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Discharge Capacity of a Piano Key Weir with Curvilinear Keys

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Abstract: *The Piano Key Weir (PKW) has emerged as a cost effective and viable solution for dam rehabilitation and new projects with high level of space constraints. The geometrical dimensions of PKW are main factors affecting their discharging capacity. Since, it is a relatively new type of weir that has only been developed in recent years, the description of the effect of its geometrical parameters is still immature. The geometric designs of these weirs presented in the literatures incorporate only linear floor slope of the keys. For better understanding of the influence of curvilinear shapes of outlet key slopes on discharge capacity, an experimental study was conducted. In general, the results showed that PKW with ogee shaped outlet key is more efficient than the linear shaped counterpart for heads higher than its design head. The maximum increase in coefficient of discharge of weir model with curvilinear outlet key in comparison to model with linear outlet key was 5.2%.*

Keywords: *Piano key weir, Hydraulic design, Weir discharge efficiency.*

1. INTRODUCTION

The ability to control water through structures like dams has facilitated the development of human societies throughout history. The spillway or weir is the safety component of the dam that releases flood in a controlled manner. It consists of a passage constructed in the dam body or in the reservoir bank to allow the evacuation of extreme floods. The reports on incidents of dam failures in recent past have shown that inadequate capacity of the spillway was the cause for a third of these accidents (Schleiss, 2011). The strong motivation to maximize the discharging capacity of spillway have resulted in development of various non-linear crest geometries. The Piano Key Weir (PKW) is a modified labyrinth-type weir that makes use of inclined apexes in order to maximize the allowable weir length that can fit in a given channel width. The PKWs have emerged as an innovative and viable solutions for both dam rehabilitation and new projects with space constraints.

The concept of PKW was presented more than 20 years ago by Hydrocoop (Blanc & Lempérière, 2001; Lempérière & Ouamane, 2003). After a few years of elaborate conceptualization, the first PKW was built by Electricité de France (EDF) in 2006 at Goulours dam in France (Laugier, 2007). Many other PKWs are currently under different stages of design, construction and operation around the world: France, Vietnam, India, and South Africa (Singhal & Sharma, 2011; Khanh, 2013; and Erpicum, et al 2017).

The geometry of PKW is complex as it is governed by large sets of parameters. A naming convention was specifically developed in some laboratories to amalgamate the notations (Pralong, et al 2011). The chief geometric parameters are the width of the inlet and outlet keys, denoted W_i and W_o respectively, the height of weir P, depth below inlet key P' the width of one cycle or PKW unit W_u, the total number of PKW units N_u, the total stream wise crest length B, the lengths B_o and B_i of the up- and downstream overhangs, the base length B_b and the thickness of wall T. Most of these defining parameters for PKW with three cycles are depicted in Figure 1. The width of a PKW unit W_u is equal to $W_i + W_o + 2T$ and the total width W of the weir is equal to $N_u \times W_u$. The developed crest length L_u of a PKW unit is equal to $W_u + 2B$ and the total developed crest length L of the weir is calculated as $N_u \times L_u$ (Erpicum, et al 2017).

A series of both experimental and numerical studies have been conducted by various investigators to enumerate the discharge capacity of the PKW. Leite Ribeiro et al (2012) conducted a set of experiments on several PKWs with overhangs on both upstream and downstream (Type-A) and identified the primary and secondary parameters affecting the flow. They formulated a head–discharge relation for PKW by providing an expression for increased discharge ratio of PKW with respect to a rectangular sharp-crested weir. Similarly, other comprehensive and systematic model tests have resulted in more complex design equations with a rather good accuracy within the limits of the parameter range specified by the researchers (Cicero & Delisle, 2013; Crookston, et al 2018 and Kumar, et al 2019). A parametric study to investigate thirty-one different models of this weir with different height, keys widths and overhangs lengths of the PKW with *L/W* equal to 5 was conducted at University of Liege, Belgium (Machiels, et al 2014). Mahabadi & Sanayei (2020) evaluated the implementation of bilateral side slopes in the outlet key and its impact on efficiency through numerical simulations.

The available literatures indicate that all the studies conducted to date have only incorporated PKWs with linear slopes of the inlet and outlet keys. Therefore, the influence of curvilinear shapes of key slopes on its discharge capacity is not known. This study presents the experimental results for the discharge efficiency of PKW with linear and curvilinear slopes in the outlet key.

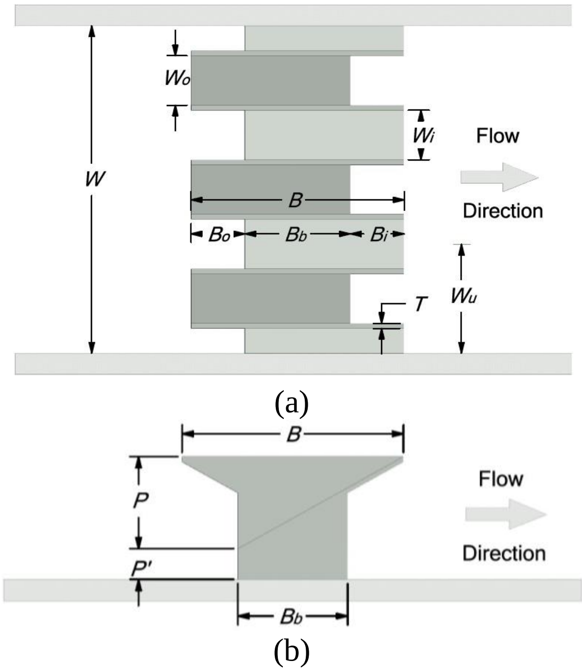


Figure 1 - Typical geometry of PKW: (a) plan; (b) side-elevation.

2. METHODOLOGY

2.1. Geometry of Models

In this study, two laboratory-scale models of Type-A PKW with varying profiles of slope in the outlet key have been tested. The first PKW model with three cycles and standard linear slopes in both inlet and outlet keys is identified as PKW-L. All the parameters of this model are similar to the one used by Kumar, et al (2019) and are as follows: B = 0.254m, B_i = B_o = 0.064m, W_i = W_o = 0.059m, P = 0.105m, P' = 0.035m and W = 0.39m. Another model with all geometric parameters consistent with the PKW-L except for the slope profiles of outlet keys is referred to as PKW-CL. An overview of both these models are depicted in Figure 2 (a and b).

The curvilinear profile of the outlet key slopes selected for PKW-CL weir was the downstream ogee profile based on Waterways Experiment Station (WES) standard spillway shape given the following equation.

$$X^n = K \times H_d^{(n-1)} \times Y \quad (1)$$

Where, X and Y are coordinates of profile with the origin at the highest point of the outlet key crest. H_d is the selected design head for the profile. K and n are parameters which depend on the slope of upstream face and were taken corresponding to vertical slope as K = 2 and n = 1.85. For reverse curve, the radius r was taken as half of H_d and the angle of 60° was provided (see Figure 2c).

This shape is derived from lower surface of a free-falling nappe and is known for its ability to pass flows efficiently and safely (Savage & Johnson, 2001). A reverse curve was provided at the lower end of the key slope to smoothly guide the falling jet towards downstream. The schematic diagram with details of the curvilinear profile has been depicted in Figure 2 (c). The design head over the crest (H_d) had to be fixed to derive the profile of the slope for the model with curvilinear outlet keys. Since, PKWs are highly efficient at lower heads, majority of these weirs developed till date have total design head to weir height ratio (H_d/P) of less than one (Crookston, et al 2019). Accordingly, the profile of the outlet slopes of this model was assumed for H_d/P value of 0.5.

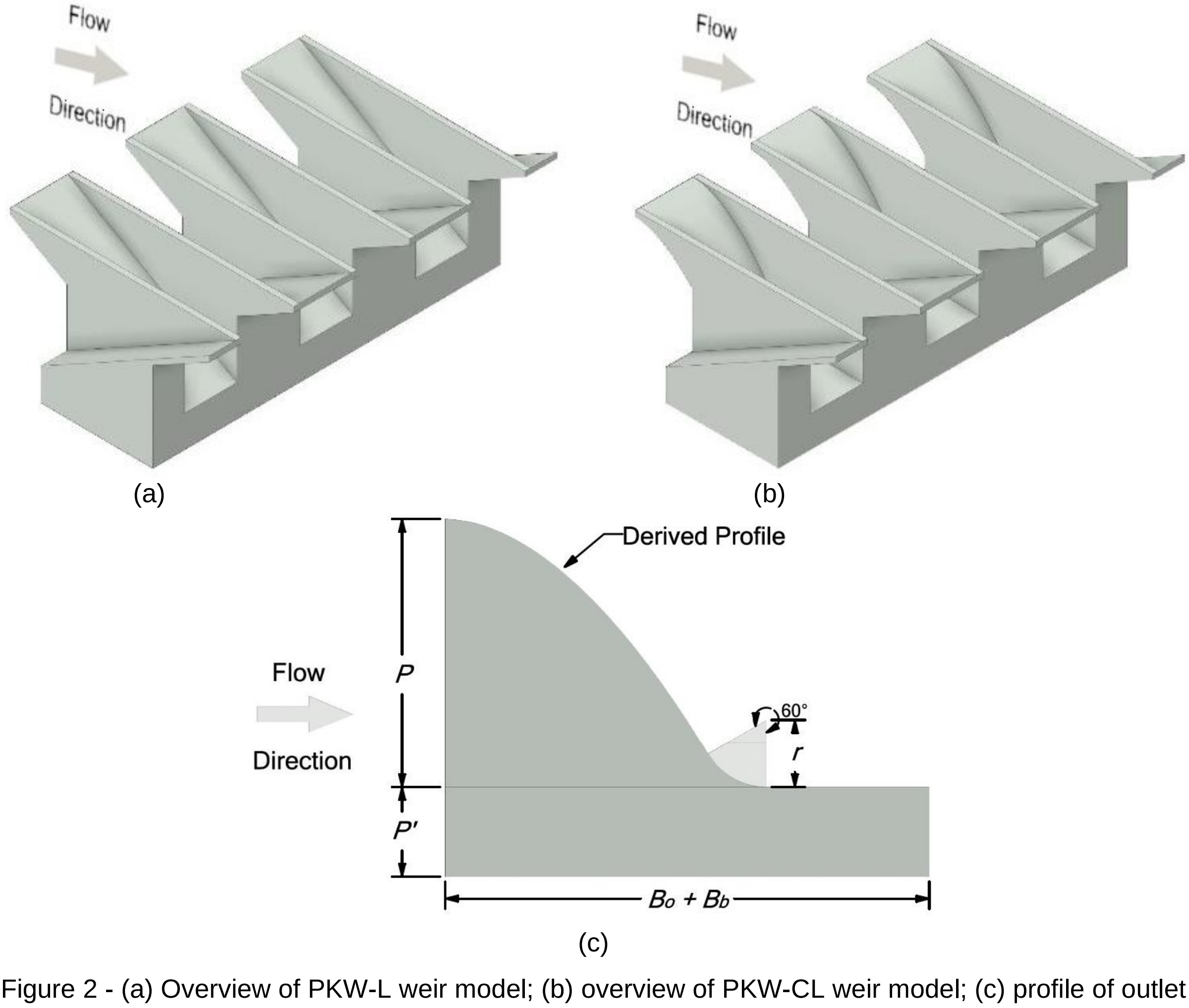


Figure 2 - (a) Overview of PKW-L weir model; (b) overview of PKW-CL weir model; (c) profile of outlet key for PKW-CL weir model.

2.2. Experimental Setup

The experiments were conducted in a rectangular flume of length 15m, width 0.39m and height 0.52m. A major section of flume consisted of glass side walls which allowed for visualization of flow over the weir. A recirculating tank was provided at the end of the flume for the storage of water and re-circulation of flow. A pump was installed to supply water through an inlet pipe having inner diameter of

0.1m. The discharge was regulated using a control valve fitted in this inlet pipe. An ultrasonic flow meter with an accuracy of 1% was used to measure the discharge flowing in the pipe. The entrance of the flume was equipped with honeycomb grid walls to minimize the disturbances in the flow as shown in Figure 3. Also, flow straighteners and wave suppressor were provided near the entrance to suppress cross currents and surface disturbances, respectively. A point gauge system having a least count of 0.1mm was used to measure the water level.

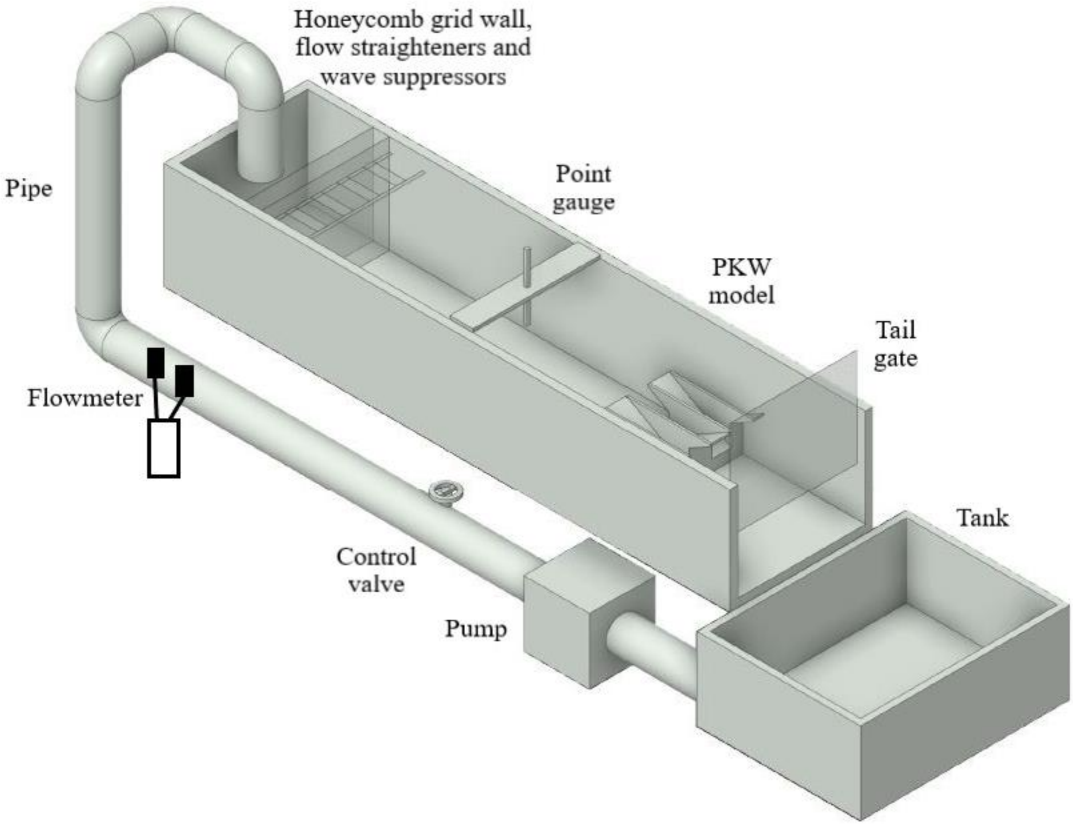


Figure 3 - Schematic of the experimental setup.

The models of the PKW were fabricated using plastic sheets of 6mm in thickness as per geometric dimensions mentioned earlier. For curvilinear slopes, the plastic sheets were heated and then pressed into the desired profile. These weirs were then attached to the base of the flume using sealant to ensure water-tight joints. The point gauge system was positioned at 2×*P* (i.e. 0.21m) upstream from outlet crest to measure the water level. The tests on each PKW model were performed for flows ranging from 5×10^{-3} m^3/s to 35×10^{-3} m^3/s. The point gauge was used to measure the water level for each discharge after the flow had stabilized for a minimum of 15 minutes. At least three readings were taken for the water level consecutively to ensure that steady state had been achieved, given that all the readings were in agreement.

3. RESULTS

The discharge capacity of the PKW can be described by the common weir formulation as given below (Kumar, et al 2019)

$$Q_{PKW} = \frac{2}{3} C_{PKW} W \sqrt{2gH^3} \tag{2}$$

Where, Q_{PKW} is discharge over the weir, C_{PKW} is coefficient of discharge, g is acceleration of gravity, W is total width of the weir and H is total upstream head.

The coefficient of discharge (C_{PKW}) lumps the effect of geometric parameters on the discharge efficiency of the weir. The variation of this coefficient for PKW-L and PKW-CL models with the normalized total head given by the ratio *H/P* is shown in Figure 4. According to the data observed, the discharge efficiency of PKW-L was higher for the lower head values of $H/P < 0.46$. As the head increased, PKW-CL became more efficient than the former for $H/P > 0.46$. Nevertheless, both of these weirs showed similar trends of significant loss of efficiency with increasing head.

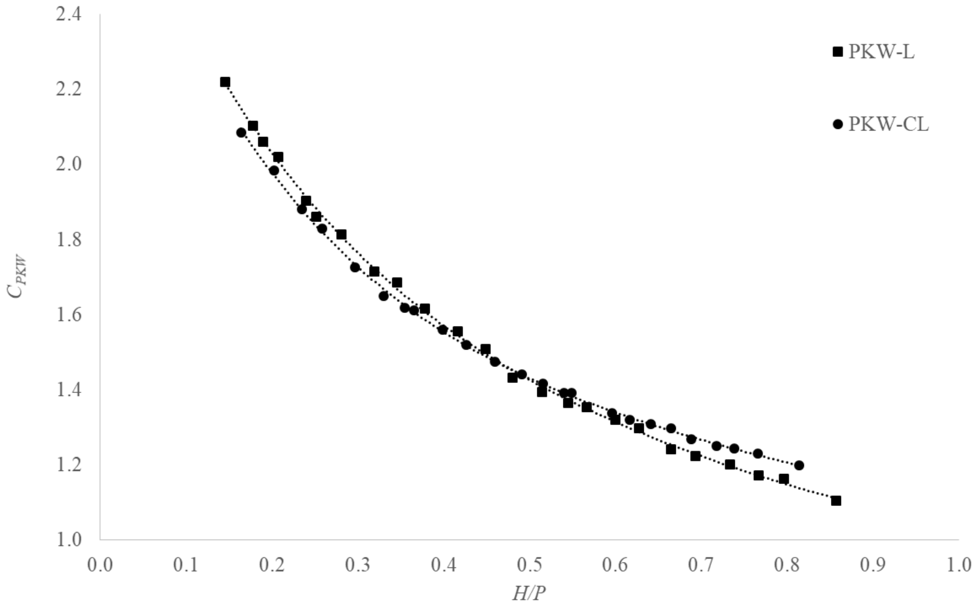


Figure 4 - C_{PKW} versus *H/P* data for PKW-L and PKW-CL weirs.

The comparisons of discharge efficiencies as the ratio of C_{PKW} value of PKW-CL with respect to that of PKW-L weir are presented in Figure 5. These results suggest that the discharge efficiency of PKW-CL is relatively enhanced as the head over the weir becomes equal to or greater than the design head of the outlet key slopes. PKW-CL shows a maximum increase in efficiency by 5.2% for $H/P = 0.81$. However, ogee profile provided in the outlet keys has a negative impact on the discharge capacity for hydraulic heads below its design head for the tested model.

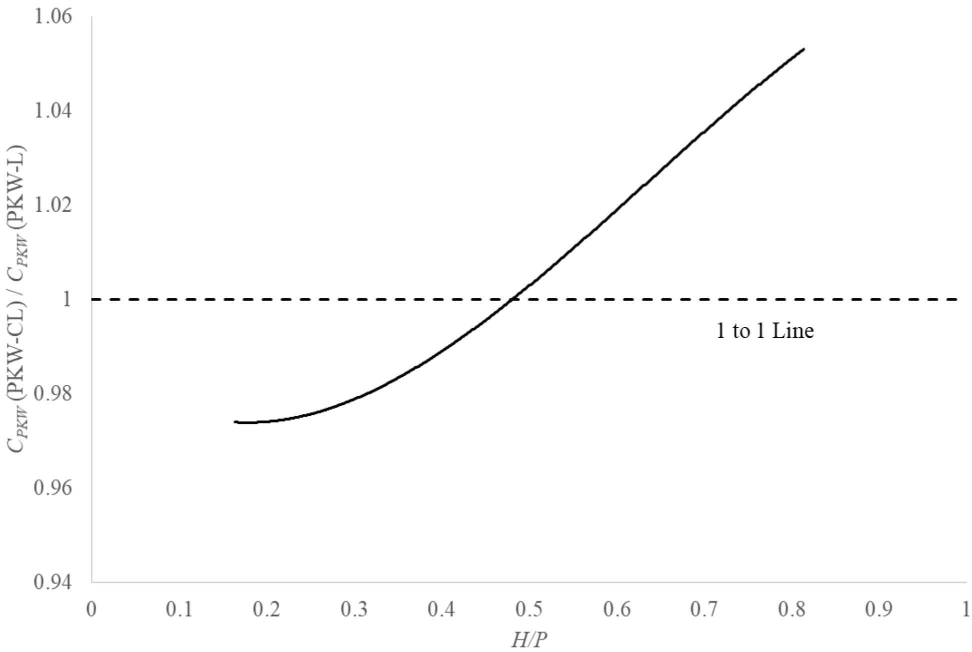


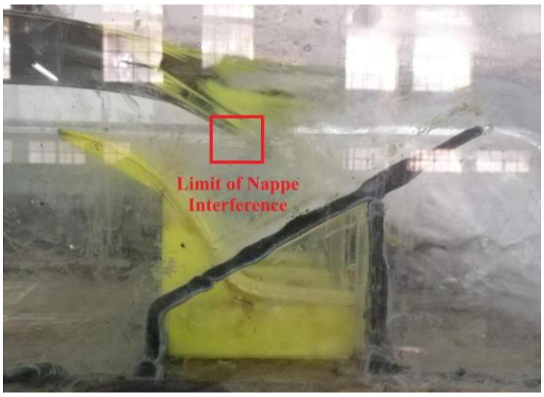
Figure 5 – C_{PKW} (PKW-CL) / C_{PKW} (PKW-L) versus *H/P* data.

4. DISCUSSION

The flow passing over a PKW is three-dimensional and comprises of following portions: a normal jet flow over the up- and downstream crests and a lateral jet flow over the sidewalls. At low upstream heads, the normal and lateral jets flowing into the outlet key are close to the walls. As the head increases, these jets spring and collide with each other in the downstream region of the outlet key. This interference of jets in the downstream of outlet crest reduces the discharging ability of the outlet portion. Thus, the significant loss in the efficiency of both PKW models with increasing head can be attributed to the nappe interference.

The influence of curvilinear outlet key profiles on the discharge efficiency of the PKW can, in part, be explained as follows. The shape of the ogee profile is derived from the lower surface of an aerated nappe flowing over sharp crest for a single upstream head. So, for the heads lower than this design head, the efficiency is reduced due to the bed surface resistance. At higher heads, this resistance to the flow over the key slope diminishes and its ability to evacuate the flow without separation is improved. Furthermore, the slopes of the curvilinear profiles are steeper than the linear profile for major portion of the outlet key and hence allows for rapid exit of flowing stream. Consequently, the limits of nappe interference for PKW-CL were observed to have moved less towards the downstream than for PKW-L under similar high flow conditions as shown in Figure 6 (a and b).

(a)



(b)

Figure 6 - Limit of nappe interference for $Q_{PKW} \approx 3\times10^{-2}$ m^3/s (a) PKW-L at H/P= 0.76; (b) PKW-CL at H/P = 0.73.

5. CONCLUSION

To study the effect of shape of outlet key slope on the discharge capacity of PKW, two experimental models with linear slope (PKW-L) and curvilinear slope (PKW-CL) were tested. The conclusions based on the results from this study are as follows:

- For flow conditions resulting in hydraulic head (H) higher than the design head (H_d), the discharge efficiency of PKW-CL became moderately higher than PKW-L. The maximum increase in coefficient of discharge (C_{PKW}) of PKW-CL in comparison to PKW-L was 5.2% for 0.16< H/P <0.81.
- The ogee profile of PKW-CL had negative influence on its discharge efficiency for flows with $H < H_d$ due to bed surface resistance at outlet. Thus, its C_{PKW} value was less than that of PKW-L for these low flow conditions.
- Both weirs showed considerable decrease in their discharge capacity with increase in H because of interference of normal and lateral jets flowing into the outlet keys. However, the limit of nappe interference in case of PKW-L was observed to be further downstream than in PKW-CL for high flows leading to better performance of the latter.

This paper presents results for a single PKW model with an ogee shaped outlet keys. Tests on more curvilinear profiles will help to reinforce the findings of the present study. Further, additional research to investigate modifications of the general PKW elements is deemed necessary to further enhance its hydraulic behaviour. More detailed evaluations of these variations will provide greater comprehension towards the optimal geometric design of these weirs.

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