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Hydraulic Conditions Created by Passing Flow Through and Over a Combined Weir

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Abstract

In this study, a novel broad-crested weir was designed to investigate the effect of varying rectangular gate widths (vertical slots) on the discharge coefficient and free surface profile of a compound weir. Six weir models with vertical slots were theoretically and experimentally examined in a laboratory flume under uniform flow conditions. Each weir model measured 9.5 cm in height, 30 cm in length, and 10 cm in width. The vertical slots were uniformly 7.5 cm in height, with six different widths ranging from 0.5 cm to 3.0 cm, corresponding to a range of opening area ratios (OAR) from 10% to 60%. Under different head conditions, six flow rates between 10 and 35 m³/hr were tested. Dimensional analysis and multivariable regression techniques were applied to derive a formula relating the discharge coefficient to key influencing variables. These variables include the ratio of total energy head to flume width (*Ht/B*), the ratio of upstream water head to flume width (*Hw/B*), and the ratio of slot width to flume width (*Bg/B*). The results indicated that the discharge coefficient (C_d) of the compound weir increases with both *Ht/B* and *Hw/B*, and with increasing slot width (*Bg/B*). The proposed model, which describes the relationship between measured and computed discharge coefficients, demonstrated excellent accuracy, with R^2 = 0.998. Furthermore, the findings showed that the width of the weir openings has a significant impact on upstream water depth, downstream free surface profiles, and the hydraulic characteristics of the resulting flow transitions.

Keywords: Combined Weir; Discharge Coefficient; Free Surface Profiles; Experimental Work; Open Channel Flow.

1. Introduction

A Rectangular Broad-Crested Weir (RBCW) is a hydraulic structure commonly used for flow control and discharge measurement in natural streams and irrigation canals. The traditional RBCW features a crest that extends horizontally in the flow direction, long enough to support the formation of a stable nappe. A weir is classified as an RBCW when the ratio of the head over the crest (Hw) to the weir length (Lw) is greater than 0.10 and less than or equal to 0.40 [1]. The discharge characteristics of flow over RBCWs have been investigated experimentally in several studies [2–4] and numerically by Al-Hashimi et al. [5] and Jiang et al. [6]. Zhuk et al. (2021) examined the discharge coefficient of narrow RBCWs with vertical sidewalls and found that the discharge coefficient decreases as the relative length ratio (L/h) increases [7]. Significant energy dissipation can also be achieved using stepped weirs. Studies [8–10] have proposed formulas to estimate the upstream water level in traditional RBCWs.

Solid weirs are typically constructed from concrete, allowing water to flow completely over the crest, resulting in high turbulence. This leads to reduced approach flow velocity, sediment accumulation, and adverse effects on fish spawning. To address these issues, researchers have suggested using broad-crested porous weirs (such as gabion weirs) or RBCWs with openings (combined weirs) to help reduce turbulence and improve flow conditions over such structures.

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Combined weirs are designed with different shapes; usually RBCW or sharp-crested weirs with openings. Nouri et al. (2023) numerically investigated the discharge coefficient of a combined broad-crested weir using different parameters [8]. It was found that the dimensionless parameter h1/H is the most effective parameter. The characteristics of the sharp-crested weir type of the combined triangular weir over a rectangular gate were studied to examine the effect of the geometry and flow parameters on the discharge, and a proposed semi-empirical discharge equation was deduced [11].

Much research on flow on porous RBCW has been carried out to estimate discharge coefficient. Models of RBCWs were experimentally investigated for predicting the discharge coefficient in free and submerged flow conditions [12-14]. carried out Experimental work on gabion weir models was carried out to study the influence of gravel diameter (dm), dimensions of the gabion weir (length, L, and height, H), and the discharge per unit width of the waterway (q) on the upstream water depth. In addition, dimensional analysis was used in creating a relationship that correlates the different parameters that showed good results.

Numerically, porous RBCW was simulated to estimate the discharge coefficient under free-flow conditions; new relationships were extracted in calculating the discharge coefficient [15]. Different weir shapes as well as porous RBCW were numerically investigated. An investigation of the impact of the grain sizes on the upstream water depth in the vicinity of a porous rectangular broad-crested weir under through-flow conditions was investigated. The results showed a reduction in the discharge coefficient (C_d) as the average diameter of particles decreased. [16, 17] investigated the impact of the grain sizes on the upstream water depth in the vicinity of a porous rectangular broad-crested weir under through-flow conditions. In addition, their results reveal that upstream depth is sensitive to the grain sizes. Under free and submerged flow conditions, the hydraulic performance of porous RBCW with four different porosities was experimentally investigated [18]. It was found that the discharge coefficient in submerged flow conditions is lower than the free flow's discharge coefficient by 20%. Basnet and Constantinescu (2017) investigated the flow dynamics around vertical plates with openings of porosities within the range of zero and 36%. The results showed that, for porosity less than 30%, the main recirculation eddy in the wake remains attached to the plate. For porosities greater than 30%, the main recirculation eddy will be away from the porous plate [19].

Several studies have been conducted on combined weirs. For example, Negm et al. (2004) performed experimental research to examine the geometric parameters influencing the flow rate in a combined structure consisting of a rectangular weir and a rectangular gate [20]. Their findings revealed that both the upstream flow depth relative to the gate opening and the distance between the weir and the gate significantly affect discharge estimation. Hayawi et al. (2008) studied the flow characteristics over a triangular weir and through a rectangular gate under free-flow conditions [21]. Al-Saadi (2013) investigated the discharge coefficient of combined weirs with different gate shapes [22]. Guven et al. (2013) experimentally analyzed the interaction of flow over a rectangular broad-crested weir (RBCW) and a box culvert structure, showing that the discharge coefficient (C_d) is influenced by the ratio of upstream water head to the culvert opening height [23].

Nouri and Hemmati (2020) explored, both experimentally and numerically, the geometric effects of openings on the discharge coefficient [24]. They found that increasing the ratio of gate opening height to weir height, as well as the ratio of gate width to total structure width, leads to a decrease in C_d. Zeinivand et al. (2024) examined how gate sizes affect C_d in a structure combining a free-over sharp-crested weir and an underflow gate [25]. Their results showed that C_d increases with both the number and size of the gates and is positively correlated with the ratio H/P, where H is the pressure head and P is the weir height.

Weirs with openings help reduce sediment accumulation upstream of the structure and can be used under both free and submerged flow conditions [26]. Numerous studies have been conducted to estimate the discharge coefficient and flow rate for combined structures under various hydraulic conditions. The discharge coefficient of Fayoum weirs with openings was experimentally assessed by passing flow over the weir and through the openings, revealing an average C_d of 0.623 [27]. The hydraulic behavior of flow in a combined weir with a slot was also experimentally studied [20, 28]. A general equation was developed that relates total discharge to the relative head over the weir and the relative diameter of the circular slot [28]. Samani and Mazaheri (2009) experimentally evaluated sharp-crested weirs with openings to study the stage–discharge relationship [29], reporting good agreement between calculated and measured values.

Weir models with one circular opening for different heights and opening diameters were investigated [30]. Saad & Fattouh (2016) investigated the discharge coefficient of broad-crested weirs with one, two, and three openings with different diameters, D, and heights from the bed, Z [31]. The results indicate that C_d decreases as D/Z decreases. Ohmoto & Une (2018) investigated the effect of an opening in a weir structure on the riverbed morphology and flow pattern [32]. It was found that most of the scouring takes place around the opening. Salehi & Azimi (2019) experimentally investigated six combined weir-gate structures to estimate the overall discharge characteristics of flow over weirs and under gates [33]. Jalil & Abdulsatar (2013) experimentally investigated the parameters that affect the head-discharge relationship through oblique weir gates using dimensional analysis [34]. The results showed that the major parameters were the water head on the weir Hw, the ratio of the oblique length w to the channel width B, and the weir height P. Al-Suhaili et al. (2014) experimentally investigated the discharge coefficient of a combined weir with three equal and unequal rectangular bottom openings. It was found that the highest value of C_d is for equal sizes of three openings. This value was found to be sensitive to the width opening [35]. Fu et al. (2018) derived the discharge coefficient of a combined-orifice weir structure via a simplified discharge formula under submerged flow conditions [36].

A broad-crested weir with rectangular vertical slots (RBCWVS) is a novel hydraulic structure, similar to a combined weir, designed to enhance discharge capacity and hydraulic performance. Various types and dimensions of gates in combined weirs have been investigated by numerous researchers. According to the literature, most combined weirs are either broad-crested or sharp-crested weirs with circular openings [12, 20, 26, 31], or weirs featuring rectangular bottom openings of limited dimensions, known as Fayoum weirs [35, 37, 38].

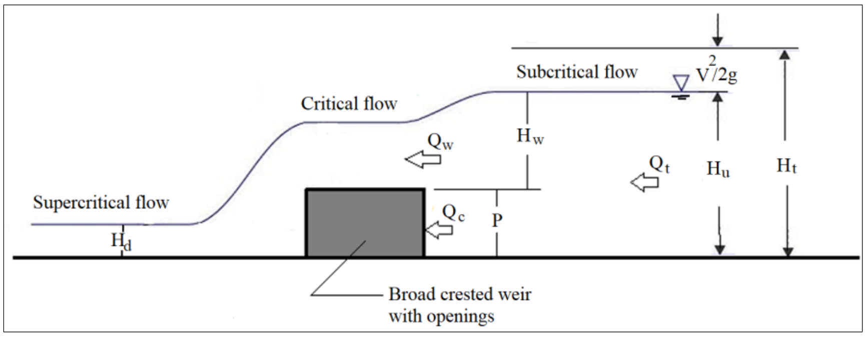
In an RBCWVS configuration, water flows both over the crest and through the vertical slots, allowing for higher discharge rates compared to solid weirs under the same head and geometric conditions. This design also dissipates more energy due to the interaction between the flow nappe over the crest and the flow through the vertical slots. Nouri et al. (2023) numerically investigated the geometric impact of the openings on the discharge coefficient using computational fluid dynamics (CFD) [8]. Similarly, Alsaydalani (2024) experimentally analyzed a compound sharp-crested weir with a semi-circular gate for flow measurement and control [39]. The results indicated that the combined structure could convey 2 to 10 times more discharge than a conventional sharp-crested weir, with discharge coefficient values ranging from 0.46 to 0.89 and an average of 0.675.

A numerical model validated with flume experiments using gate openings of 10, 15, and 20 mm also examined the drag coefficient under varying bed roughness conditions. The findings showed that the drag coefficient increased with a decrease in both stem Reynolds number and Froude number, and this effect was more pronounced over rough beds with large particles [40, 41].

Despite extensive research on combined weirs, no prior studies have focused specifically on gated weir structures with multiple rectangular vertical slots. Therefore, the objective of this research is to investigate the impact of using multiple symmetrical rectangular slots with varying widths on the discharge coefficient (C_d) in a broad-crested weir structure. Additionally, the study aims to assess how slot width influences water surface profiles and upstream water levels.

2. Theoretical Analysis

For broad-crested weirs with a square-edged entrance $0.1 \leq \frac{H_w}{L_w} \leq 0.4$. The flow toward the combined structure of weir and gate is a fall over the weir and flow through the gate; the two discharge capacities depend on the depth of water in the channel upstream of the combined structure. As upstream flow depth exceeds the weir crest (P), combined flow conditions occur as weir flow and orifice flow (see Figure 1).



(a)

(b)

Figure 1. (a) Sketch of flow over and through a rectangular broad crested weir with rectangular vertical slots, (b) A photograph from the experimental runs

For the weir-orifice (combined) flow structure, the total theoretical discharge (Q_t) through the combined structure obtained by adding value of flow pass through rectangular slots Q_c and flow over the weir Q_w as follows:

$$Q_t = Q_w + Q_c \tag{1}$$

where;

$$Q_c = NB_g h\sqrt{2g(H_t - H_d)} \tag{2}$$

$$Q_w = (\tfrac{2}{3})^{3/2}\sqrt{g}\, BH_w{}^{3/2} \tag{3}$$

The actual discharge of the combined structure is introduced by adding the coefficient of discharge C_d to the theoretical discharge equation as follows:

$$Q_{act} = C_d[NB_g h\sqrt{2g(H_t - H_d)} + BH_w{}^{3/2}] \tag{4}$$

where N is number of rectangular openings, (dimensionless), h is height of the rectangular opening, (L), B_g is width of the rectangular opening, (L), B is width of the weir, (L), g is gravitational acceleration, (LT^{-2}), H_w is the height of water head upstream the weir, (L), H_t is the upstream total energy head, (L), H_u is water depth upstream the weir structure (L), H_d is water depth downstream the weir structure. (L), and C_d is discharge coefficient (dimensionless).

2.1. Dimensional Analysis

The independent variables affecting the total discharge flowing over weirs and through gates opening can be given as:

$$Q = f_1(H_t,\ H_{w,}\ B\ , B_{g,}\ g, \rho, \mu) \tag{5}$$

where, H_t is upstream flow depth + velocity approach ($\frac{v^2}{2g}$), $H_w$is head of water over the weir, B is flume width , B_g is width of the rectangular opening, g is gravitational acceleration, ρ is mass density of water, and μ is dynamic viscosity of water.

Using Buckingham π theory, the dimensionless parameters were derived as follow:

$$\frac{Q}{BH_w\sqrt{gH_w}} = f\left(\frac{B_g}{B}, \frac{H_t}{B}, \frac{H_w}{B}, W_e, R_e\right) \tag{6}$$

In this equation, W_e and R_e indicate the Weber and Reynolds numbers. In turbulent flow, the effect of fluid viscosity on flow hydraulic parameters is negligible therefore Re was ignored in Equation 6. The water level over the weir was roughly 6 mm, therefore we may ignore the Weber number W_e in Equation 6. The proposed equation can be calculated simply as:

$$C_d = f\left(\frac{B_g}{B}, \frac{H_t}{B}, \frac{H_w}{B}\right) \tag{7}$$

Nonlinear regression analysis can be used by the SPSS program to link the dimensionless parameters in Equation 7 to obtain an equation that can be used to calculate the discharge coefficient of the flow passing through the combined structure of a rectangular broad-crested weir with multiple gates. The following equation of discharge coefficient is as follows:

$$C_d = -1.203 + 5.272\left(\frac{B_g}{B}\right)^{0.949} + \left(\frac{H_t}{B}\right)^{1.576} + \left(\frac{H_w}{B}\right)^{-0.006}$$
$$R^2 = 0.998 \tag{8}$$

3. Materials and Methods

3.1. Experimental Works

The hydraulic experiments were carried out in a tilting glass-walled recirculating laboratory flume with a working section length of 5.0 m and 30 cm wide and deep under uniform flow conditions in the hydraulic and hydrology laboratory of the Faculty of Engineering, Mustansiriyah University, Baghdad, Iraq. The flume is provided by upstream and downstream reservoirs and by a tail gate at the downstream end of the flume's working section to control the water level. The upstream end of the flume was provided by a honeycomb screen to dissipate the flow turbulence of the incoming flow. The flume is supplied by water from the u/s tank with the dimensions (1.5 m length, 1.25 m width, and 1.0 m depth) by a pump through a pipe (see Figure 2). A point gauge with an accuracy of ± 0.01 mm was used for measuring the water surface profiles. The flume was set to a constant bed slope of 0.0005.

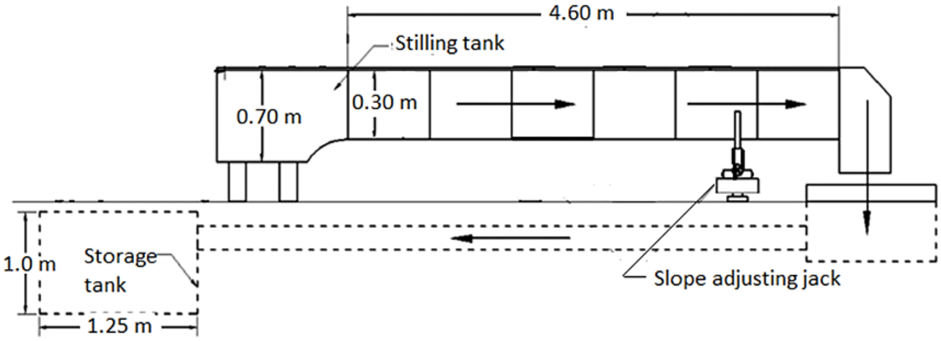
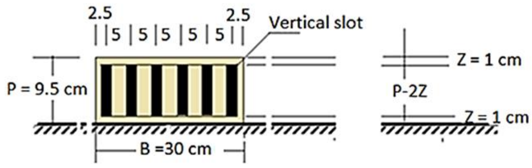


Figure 2. The experimental flume

The broad-crested weir used in this study had a fixed length of 10 cm, a height of 9.5 cm, and a width of 30 cm. It was positioned 215 cm from the inlet of the flume. The weir model was specifically designed to allow flow both over and through it. To achieve this, six rectangular openings were uniformly distributed along the length of the weir, with a center-to-center spacing of 5 cm. Each opening had a consistent height of 7.5 cm, beginning 1.0 cm above the weir's bottom edge and ending 1.0 cm below its top edge. The widths of the openings varied at 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 cm, as illustrated in Figure 3. The openings were symmetrically arranged, starting 2.5 cm from the right edge of the weir and ending 2.5 cm before the opposite edge. This configuration resulted in varying Opening Area Ratios (OARs) of 10%, 20%, 30%, 40%, 50%, and 60%, corresponding to the respective gate widths. Six flow rates (10, 15, 19, 25, 30, and 35 m³/hr) were tested during the experiments. Prior to installing the weir in the flume, uniform flow conditions were established. A calibrated flow meter, verified using the volumetric method, was employed to measure discharge rates. For overtopping flow conditions, water depths were recorded at 10 cm intervals from 0.85 m to 2.15 m upstream of the weir. Along the entire length of the weir, measurements were taken at 1 cm intervals, continuing to the downstream end at 2.25 m. Beyond the weir, water depths were measured from 2.25 m to 2.35 m at 2 cm intervals, and at 5 cm intervals thereafter. Table 1 summarizes the flow conditions. All measured Froude numbers were less than 1, indicating that the experiments were conducted under subcritical flow conditions.



(a)

(b)

Figure 3. (a) dimensions of the weir and the rectangular slots (openings), (b) a photograph of the weir physical model

Table 1. Flow conditions

Discharge Q (m³/hr)	Weir opening width (cm)	Total head H_t (cm)	Head over the crest H_w (cm)	Froude number Fr	Discharge coefficient C_d
10	0.5	13.52	2.80	0.09	0.164
15		14.45	3.86	0.12	0.200
19		15.17	4.50	0.15	0.220
25		16.01	5.60	0.18	0.264
30		16.74	6.35	0.20	0.284
35		17.04	6.70	0.23	0.295

10	1	12.33	1.50	0.11	0.225
15		13.41	2.47	0.14	0.251
19		14.08	2.90	0.17	0.269
25		15.22	3.88	0.21	0.309
30		16.01	4.89	0.23	0.344
35		16.40	5.36	0.25	0.368
10	1.5	11.04	0.80	0.13	0.310
15		12.04	1.20	0.17	0.318
19		12.50	1.80	0.20	0.334
25		13.53	2.45	0.24	0.358
30		14.58	3.50	0.26	0.391
35		15.10	3.95	0.29	0.412
15	2	9.90	0.30	0.19	0.402
19		10.84	1.20	0.21	0.419
25		11.85	2.15	0.25	0.441
30		12.90	3.15	0.27	0.481
35		13.00	3.20	0.30	0.483
19	2.5	9.86	0.19	0.24	0.501
25		10.92	1.18	0.28	0.517
30		11.51	1.70	0.31	0.531
35		12.33	2.46	0.34	0.557
25	3	10.27	0.50	0.30	0.604
30		11.09	1.25	0.33	0.619
35		11.59	1.70	0.35	0.632

4. Results and Discussion

The main aim of this research is to explain the impact of a broad-crested weir involving symmetrical gates (vertical slots) having different widths on the free surface profile, upstream water level, and combined discharge coefficient *Cd*. The experimental results were analyzed, obtaining a thorough equation of the combined structure discharge coefficient formulated by regression analysis.

4.1. Influence of Slot Width on the Water Surface Profile

In this section, the experimental results for the free surface profiles over a rectangular broad-crested weir with multiple vertical rectangular slot widths are presented in Figures 4-a to 4-f. For the weir-orifice flow, water surface elevations were measured along the centerline of the flume, beginning 1.3 meters upstream of the weir at 10 cm intervals. Measurements continued at 1 cm intervals along the weir crest, followed by 2 cm intervals for 80 cm downstream, and then at 5 cm intervals for the remaining downstream section. For all slot widths, the flow state along the free surface profile transitions from subcritical upstream of the weir, to critical over the crest, and then to supercritical downstream, eventually returning to subcritical conditions. A series of flow rates ranging from 10 to 35 m^3/hr were tested for different slot widths (0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 cm). In models with smaller slot widths (0.5, 1.0, and 1.5 cm), the curvature of the free surface begins as the flow approaches the weir crest and intensifies significantly as it passes over the crest. Minor variations in nappe flow patterns were observed across all flow rates, attributable to the effects of slot width. At a flow rate of 10 m^3/hr, the downstream free surface exhibited a wavy profile due to turbulence—particularly pronounced in the model with a 0.5 cm slot width. As the discharge increased, the free surface profiles displayed more intense turbulence. For flow rates of 30 and 35 m^3/hr, significant disturbances were observed at the downstream end of the weir, including strong hydraulic jumps. Upstream of the weir, flow was seen to back up before accelerating over the crest. These observations are consistent with the findings of Daneshfaraz et al. (2019), who reported similar free surface profile behavior in weirs with one opening, two vertical openings, and two horizontal openings [42].

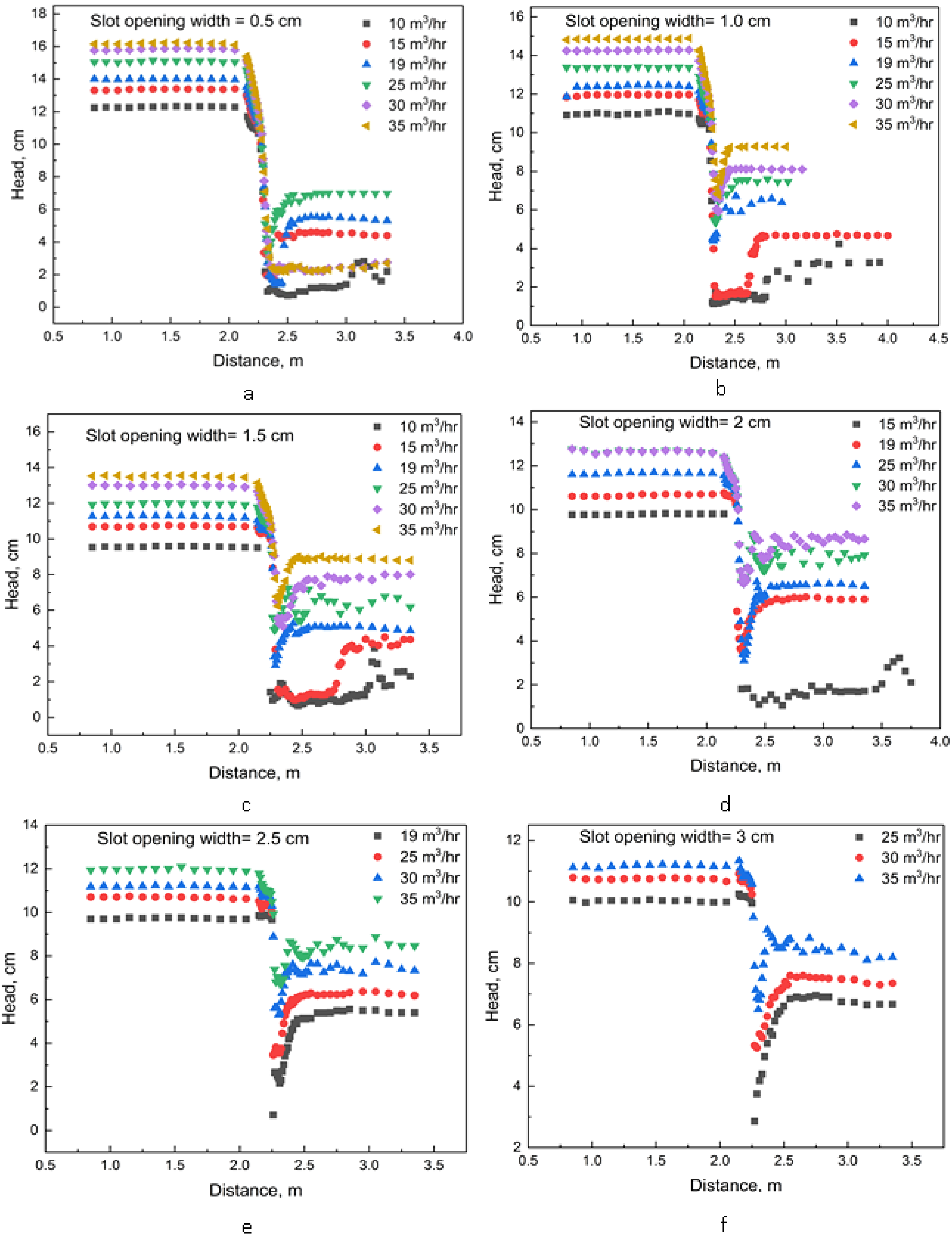


Figure 4. Free surface profiles of different flow types

As the slot width is increased from 0.5 to 1.0 cm, the free surface profiles at d/s the structure show a wavy jump for the smallest discharge, while for the rest discharges, the jump changes from supercritical to subcritical flow through the sudden dissipation of the flow energy due to high turbulence. As the slot width is increased to 2.0 cm, it was found that the flow rate of 10 m³/hr passes completely through the gates (rectangular slots), and no overtopping occurs. With the increase of the slot width to 2.5 cm and 3.0 cm, the flow rates of 10 and 15 m³/hr and 10, 15, and 19 m³/hr, respectively, cannot be overtopping the crest of the structure. In this case, the flow is behaving as an orifice flow, which is not considered in the present study.

For the traditional weir (no opening), the flow depth wased to be uniform across the channel width. While the free surface profiles are different for models with openings. For the six different models of broad-crested weirs with vertical slots, it was observed that the free water surface profiles for the different slot sizes overlapped over the crest and a bit downstream of the weir structure. Daneshfaraz et al. (2019) showed a similar trend of free surface profiles over the examined weirs with openings [42].

4.2. Impact of the Opening Size on the Upstream Water Head

Conventional broad-crested weirs are commonly used to elevate upstream water levels. The innovative structure introduced in this study—broad-crested weirs with multiple openings—can serve as an optimized design for flood control applications. In the present experimental investigation, six models of broad-crested weirs were tested, each incorporating six vertical rectangular slot openings of constant height. For all models, the slot height was kept constant at 7.5 cm, while the slot widths (B_g) were varied as 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 cm. These variations resulted in different Opening Area Ratios (OARs) of 10%, 20%, 30%, 40%, 50%, and 60%, respectively, across the total weir width (B).

At a constant discharge rate, it was observed that reducing the slot width led to an increase in upstream water levels. Smooth and symmetrical flow streamlines, indicating a clean nappe flow, were visible for the smallest slot openings. Data from Table 1 indicate that larger slot widths significantly reduce the upstream water level. The impact of slot width on the upstream head was assessed under constant discharge and varying slot widths. Compared to the 0.5 cm slot width case, upstream water levels were reduced by 32.5%, 31.4%, 14.8%, 15.3%, and 6.0% for slot widths of 3.0 cm, 2.5 cm, 2.0 cm, 1.5 cm, and 1.0 cm, respectively.

Flow acceleration and nappe formation began immediately downstream of the weir's leading edge for all discharges in models with smaller slot widths (0.5, 1.0, and 1.5 cm). As the slot width increased (to 2.0, 2.5, and 3.0 cm), a noticeable rise in the upstream water surface was observed, followed by a sudden drop. This phenomenon is attributed to the interaction between the overtopping flow and the orifice flow through the slots. These findings are consistent with previous studies conducted by Al-Hashimi et al. (2020) [43] on flow over deck slabs, as well as by Kara et al. (2014) [44] and Kara et al. (2015) [45] on bridge overtopping. Moreover, it was found that even the smallest slot opening (0.5 cm) produced significant differences in free surface profiles when compared to a solid weir with no openings.

4.3. Impact of the Opening Size on the Hydraulic Jumps

To investigate the impact of for all the slot widths on the hydraulic jump characteristics, it was shown that downstream of the combined weir structure, flow turbulence expressed as recirculation at the free surface with eddy motions and energy dissipation occurred. While, for the solid weir, it appears that the jump has a more compact and vigorous recirculation zone. For a constant slot width, the free surface profile showed a small difference in turbulence at small discharges (see Figures 4-a to 4-f). However, at high flow rates, a clear significant difference was observed in free surface turbulence. Hydraulic jumps are characterized as strong if the opening is decreased. However, with the increasing of the opening, the jumps become weaker and are characterized as undular jumps. For weir-orifice structure flows and at a constant discharge, it was observed that the length of the jump is decreased as the area of the opening is increased. However, at small discharges the jump is weaker than jumps occurring at higher discharges. For orifice flow, the jumps are characterized as longer in length and state as undular jumps. These findings agreed with the experimental results obtained by Daneshfaraz et al. (2019) [42]. Saad & Fattoh (2016) [31] showed that the maximum jump length was for the model of two openings rather than one or three openings. Findings showed that to dissipate the hydraulic jump and to shorten it, it is preferable to have one or three openings in the middle of the weir width.

4.4. Predicted Discharge versus Calculated Discharge

From Table 1 and Equation 4, the theoretical discharge versus the measured discharge was calculated and presented in Figure 5. It looks like an excellent relationship between the measured and calculated discharge with a very small difference that is induced by a statistical measure (the coefficient of determination) $R^2 = 0.995$. Zeinivand et al. (2024) [25] estimated an equation of the discharge passing over a combined sharp-crested weir with three rectangular openings. An excellent result was found between the derived equation and the measured discharge. Salehi & Azimi (2019) found a very good agreement between predicted and measured discharge relationships for six weir-gate models [33]. Mohammed et al. (2010) examined the relation between the computed from the regression analysis and the measured ones of the discharge coefficient for a combined weir with a bottom circular opening. The relationship showed a good agreement between the measured and computed values [27].

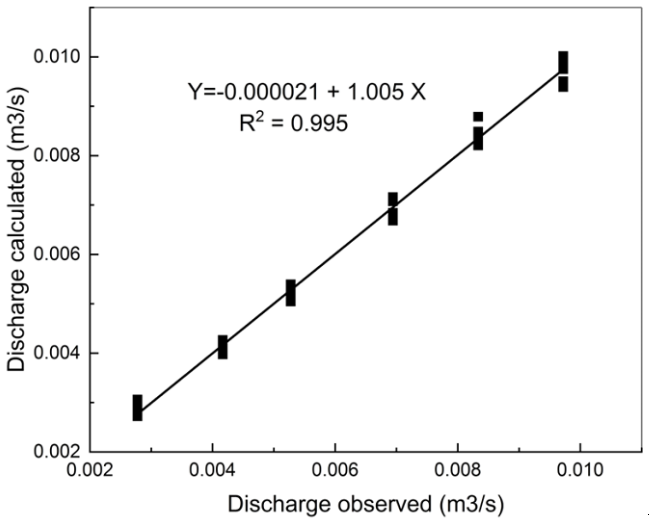


Figure 5. Comparison between the measured and the calculated discharges

4.5. Variation of Discharge Coefficient C_d with the Slot Width Parameter ($\frac{B_g}{B}$)

In this research, the discharge coefficient *Cd* was calculated based on Equation 3. The discharge coefficients for all the experimental data were calculated and tabulated in Table 1. Figure 6 shows the variation of the compound weir discharge coefficient with the non-dimensionalized parameter B_g/B for various slotted widths. It was found that an increase in the slot width increases the discharge coefficient. In more detail, for a constant slot width, it can be seen that the discharge coefficient is increased with discharge. For example, the smallest slot width has a discharge coefficient in the range of 0.06–0.30; this value of the discharge coefficient significantly increases with increasing slot width for a constant head. The highest value of the discharge coefficient was found for the biggest slot width of 3.0 cm. It showed that increasing the b/B_o and d/P enhanced the wall contact and reduced the C_{dt} since these ratios increased the gate dimensions.

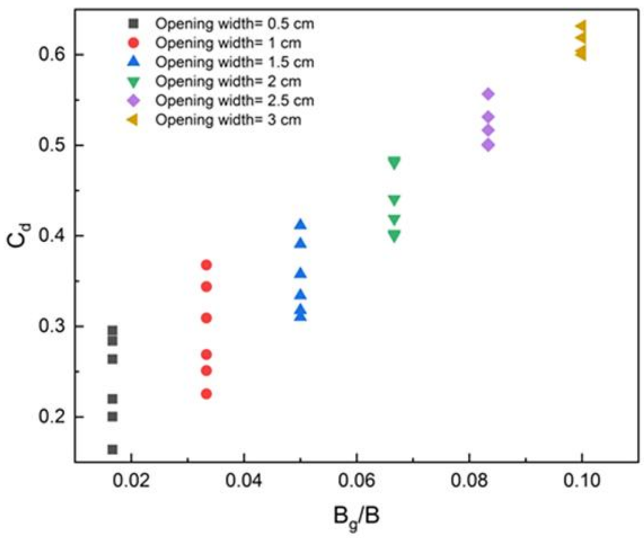


Figure 6. Variation of compound weir discharge coefficient C_d versus B_g/B for various slot widths values

4.6. Variation of Discharge Coefficient C_d with the Flow Depth Term over the Weir H_w/B

Figure 7 illustrates the variation of the compound weir discharge coefficient (C_d) with the non-dimensional parameter H_w/B for different slot widths. The discharge coefficient C_d consistently increases with the head over the combined weir across all experimental cases. As the slot widths increase from 0.0 cm to 3.0 cm—corresponding to opening area ratios ranging from 0.0% to 60%—the value of C_d also increases. This indicates that for all slot widths, the compound discharge coefficient improves as the flow depth over the broad-crested weir increases. This trend aligns with findings by Nouri and Hemmati (2020) [24], who reported that an increase in water head leads to a higher discharge coefficient, as well as Fu et al. (2018) [36], who also observed a similar positive relationship between water level and C_d.

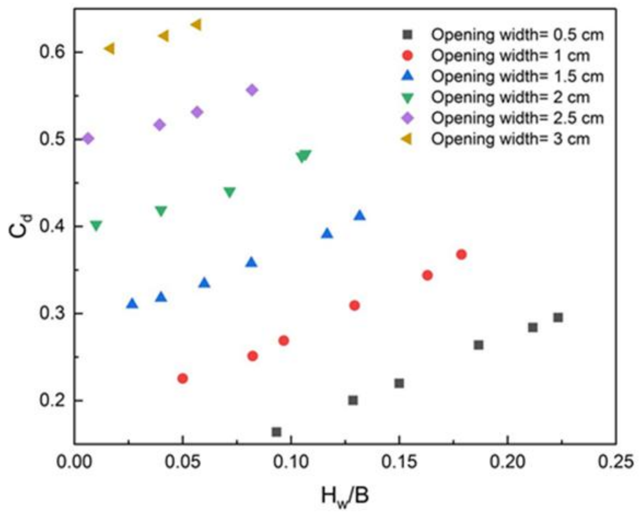


Figure 7. Variation of the combined weir discharge coefficient C_d with *the flow depth term over the combined weir* for various slot widths values

4.7. Variation of the Combined Weir Discharge Coefficient C_d with the Upstream Energy Head Term H_t/B

Figure 8 presents the calculated values of the compound weir discharge coefficient C_d plotted against the non-dimensional energy head term H_t/B for various slot widths ranging from 0.5 to 3.0 cm. As previously noted, the total upstream energy head H_t is defined as the sum of the pressure head (flow depth over the weir) and the velocity head $V^2/2g$. The results in Figure 8 show that for any given slot width, an increase in the total upstream head leads to an increase in C_d. Furthermore, C_d increases with wider slot openings. These findings are consistent with the results of Guven et al. (2013) [23], who investigated different configurations of combined broad-crested weirs with box culverts and found that the discharge coefficient rises with increased upstream head.

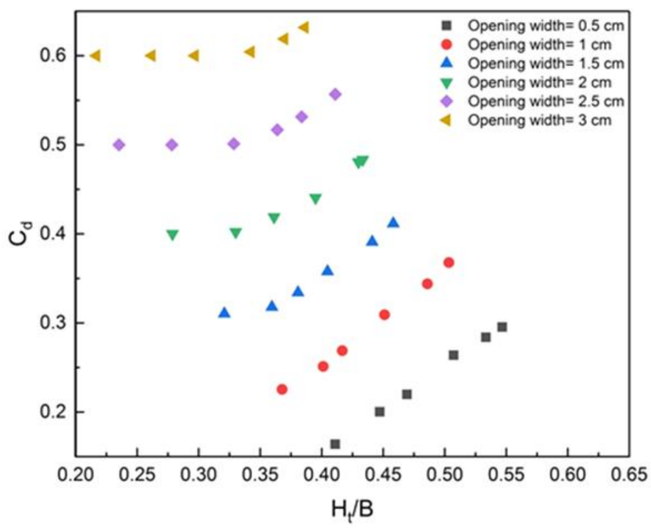


Figure 8. Variation of the combined weir discharge coefficient C_d with the energy head term H_t/B over the combined weir for various slot widths values

4.8. Comparison between Measured and Computed Discharge Coefficient

The proposed parameters play an important role in calculating the discharge coefficient based on Equation 7. Nonlinear regression analysis was used by the SPSS program to obtain an equation relating the discharge coefficient with the dimensionless parameters as pointed out by Equation 8. This equation estimated the discharge coefficient of the combined weir structure with an excellent fit with the measured values of C_d. A comparison between measured and computed compound weir discharge coefficients indicates the goodness of the fit of the model. Figure 9 depicted the relation between the measured and computed discharge coefficients. At the end of this discussion, the discharge coefficient versus opening area ratio was drawn in Figure 10. The figure shows that for a constant opening area ratio, the discharge coefficient value C_d is increased with discharge, and as the opening area ratio increases from 10% to 20% and then to 30%, and so on up to 60%, the discharge coefficient significantly increases with the size of the slot. The relationship between the average value of the discharge coefficient and the opening area ratio for the six openings is shown in Figure 11. As the opening ratio is increased, the discharge coefficient is dramatically increased with a coefficient of determination R^2 = 0.95. Nouri & Hemmati (2020) [24] and Nouri et al. (2023) [8] numerically investigated the combined discharge coefficient using computational fluid dynamics that showed an accurate estimation of C_d. This value was compared with the discharge coefficient C_d deduced by regression analysis, which showed good agreement with the numerical results. Al-Hamid et al. (1997) [11] examined the C_d values for the flow passing over a v-notch with a rectangular sluice gate. Comparison between measured and computed C_d values showed good agreement with not more than 5% error. Alsaydalani (2024) [25] experimentally examined the discharge coefficient resulting from the regression analysis of a sharp-crested weir with two rectangular and one circular opening below the rectangular gates. In a similar method, the computed C_d *is compared* with the calculated ones for the different geometries. The results showed good agreement between the computed and the calculated C_d.

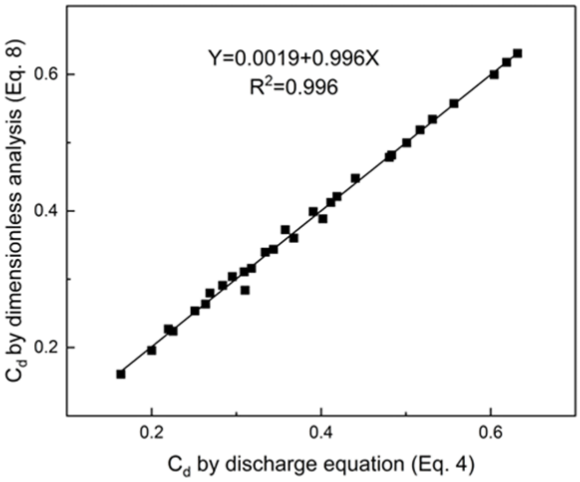


Figure 9. Comparison between measured and computed compound weir discharge coefficient

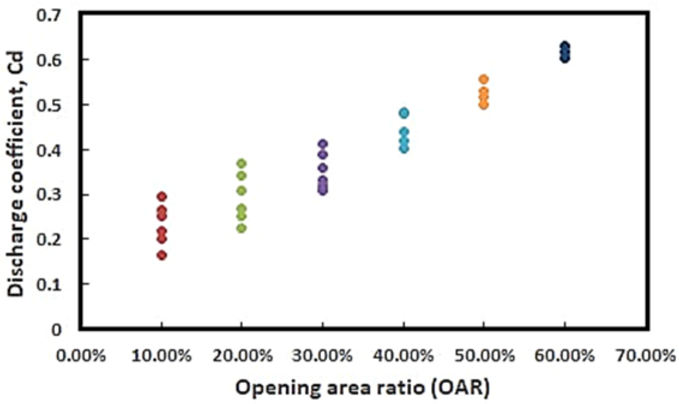


Figure 10. Discharge coefficient versus opening area ratio

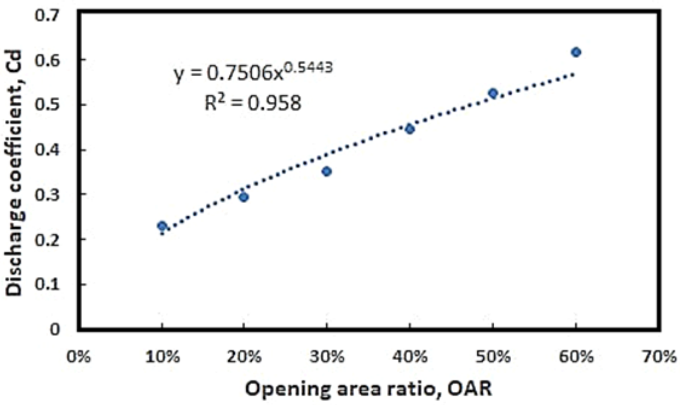


Figure 11. Mean discharge coefficient versus opening area ratio

At the end of this discussion, the discharge coefficient versus opening area ratio was drawn in Figure 10. The figure shows that for a constant opening area ratio, the discharge coefficient value Cd is increased with discharge, and as the opening area ratio increases from 10% to 20% and then to 30%, and so on up to 60%, the discharge coefficient significantly increases with the size of the slot. The relationship between the average value of the discharge coefficient and the opening area ratio for the six openings is shown in Figure 11. As the opening ratio is increased, the discharge coefficient is dramatically increased with a coefficient of determination $R^2 = 0.95$. Zeinivand et al. (2024) [25] showed the change of discharge coefficient with the number of openings (1, 2, 3, 4, and 5). *Cd* increases with increasing gate opening.

5. Conclusion

A series of laboratory experiments were performed in a rectangular flume to investigate the hydraulic performance of a combined weir flow. Six slot widths ranged between 0.50 cm and 3.0 cm with a constant slot height were selected, resulting in six opening area ratio values ranging from 10% to 60%. Six flow rates were examined to study the effect of slot width on the performance of the combined weir flows. Dimensional analysis and multivariable regression techniques were used to deduce a formula relating to the important variables that influence the discharge coefficient of the weir flow. These variables are (H_t/B), (H_w/B), and (B_g/B); the results showed that the compound weir discharge coefficient Cd increases with (H_t/B) and (H_w/B) with increasing the opening width (B_g/B). The results showed that the proposed model for depicting the relation between the measured and computed discharge coefficients showed an excellent agreement with $R^2 = 0.996$. The compound weir discharge coefficient C_d increases with the suggested variables B_g/B, H_w/B *and* H_t/B.

The head of water and the free surface profiles are significantly influenced by the OAR. An excellent relationship between the measured and calculated discharge was observed with $R^2 = 0.995$. At a very small distance from the u/s edge of the weir, the flow starts to accelerate and drop with a nappe. This scenario was observed for all the discharges and small openings (0.50, 1.0, and 1.5 cm). With increasing the slot size to 2.0, 2.5, and 3.0 cm, the water surface is backed up before it suddenly drops. Hydraulic jumps are characterized as strong if the opening is decreased. While it was observed that the length of the jump is decreased as the area of the opening is increased.

6. Declarations

6.1. Author Contributions

Conceptualization, S.M., F.M.A., N.R., and K.R.G.; methodology, S.M., F.M.A., N.R., and K.R.G.; formal analysis, S.M., F.M.A., N.R., and K.R.G.; investigation, S.M., F.M.A., N.R., and K.R.G.; data curation, S.M., F.M.A., N.R., and K.R.G.; writing—original draft preparation, S.M., F.M.A., N.R., and K.R.G.; writing—review and editing, S.M., F.M.A., N.R., and K.R.G. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

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

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Hager, W. H., & Schwalt, M. (1994). Broad-Crested Weir. Journal of Irrigation and Drainage Engineering, 120(1), 13–26. doi:10.1061/(asce)0733-9437(1994)120:1(13).

[2] Tracy, H. J. (1957). Discharge characteristics of broad-crested weirs (Volume 397). US Department of the Interior, Geological Survey, Reston, United States.

[3] Moss, W. D. (1972). Flow separation at the upstream edge of a square-edged broad-crested weir. Journal of Fluid Mechanics, 52(2), 307–320. doi:10.1017/S0022112072001430.

[4] Salmasi, F., Poorescandar, S., Dalir, A. H., & Zadeh, D. F. (2011). Discharge relations for rectangular broad-crested weirs. Tarim Bilimleri Dergisi, 17(4), 324–336. doi:10.1501/tarimbil_0000001184.

[5] Al-Hashimi, S. A., Madhloom, H. M., & Nahi, T. N. (2017). Experimental and numerical simulation of flow over broad crested weir and stepped weir using different turbulence models. Journal of Engineering and Sustainable Development, 21(2), 28-45.

[6] Jiang, L., Diao, M., Sun, H., & Ren, Y. (2018). Numerical modeling of flow over a rectangular broad-crested weir with a sloped upstream face. Water (Switzerland), 10(11), 1663. doi:10.3390/w10111663.

[7] Zhuk, V., Vovk, L., Popadiuk, I., & Matlai, I. (2021). Discharge coefficient of rectangular broad-crested weirs in narrow channels with high relative length of the threshold. Ecological Engineering and Environmental Technology, 22(6), 11–16. doi:10.12912/27197050/141877.

[8] Nouri, M., Sihag, P., Kisi, O., Hemmati, M., Shahid, S., & Adnan, R. M. (2023). Prediction of the Discharge Coefficient in Compound Broad-Crested-Weir Gate by Supervised Data Mining Techniques. Sustainability (Switzerland), 15(1), 433. doi:10.3390/su15010433.

[9] Djunur, L. H., Pallu, M. S., Karamma, R., & Bakri, B. (2024). Effect of Porous Rectangular Type Baffle Block Angle on Hydraulic Jump Downstream of Spillway. Civil Engineering Journal, 10(10), 3173-3193. doi:10.28991/CEJ-2024-010-10-04.

[10] Hadano, K., Tatara, K., Nagano, H., & Muraoka, K. (2023). Evaluation of the Upstream Water Level of the Flow Over Finite-Length Weirs with Rectangular Cross-Section in the Flow Direction. Journal of Japan Society of Civil Engineers, 11(1), 23–00138. doi:10.2208/journalofjsce.23-00138.

[11] Alhamid, A. A., Negm, A. A. M., & Al-Brahim, A. M. (1997). Discharge Equation for Proposed Self-cleaning Device. Journal of King Saud University - Engineering Sciences, 9(1), 13–23. doi:10.1016/S1018-3639(18)30664-0.

[12] Mohamed, H. I. (2010). Flow over Gabion Weirs. Journal of Irrigation and Drainage Engineering, 136(8), 573–577. doi:10.1061/(asce)ir.1943-4774.0000215.

[13] Salmasi, F., & Sattari, M. T. (2017). Predicting discharge coefficient of rectangular broad-crested gabion weir using M5 tree model. Iranian Journal of Science and Technology - Transactions of Civil Engineering, 41(2), 205–212. doi:10.1007/s40996-017-0052-5.

[14] , Al-Mohammed, F. M., & Mohammed, S. H. (2015). Flow through and over gravel gabion weirs. Journal of Kerbala University 13(25), 193-205.

[15] Safarzadeh, A., & Mohajeri, S. H. (2018). Hydrodynamics of Rectangular Broad-Crested Porous Weirs. Journal of Irrigation and Drainage Engineering, 144(10), 4018028. doi:10.1061/(asce)ir.1943-4774.0001338.

[16] Fathi-moghaddam, M., Sadrabadi, M. T., & Rahmanshahi, M. (2018). Numerical simulation of the hydraulic performance of triangular and trapezoidal gabion weirs in free flow condition. Flow Measurement and Instrumentation, 62, 93–104. doi:10.1016/j.flowmeasinst.2018.05.005.

[17] Shariq, A., Hussain, A., & Ahmad, Z. (2020). Discharge equation for the gabion weir under through flow condition. Flow Measurement and Instrumentation, 74, 101769. doi:10.1016/j.flowmeasinst.2020.101769.

[18] Salmasi, F., Sabahi, N., & Abraham, J. (2021). Discharge Coefficients for Rectangular Broad-Crested Gabion Weirs: Experimental Study. Journal of Irrigation and Drainage Engineering, 147(3), 4021001. doi:10.1061/(asce)ir.1943-4774.0001535.

[19] Basnet, K., & Constantinescu, G. (2017). The structure of turbulent flow around vertical plates containing holes and attached to a channel bed. Physics of Fluids, 29(11), 115101. doi:10.1063/1.5009310.

[20] Negm, A. A. M., Al-Brahim, A. M., & Alhamid, A. A. (2002). Combined-free flow over weirs and below gates. Journal of Hydraulic Research, 40(3), 359–365. doi:10.1080/00221680209499950.

[21] Hayawi, H. A. M., Yahia, A. A. G., & Hayawi, G. A. M. (2008). Free combined flow over a triangular weir and under rectangular gate. Damascus University Journal, 24(1), 9-22.

[22] AL-Saadi, A. K. I. (2013). Study coefficient of discharge for a combined free flow over weir and under gate for multi cases. Euphrates journal of agriculture science, 5(4), 26-35.

[23] Guven, A., Hassan, M., & Sabir, S. (2013). Experimental investigation on discharge coefficient for a combined broad crested weir-box culvert structure. Journal of Hydrology, 500, 97–103. doi:10.1016/j.jhydrol.2013.07.021.

[24] Nouri, M., & Hemmati, M. (2020). Discharge coefficient in the combined weir-gate structure. Flow Measurement and Instrumentation, 75, 101780. doi:10.1016/j.flowmeasinst.2020.101780.

[25] Zeinivand, M., Barani, S., & Ghomeshi, M. (2024). Investigating the process of changing the discharge coefficient of the flow passing through the combined structure of rectangular sharp-crested weir with multiple-gates. Ain Shams Engineering Journal, 15(2), 102418. doi:10.1016/j.asej.2023.102418.

[26] Daneshfaraz, R., Minaei, O., Abraham, J., Dadashi, S., & Ghaderi, A. (2021). 3-D Numerical simulation of water flow over a broad-crested weir with openings. ISH Journal of Hydraulic Engineering, 27(S1), 88–96. doi:10.1080/09715010.2019.1581098.

[27] Abdel Halim, N. A., Sherif, M. M., & El-Zaher, A. S. (1991). On the Fayoum weirs with orifices. Journal of Engineering and Applied Science, 38(5), 893-904.

[28] Elazizy I.M. (2005). Hydraulic characteristics of weir with a slot. Engineering Research Journal, 2005(99), 149–63.

[29] Samani, J. M., & Mazaheri, M. (2009). Combined Flow over Weir and under Gate. Journal of Hydraulic Engineering, 135(3), 224–227. doi:10.1061/(asce)0733-9429(2009)135:3(224).

[30] Mohamed, H. I., Abozeid, G., & Shehata, S. M. (2010). Hydraulics of clear and submerged overfall weirs with bottom circular-openings. Ain Shams Engineering Journal, 1(2), 115–119. doi:10.1016/j.asej.2011.03.004.

[31] Saad, N. Y., & Fattouh, E. M. (2017). Hydraulic characteristics of flow over weirs with circular openings. Ain Shams Engineering Journal, 8(4), 515–522. doi:10.1016/j.asej.2016.05.007.

[32] Ohmoto, T., & Hirotaka, U. (2019). Effects Of Weir Within Opening on Bed Configuration and Flow Structure. 38th IAHR World Congress: Water: Connecting the World, 38, 33–40. doi:10.3850/38wc092019-0740.

[33] Salehi, S., & Azimi, A. H. (2019). Discharge Characteristics of Weir-Orifice and Weir-Gate Structures. Journal of Irrigation and Drainage Engineering, 145(11), 4019025. doi:10.1061/(asce)ir.1943-4774.0001421.

[34] Jalil, S. A., & Sarhan, S. A. (2013). Experimental study of combined oblique weir and gate structure. ARPN Journal of Engineering and Applied Sciences, 8(4), 306-315.

[35] Al-Suhaili, R. H., Al-Baidhani, J. H., & Al-Mansori, N. (2014). Hydraulic characteristics of a rectangular weir combined with equal and unequal size three rectangular bottom openings. International Journal of Computational Engineering Research, 4(1), 13-29.

[36] Fu, Z. F., Cui, Z., Dai, W. H., & Chen, Y. J. (2018). Discharge coefficient of combined orifice-weir flow. Water (Switzerland), 10(6), 699. doi:10.3390/w10060699.

[37] El-Belasy, A. M. (2013). Developing Formulae for combined weir and orifice (case study: EL-Fayoum weirs). Alexandria Engineering Journal, 52(4), 763–768. doi:10.1016/j.aej.2013.08.001.

[38] El-Baradei, S. A., El-Abd, M., & Hazem, N. (2024). Estimate of Power Output from Hydraulic Jumps Generated Downstream from Barrages. Journal of Human, Earth, and Future, 5(1), 72-84. doi:10.28991/HEF-2024-05-01-06.

[39] Alsaydalani, M. O. A. (2024). Discharge Coefficient of a Two-Rectangle Compound Weir combined with a Semicircular Gate beneath it under Various Hydraulic and Geometric Conditions. Engineering, Technology and Applied Science Research, 14(1), 12587–12594. doi:10.48084/etasr.6605.

[40] Gubashi, K. R., Al-Hashimi, S. A., Mulahasan, S., & Al-Madhhachi, A. S. T. (2024). A Numerical Model to Evaluate Flow Characteristics in a Circular Vegetation Patch for Flume Experiments. Journal of Applied Science and Engineering, 28(1), 75–91. doi:10.6180/jase.202501_28(1).0008.

[41] Gubashi, K. R., Mulahasan, S., Jameel, M. A., & Al-Madhhachi, A. S. T. (2022). Evaluation drag coefficients for circular patch vegetation with different riverbed roughness. Cogent Engineering, 9(1), 2044574. doi:10.1080/23311916.2022.2044574.

[42] Daneshfaraz, R., Majedi Asl, M., Razmi, S., Norouzi, R., & Abraham, J. (2020). Experimental investigation of the effect of dual horizontal screens on the hydraulic performance of a vertical drop. International Journal of Environmental Science and Technology, 17(5), 2927–2936. doi:10.1007/s13762-019-02622-x.

[43] Al-Hashimi, S. A. M., Al-Osmy, S. A. T., & Mulahasan, S. (2020). Water surface profile and flow pattern simulation over bridge deck slab. Journal of Engineering Science and Technology, 15(1), 291–304.

[44] Kara, S., Mulahasan, S., Stoesser, T., & Sturm, T. (2014). Water surface response to flow through bridge openings. River Flow, 693–699, CRC Press, Boca Raton, United States. doi:10.1201/b17133-95.

[45] Kara, S., Stoesser, T., Sturm, T. W., & Mulahasan, S. (2015). Flow dynamics through a submerged bridge opening with overtopping. Journal of Hydraulic Research, 53(2), 186–195. doi:10.1080/00221686.2014.967821.