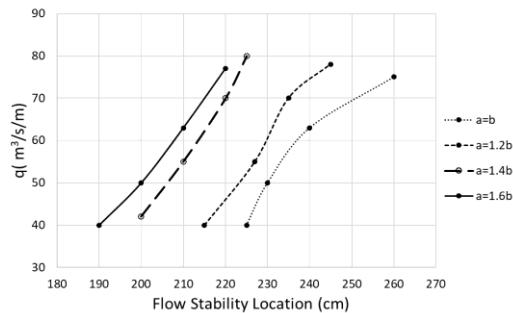


Fig. 9 Relationship between unit discharge and flow stability location for all models

4. CONCLUSION

This experimental study presented the results of a contracted arched sharp-crested weir for four values of the curvature axes parallel to the direction of the flow (a) to the axis perpendicular to the direction of the flow (b), with a ratio (a/b) equal to 1, 1.2, 1.4, and 1.6. The results were compared with the traditional contracted weir with a sharp crest in terms of (C_d), ($\eta\%$), and flow stabilization location downstream of the weir. The results showed that the (C_d) of the arched sharp-crested weir is higher than that of the sharp-crested weir and increases as the ratio (a/b) increases due to the increase in the weir crest length and thus its ability to pass higher discharges. This characteristic is one of the advantages of arched weirs in reducing the effects of flooding in areas upstream of the weir.

Regarding flow energy dissipation, the energy dissipation value of the contracted arched sharp-crested weir was higher than that of the sharp-crested rectangular weir, despite the decrease in depth above the weir edge due to the collision of

falling water near the channel center downstream of the weir. This increase in energy dissipation is inversely proportional to the ratio (a/b) due to the decrease in depth above the weir and, consequently, the decrease in the fall distance.

The location of flow stabilization downstream of the weir is one of the most important criteria for evaluating the performance of weirs, as it determines the length of the stalling basin. The results showed a significant reduction in turbulence length, which directly affects the required length of the settling basin and, consequently, the construction cost. In addition, a secondary hydraulic jump was observed in the arched weir. This hydraulic jump played a significant role in dissipating the energy. Finally, in most practical applications, the channel bed is movable; therefore, investigating the score depth downstream of the arched weir for different a/b ratios is recommended for future research.

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