

The influence of inlet to outlet width ratio on The hydraulic performance of piano key weir (PKW-type A)

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ABSTRACT

A piano key weir (PKW) is a modified version of non-linear weirs and it can be obtained via amending the centerline length of the weir by a small footprint. It is developed to increase the hydraulic performance of the linear weirs via increasing the pass discharge and the energy dissipation. A laboratory investigation is conducted on five physical PKW (Type A) models to investigate the effect of inlet to outlet width ratio (W_i/W_o) on the hydraulic performance of PKWs. The results showed that the (W_i/W_o) ratio has a predominant influence on the hydraulic performance of PKW. It was found out that the best hydraulic performance was obtained with W_i/W_o ratio equal to 1.25 among other investigated W_i/W_o ratios because the discharge coefficient was the highest for the given discharge and head. Further, the results revealed that the variation of W_i/W_o ratio from 1.25 had a negative impact on both discharge coefficient (C_{dw}) and efficiency. It was found out that the percentages of reduction in discharge coefficient when $W_i/W_o=0.8, 1, 1.5$ and 2 were 11%, 6%, 2% and 8%, respectively in comparison with the $W_i/W_o=1.25$. Similarly, for these W_i/W_o ratios, the percentages of reduction in discharge decrease by 11%, 6.5%, 2.35% and 9%, respectively, relatively to $W_i/W_o=1.25$. The linear regression equations' coefficients for the PKW models varied from 0.983 to 0.994, which means the performance of the models are good for the given W_i/W_o ratios.

Key words: discharge coefficient, energy dissipation, hydraulic structures, piano key weir, weirs

HIGHLIGHTS

- The study was conducted in a laboratory that has a big open channel, which means the physical model scale is preferable by hydraulic community.
- Merging the piano key weir within the existing spillway structure in the dams becomes a necessary action to be performing since the flash flood increased due to the climate change. This aids enhancement.

1. INTRODUCTION

Dams and reservoirs have been constructed to control the floods and supply water for drinking, irrigation, industrial, restoration, hydro-electrical and navigation purposes (Sayl *et al.* 2016). However, their efficiency and safety operations management remain a big challenge facing public administrators and decision makers. Furthermore, the impact of climate change has been viewed worldwide and leads to exacerbate the flood events (Phelps *et al.* 2021). This means the predicted design of flood discharges in many urban areas will be radically increased (Qutbudin *et al.* 2019). Therefore, many of existing dams need urgent rehabilitation to enhance the safety operations of these structures by increasing their discharge capacity and consequently providing a protection for the people in vulnerable areas downstream of these structures (Sami Al-Janabi *et al.* 2020; Sharafati *et al.* 2020). The maximum water level in the reservoir is one of the important parameters that represent the hydrological safety of the dam (Bianucci *et al.* 2013; Micovic *et al.* 2015; Gabriel-martin *et al.* 2017), whereas the initial water level in the reservoir is a substantial variable for the evaluation of dam overtopping in the flood periods (Kwon & Moon 2005). Another aspect should be taken in consideration during the operation period of dams; that is, the gates that may not work properly during floods when needed because of failure in operation due to human, mechanical and electrical disruption (Lemarchand *et al.* 2002; Lewin *et al.* 2003; Patev & Putcha 2005).

Investigations of dam failures worldwide and their causes indicate that the insufficiency of spillway discharge capacity results in about 23% of dam failures (Abhash & Pandey 2020). In addition, the insufficiency of spillway

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capacity can cause overtopping of flow over the dams. This may lead to local scour downstream of dams, erosion of dam protection system and seepage through the dam body, which may cause the dam failure. Suitable hydraulic design of dams will contribute to the good knowledge of river and canal engineering sustainability and management (Sharafati *et al.* 2019; Yousif *et al.* 2019). Therefore, the piano key weir (PKW) is used to increase the discharge capacity of these structures. This type of weir is an innovative alternative to non-linear labyrinth weirs (Ouamane & Lempérière 2003). Generally, increasing the safety of dams depends on physical aspects, economic circumstances and the availability of engineering professions (Abhash & Pandey 2020). Commonly, the weir's discharge capacity increases via two amendments: (a) the length of the weir can be increased by changing the weir length from linear to non-linear configuration or (b) by reducing the crest weir height (Anderson 2011). However, increasing the weir length is typically impractical due to dam geometry limitations and/or economic reasons (Sharafati *et al.* 2019). In addition, lowering the height of the spillway is economically inefficient as it contributes to a reduction in the maximum water level in the reservoir and thereby decreases the reservoir's storage capacity. Using nonlinear weir (i.e. increasing the weir's crest length) is thus a realistic and viable alternative (Anderson 2011). In this respect, the PKW offers an excellent alternative for mitigating dam danger. Firstly, they reduce the chance of gates to be not opening during flooding period because of the free flow of PKWs. Secondly, PKWs have a higher discharge efficiency, which allows the global storage volume to recover (Ouamane & Lempérière 2003) and (Tiwari 2016). In addition, the PKWs have a greater ability to discharge high flow during flood at a lower water level than that of a gated dam when the reservoir is below the normal level of extreme flooding (Lempérière & Vigny 2011). Furthermore, the other nonlinear weirs; namely the labyrinth weirs have many drawbacks. They require a massive quantity of reinforced concrete for construction (Emin *et al.* 2010). More importantly, the performance of weir is significantly reduced at high discharges. In addition, the nonlinear weirs cannot be constructed on limited footprint, as they need a larger foundation base (Lempérière *et al.* 2011). Therefore, using PKWs by the hydraulic engineers is an optimum option that has the cost effective and hydraulically efficient structure (Yousif 2020). This is accomplished by the ability to install the PKW on top of existing dams due to its reduced footprint (Ouamane & Lempérière 2003), and by the increased discharge of PKW due to increased crest length by several times relative to conventional crosswise weir crest length. The sloped bottom of inlet and outlet keys further enhances a PKW's hydraulic efficiency (Laugier *et al.* 2009; Anderson & Tullis 2012, 2013).

The flow over the PKW is highly affected by its geometrical variables and each variable affects the weir's hydraulic performance. Recently, extensive experimental and numerical investigations have been carried out to understand the hydraulic behavior of PKWs. Different types of PKWs have been introduced since the invention of the PKW in 1998. Mainly, four types of PKWs are existing and these are categorized according to the existence of overhangs on upstream and downstream of the weir as shown in Figure 1 (Lempérière *et al.* 2011). The type-A PKW has overhangs on both the upstream and downstream of the weir; whereas the type-B PKW has only upstream overhangs; and type-C only has downstream overhangs. Finally, the type-D PKW is without overhangs as shown in Figure 1 (Lempérière *et al.* 2011; Ribeiro *et al.* 2012; Bashiri *et al.* 2016). Pralong *et al.* (2011) described the standard notation of the geometrical parameters of PKW, which is used herein as shown in Figure 2.

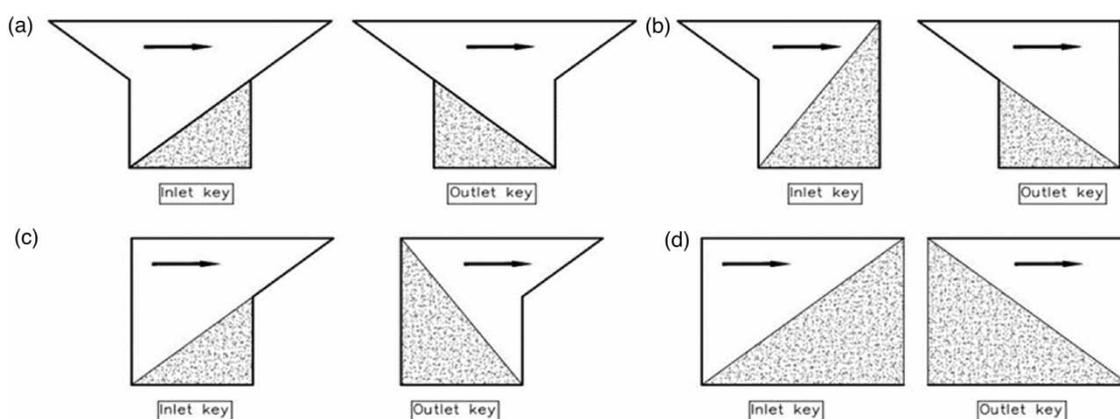


Figure 1 | Types of PKW (a) Type-A, (b) Type-B, (c) Type-C, (d) Type-D (Lempérière *et al.* 2011).

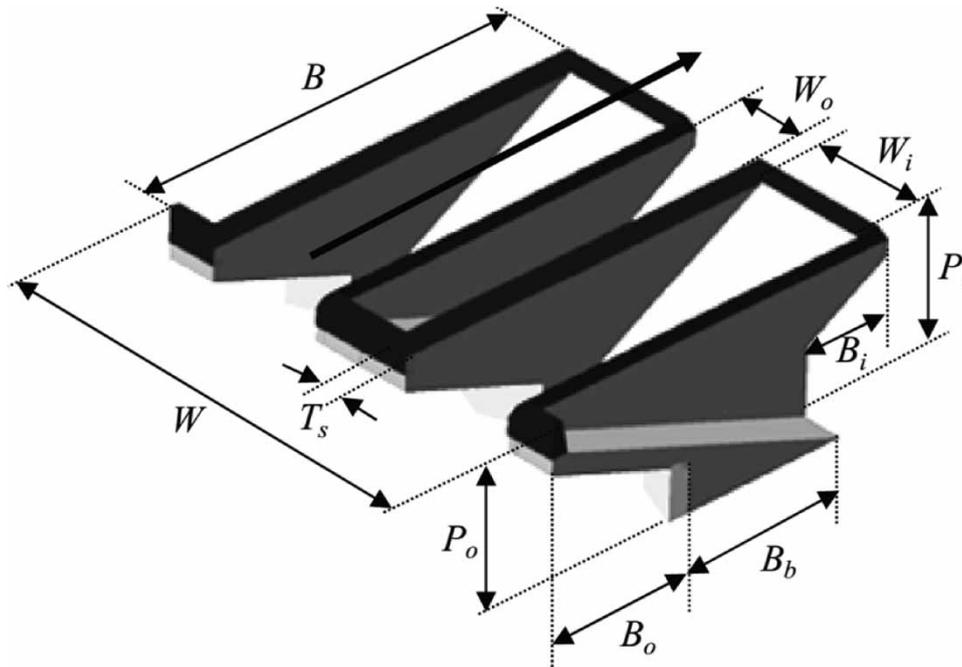


Figure 2 | Reproduced from (Pralong *et al.* 2011) Isometric view on a PKW with its fundamental parameters.

The flow over a PKW is complex and its discharge capacity is highly influenced by its geometrical parameters. Therefore, many experimental studies have been carried out to study the effects of geometrical features on the PKW's hydraulic behavior. A type-A PKW usually is preferred because its geometry is better prefabricated on the pre-cast concrete construction (Ouamane & Lempérière 2003). The effect of inlet key to outlet key width ratio (W_i/W_o) on hydraulic performance has been investigated by many researchers. Lempérière & Jun (2005) and Barcouda *et al.* (2006) found out that the $W_i/W_o=1.2$, is near optimum ratio. Hien *et al.* (2006) investigated PKWs with $W_i/W_o=1.5$. However, the advised ratio of the $W_i/W_o=1.2$, which is probably more efficient. Yet no data are available to validate this finding. Ouamane & Lempérière (2006) studied experimentally three PK weirs with varying W_i/W_o ratios of 0.67, 1.0, and 1.5. They found out that the discharge capacity increases by increasing W_i/W_o . Ouamane & Lempérière (2006) claimed that $W_i/W_o=1.2$ increased the discharge efficiency by 5%, relative to $W_i/W_o=1$, although the data of $W_i/W_o=1.2$ for a PK weir were not existing as a part of that study. Later, (Lempérière 2009) suggested that the ratio of $W_i/W_o=1.25$ was close to optimal.

The ratio of $W_i/W_o=1.43$ was used for the PKW built at the Goulours dam and $W_i/W_o=1.41$ was adopted for the PKW at Saint-Marc dam (Ribeiro *et al.* 2007; Laugier *et al.* 2009). Generally, all the previous studies agree that $W_i/W_o > 1.0$ yields a higher discharge efficiency than $W_i/W_o < 1.0$. However, no optimum W_i/W_o ratio has been recommended yet.

In addition, the ratio of inlet key to outlet key width plays an important role in non-rectangular PKWs. Hence, many experimental investigations have been conducted to study the non-rectangular configuration of PKWs to increase the discharge capacity of PKWs. Cicero *et al.* (2013) studied the hydraulic performance of trapezoidal PKW type- A. In their study, the W_i/W_o ratio taken was equal to 1. They found out that when the sidewall angle changed to 5 degrees with hydraulic constraint (same L/W of rectangular PKW), the efficiency of the weir gained an increase between 5% to 20% relative to rectangular PKW with $W_i/W_o=1$. Furthermore, Khassaf & Al-Baghdadi (2015) studied experimentally five physical PKW models. In their study, the rectangular PKW had a $W_i/W_o=1.25$. They found out that increasing the sidewall angle by 5 degrees in trapezoidal models had a slight impact on the PKW performance where the discharge capacity only gained 4%. However, most recently, Yousif (2020) studied the hydraulic performance of non-rectangular weirs experimentally. In his study, the standard rectangular type-A PKW had a $W_i/W_o=1.25$ and three non-rectangular PKWs with changing the sidewall angle in each model by 3, 5 and 7 degrees. He found out that the deviation of the sidewall angle by any degree from rectangular configuration had a negative impact on the hydraulic performance of a PKW where the discharge capacity was decreased by 4, 12 and 18% for the sidewall angles equal to 3, 5 and 7 degrees, respectively.

Hence, according to the studies of PKWs in non-rectangular configurations, the ratio of W_i/W_o is an important variable that affects the discharge capacity of PKW and can affect the decision of selecting the type of PKW.

Although few experimental investigations have been carried out in the past to study the impact of inlet key to outlet key width ratio, there is insufficient information about the effect of this parameter on the discharge capacity and coefficient of this type of weirs. Therefore, this experimental investigation was conducted to enhance the understanding of the impact of inlet to outlet key width ratio on the hydraulic performance of a type-A PKW.

2. EXPERIMENTAL SETUP

Systematic PKW model experiments were carried out at the hydraulic laboratory of College of Engineering/University of Duhok in a straight rectangular channel 10 m long, 0.6 m wide, and 0.6 m high as shown in Figure 3. The sides and base of channel were made of 6 mm-thick glass. The channel base and side rails were levelled before starting the experimental work. The channel has a recirculated system connected to a pump with a maximum discharge of 50 liter per second. The entrance box with dimensions 1 m width, 1 m length and 2 m height at the beginning of the channel was connected to the channel entrance. The entrance box contained two layers of energy dissipation screens to dissipate the energy of flow and consequently reach a uniform flow condition in a shorter length of the channel entrance. A point gauge with an accuracy of reading to ± 0.01 mm was used to measure the flow depth in the channel and it was carried on steel rails on the channel sides. Throughout the experiments, the water depth in the channel was recorded at a position 50 cm upstream of the PKW models. A pump with a maximum discharge capacity of 50 liters/second was used to supply water to the channel and for this study the range of discharge was between 7.1 and 42.9 liters/second. An electronic flow meter with accuracy of 0.01 liters/second was connected to the pump used to measure the discharge. Each piano key model was installed at location of 5 m downstream of the entrance of channel to secure the fully developed flow section. The flow downstream of PKW models was discharged through the main channel and a side opening at a position of 0.5 m downstream of PKW models as shown in Figure 3.

A platform was used to carry the PKW models. Each PKW model was fixed on the platform by two screws.

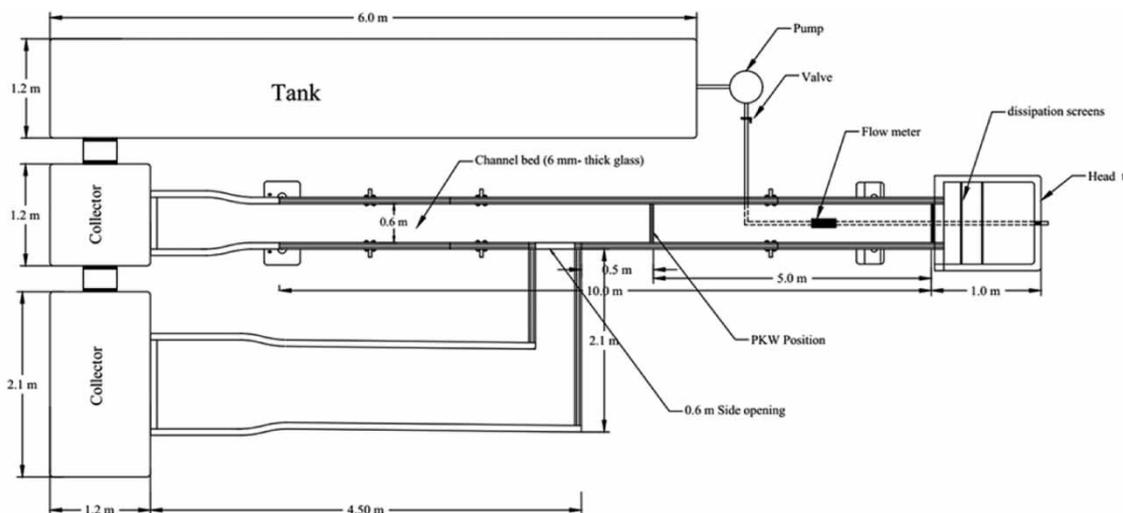


Figure 3 | Top view of experimental setup.

Then a silicon rubber was applied to all contact areas between the sides of channel, PKW model and the platform to enhance the stability of the PKW model during the operation as well as avoiding water leakage. Prior to recording the depth of flow in each experiment, 15 minutes were given to the flow to be circulated in the channel to secure the uniform and steady flow condition.

Finally, in each piano key model, the discharge and depth of flow were recorded. For each PKW model, the flow depth was recorded at least 10 times. To reduce the scale effects (effect of surface tension and viscosity), flow depths less than 3 cm were not considered, as recommended by *Erpicum et al. (2016)*.

3. GEOMETRIC FEATURES OF A PIANO KEY WEIR

Unlike the linear weirs, there are many geometrical features that affect the PKW's hydraulic performance. The terminology described by Pralong *et al.* (2011) for a type-A PKW is used herein. The fundamental geometrical parameters' definitions for a PKW are given in Table 1. In this study, five physical PKW models have been designed according to the recommendation of Lempérière (2009). In these models, the dimensions of geometrical parameters of sidewalls and slope of inlet key and outlet key are kept constant as shown in Figure 4. In order to achieve the aim of this study, in each PKW model the inlet to outlet (W_i/W_o) ratio has been changed. Each PKW model has three cycles of inlet and outlet keys to increase the practical use of these models. Figure 5 shows a schematic plan view of the PKW. Table 2 shows the dimensions of geometrical parameters of PKW models used in this study.

Table 1 | Notations of standard PKW fundamental parameters (Pralong *et al.* 2011)

Parameter symbol	Definition
B	Side wall crest length of PKW, $B=B_b+B_i+B_o$
B_o	Overhang length of upstream outlet key
B_i	Overhang length of upstream inlet key
B_b	Width of PKW base
P	Crest height of PKW (including possible parapet walls)
P_d	Height of dam (or any plat form under the PKW)
W	Channel width
W_i	Width of inlet key
W_o	Width of outlet key
T_s	Thickness of the side wall
L	Length of crest of PKW along the overflowing crest axis

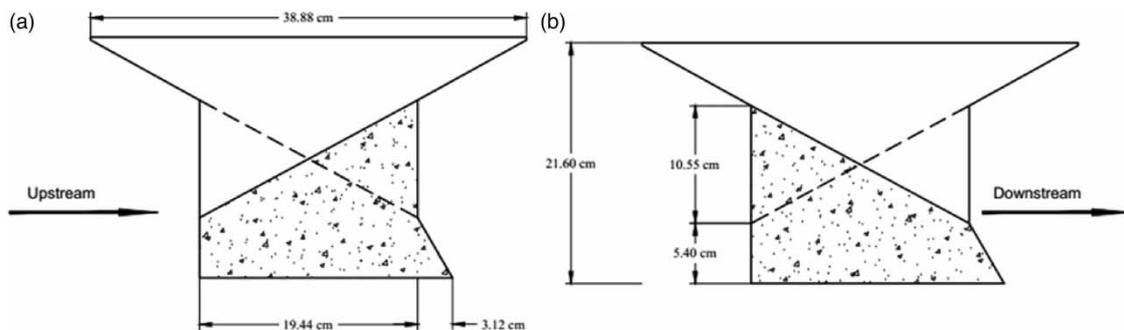


Figure 4 | Details of PKW sidewalls. (a) Sidewall inlet key (b) Sidewall Outlet key.

The PKW models in this study have been fabricated using 2 mm-thick acrylic sheeting and a computer numerically controlled (CNC) to cut the parts of the PKW models. A quick glue was used to assemble the parts of PKW and a silicon rubber was used between the parts to avoid leakage inside the weirs under operation. The ratios of important geometries of PKWs were selected as follows: ($L/W=4.885$, $B/P=1.8$, $B_i/B=0.25$ and $B_o/B=0.25$). A platform was fixed under each model so that the dam height ratio $P_d/P=0.6$ would secure free flow conditions (Yousif 2020). All the models tested in this investigation have a flat top crest.

4. RESULTS ANALYSIS AND DISCUSSION

4.1. Variation of discharge coefficient (C_{dw}) with W_i/W_o

The discharge of a PKW can be determined using the equation of traditional rectangular linear weir that is relevant to British Standard Institution (British Standard Institution 1965). Thus, the discharge coefficient can be

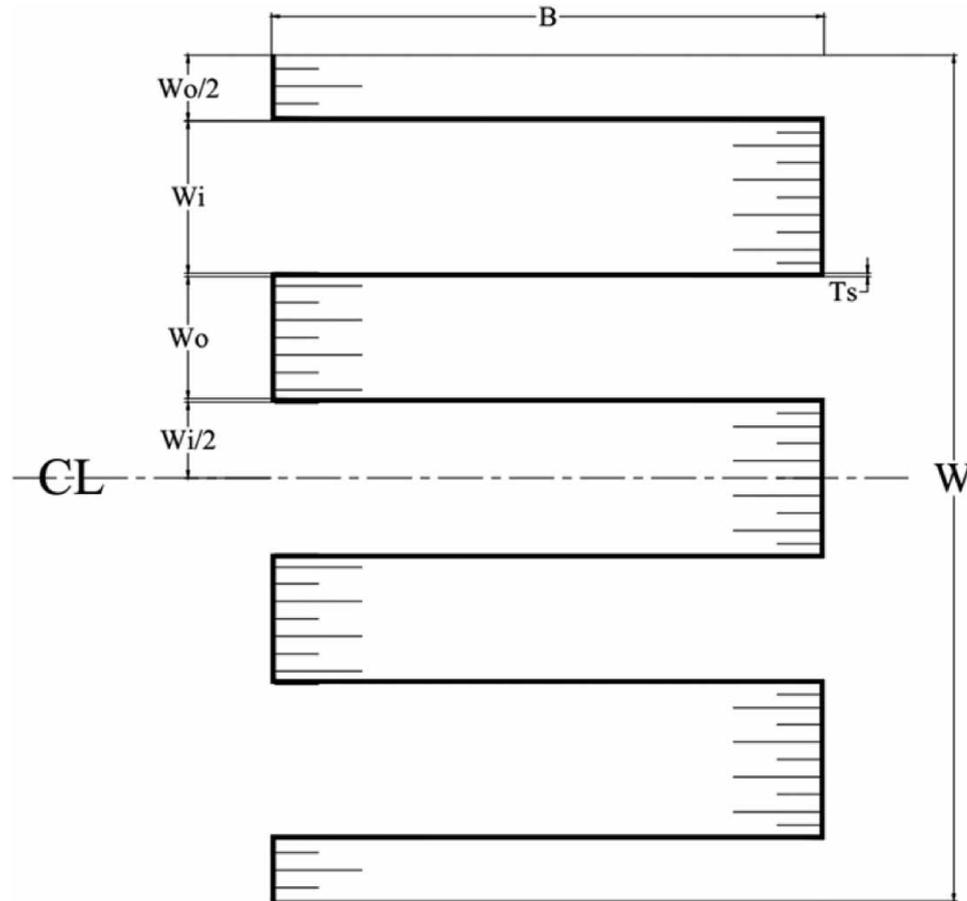


Figure 5 | Schematic plan of PKW.

Table 2 | Geometrical features of the PKW models used in this study

PKW Model	B (cm)	P (cm)	Ts (cm)	B _i =B _o (cm)	W _i (cm)	W _o (cm)	P _d (cm)
W _i /W _o =0.81	38.88	21.6	0.2	9.72	8.80	10.80	13
W _i /W _o =1.00					9.80	9.80	
W _i /W _o =1.25					10.80	8.64	
W _i /W _o =1.51					11.80	7.80	
W _i /W _o =2.01					13.10	6.50	

evaluated as follows:

$$C_{dw} = Q / \left(\frac{2}{3} \sqrt{2g} W H_o^{\frac{3}{2}} \right) \quad (1)$$

where: Q is the PKW discharge, C_{dw} is the discharge coefficient of the PKW, g is the acceleration due to gravity, W is the channel width and H_o is the total head over the weir crest.

To detect the effect of W_i/W_o on discharge coefficient and capacity, five PKW models, described herein as $W_i/W_o=0.8, 1, 1.25, 1.5$ and 2 , were prepared.

The results show that the discharge coefficient C_{dw} is highly influenced by the change in W_i/W_o ratio as shown in **Figure 6** where the $W_i/W_o=1.25$ is hydraulically performing better than other W_i/W_o ratios where C_{dw} value is higher than the values of C_{dw} of other W_i/W_o ratios for a given discharge. The percentage of reduction in C_{dw} for $W_i/W_o=1.5$ can reach 2% relative to $W_i/W_o=1.25$ under the same discharge. However, this reduction in C_{dw} increases with further deviation of W_i/W_o from 1.25 where the percentage of reduction in C_{dw} for W_i/W_o

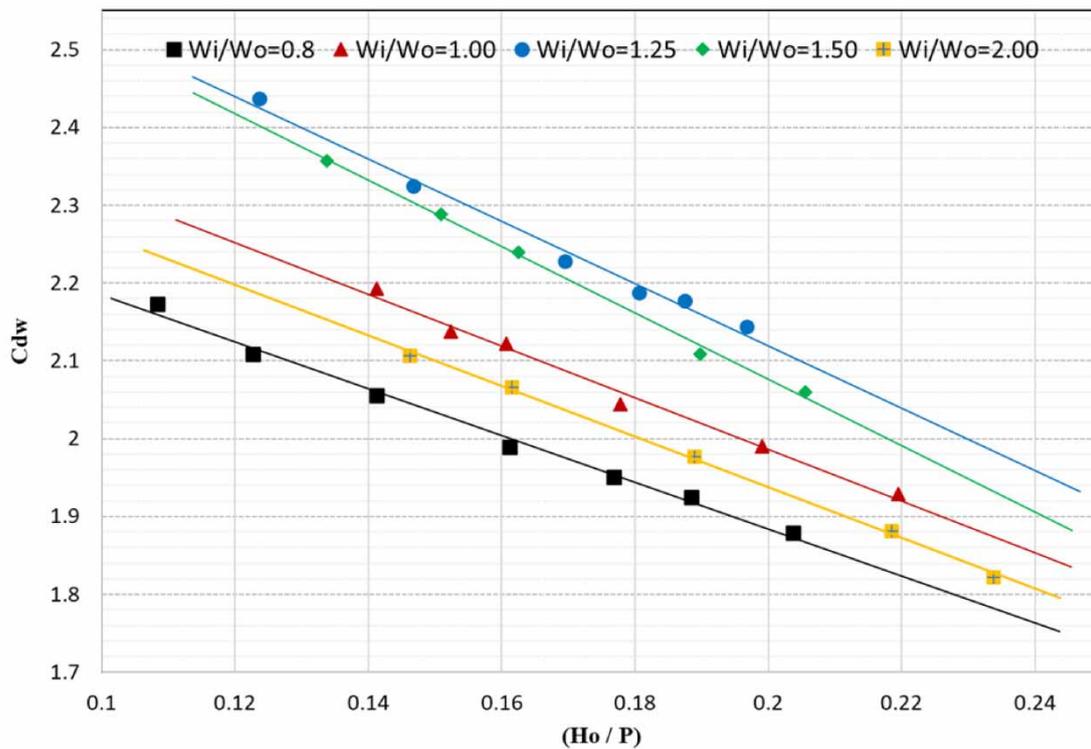


Figure 6 | The relationship between discharge coefficients with Ho/P under different Wi/Wo ratios.

Wo=1 reached 7%. Furthermore, the reduction percentage in C_{dw} for Wi/Wo=2 and 0.8 was equal to around 10 and 13%, respectively. This suggests that the Wi/Wo=1.25 is close to the optimum ratio. Additionally, it can be concluded that the ratios of Wi/Wo less than 1 and greater than 1.5 should be avoided in the design of PKWs. Similar results were arrived at by Lempérière & Jun (2005), Barcouda *et al.* (2006) and Hien *et al.* (2006) as they recommended that Wi/Wo=1.2 is near the optimum ratio. More importantly, this finding is in full agreement with Lempérière (2009), who suggested that Wi/Wo=1.25 is close to optimum. Moreover, the ratio of Wi/Wo=1.25 seems to be a better choice for a rectangular PKW than non-rectangular PKW configurations as suggested by Yousif (2020). The overwhelming of hydraulic performance of Wi/Wo=1.25 to other Wi/Wo ratios can be attributed to a local submergence at the outlet keys of other PKWs Wi/Wo ratios. Additionally, the relationship between the discharge coefficients and head of flow over the crest of PKW models has been drawn as illustrated in Figure 7 which shows the direct change of C_{dw} with Ho and all models provides same patterns of the variation but in terms of the hydraulic performance notably the Wi/Wo=1.25 performs much better than other Wi/Wo ratios for all the head of flows.

4.2. Rating curve of PKW models

To illustrate the effect of Wi/Wo on the discharge capacity of PKWs, the rating curves of PKW models were plotted as shown in Figure 8. In this figure, it is quite evident that the discharge capacity of Wi/Wo=1.25 is higher than other Wi/Wo ratios. This means that any change of Wi/Wo from 1.25 has a negative impact on the discharge capacity of the weir (keeping the other geometrical parameters constant). In addition, Figure 8 shows that increasing and decreasing the Wi/Wo ratio from 1.25 have an undesirable impact on discharge capacity. The Wi/Wo=1.5 has shown a percentage of reduction in discharge capacity by 2.35% relative to Wi/Wo=1.25 at higher discharges. However, this reduction was slightly small at low discharges. Furthermore, the percentage of reduction in discharge capacity for Wi/Wo=1 and 2 was 7 and 9%, respectively. Nevertheless, the Wi/Wo=0.8 has shown a higher decrease in discharge capacity with 12.8% in comparison to Wi/Wo=1.25. Figure 9 shows the tested PKW models under operation in this study.

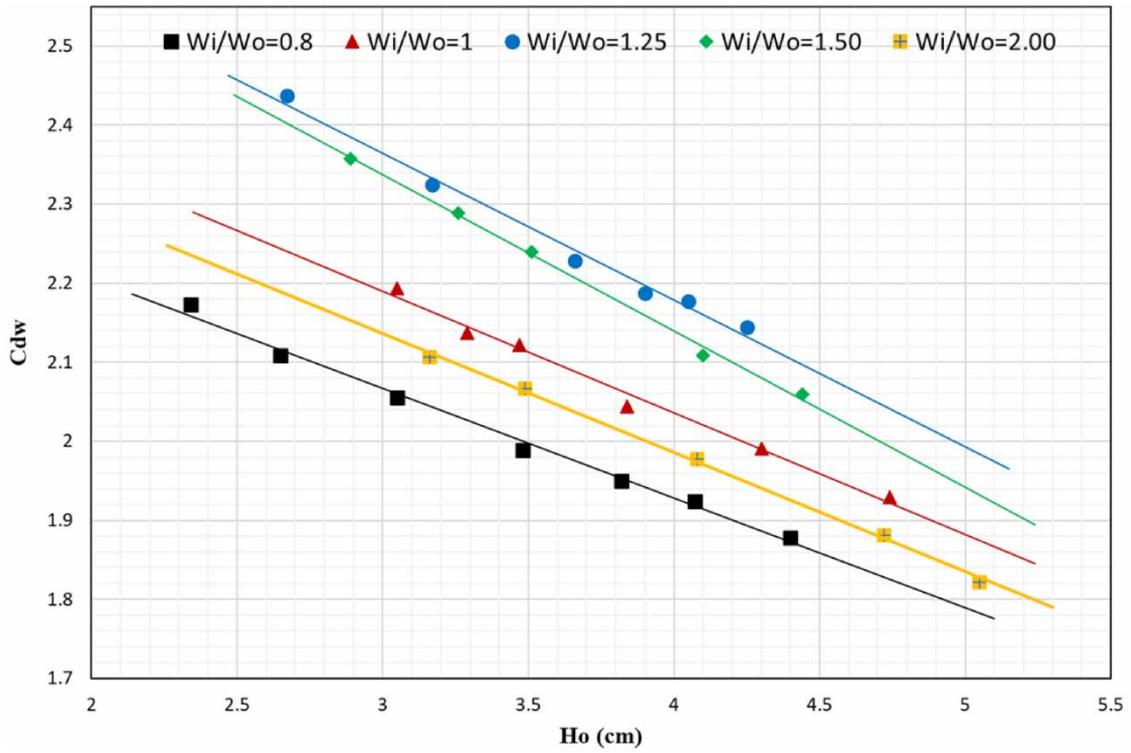


Figure 7 | The relationship between discharge coefficients with Ho under different Wi/Wo ratios.

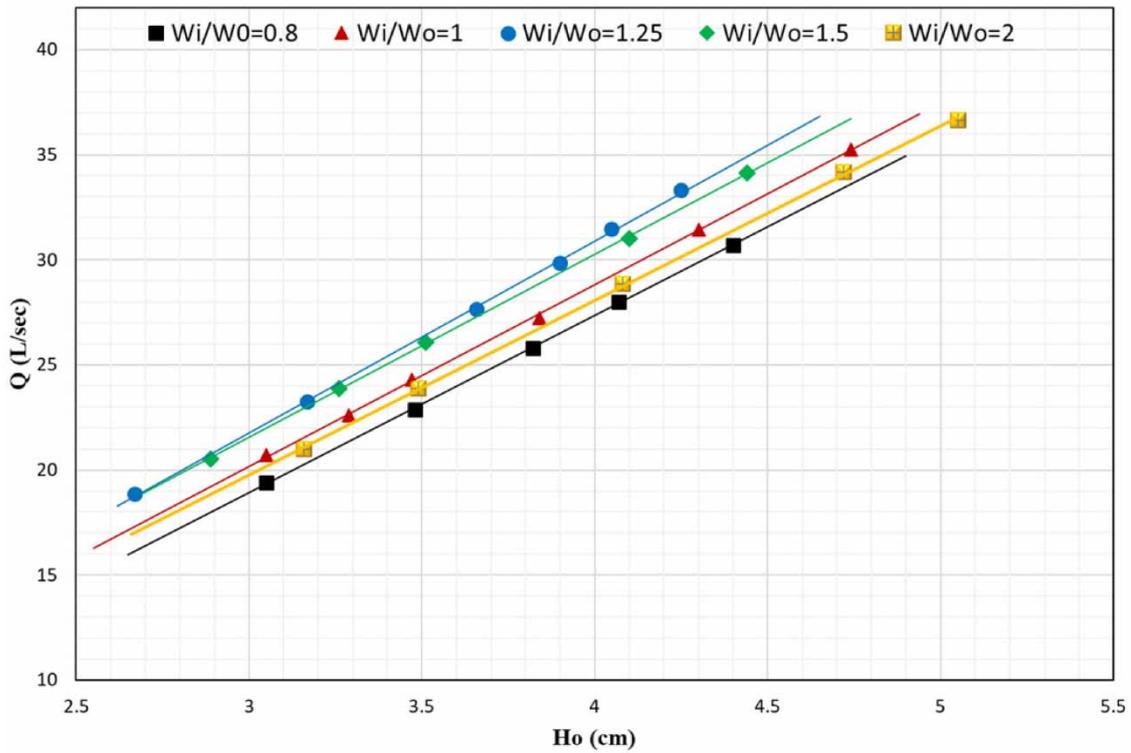


Figure 8 | Rating curves of PKW models.

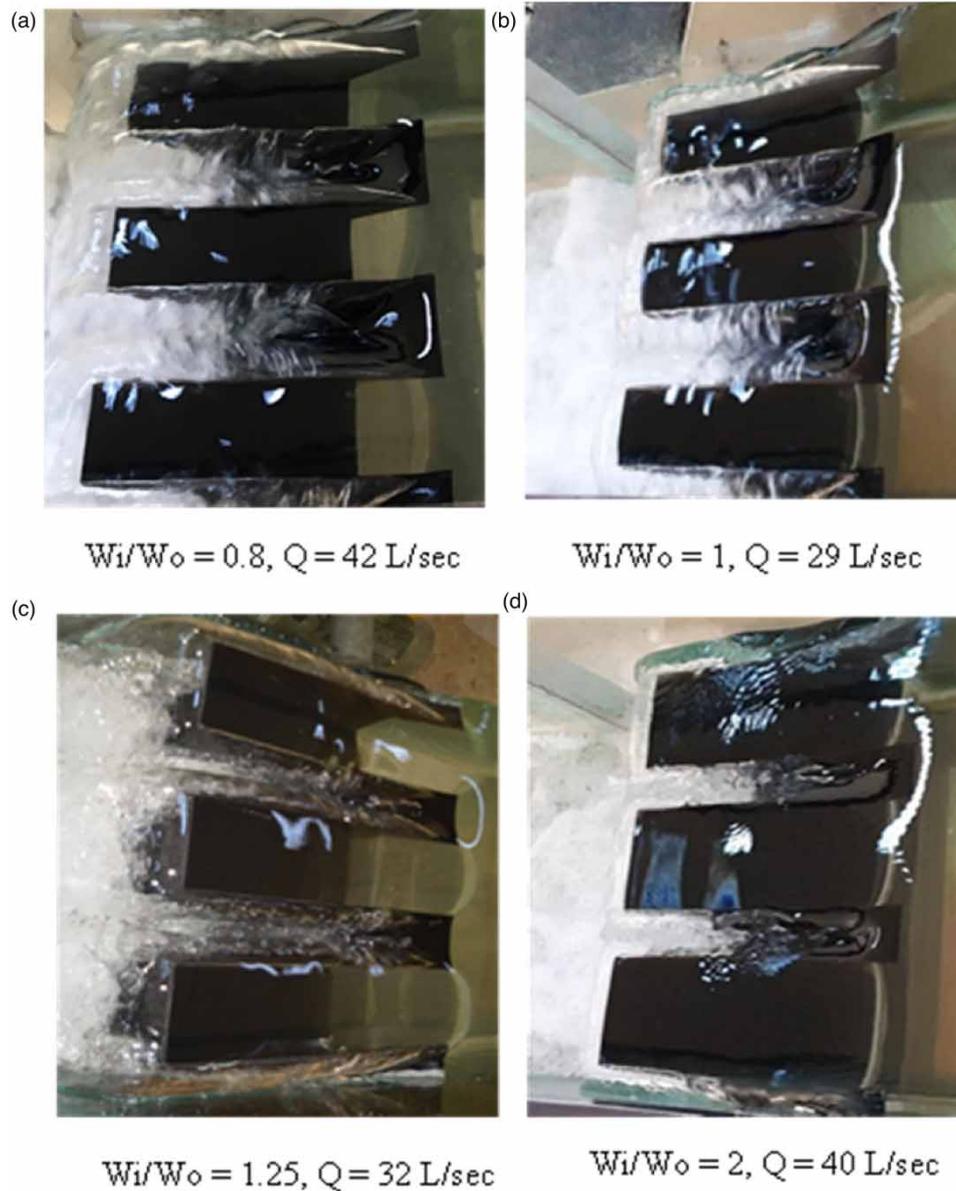


Figure 9 | PKW models under operation.

4.3. Discharge coefficients C_{dw} regression models

The tested PKW models' discharge coefficients with H_o/P can be determined using the linear regression determination as they show high correlation factors and as follows:

$$C_{dw} = x + y*(H_o/P) \quad (2)$$

where: x and y are coefficients of the Equation (2), which are given in Table 3. The equations in Table 3 are valid within the range of H_o/P given.

5. CONCLUSIONS

In this study, an attempt has been made to investigate experimentally the influence of W_i/W_o on the hydraulic performance of PKW in which the ratio has been changed five times ($W_i/W_o=0.81, 1.00, 1.25, 1.5, 2.0$) and the geometrical features were held constant for all models. Several conclusion points have been obtained from data analysis and they are listed as follows:

- i. The best hydraulic performance was obtained with W_i/W_o ratio equal to 1.25 because the obtained value of discharge coefficient was highest among the others.

Table 3 | Linear regression equations coefficients for the PKW models

PKW Model	x	y	R ²	Limitations
Wi/Wo=0.8	2.4683	-0.1361	0.9924	$0.1 \leq H_o/P \leq 0.25$
Wi/Wo=1	2.6141	-0.145	0.9839	
Wi/Wo=1.25	2.9265	-0.187	0.9928	
Wi/Wo=1.5	2.8896	-0.1861	0.9909	
Wi/Wo=2	2.5694	-0.1458	0.9942	

- ii. The variation of Wi/Wo from the ratio 1.25, either increasing or decreasing, has a negative impact on discharge coefficients and discharge capacity of PKW. It has been found that the percentages of reduction in C_{dw} for Wi/Wo=0.8, 1, 1.5 and 2 were 12, 7, 2 and 9%, respectively, relative to Wi/Wo=1.25. Similarly, in comparison with Wi/Wo=1.25 the percentages of reduction in discharge for Wi/Wo=0.8, 1, 1.5 and 2 were 12.8, 7, 2.35 and 9%, respectively.
- iii. The Wi/Wo=1.25 can be considered as close as an optimum ratio for rectangular PKW according to the results of this study and previous studies. This may enhance the selection of rectangular PKW with Wi/Wo=1.25 instead of non-rectangular PKW.
- iv. On the basis of the results of this study, it is recommended to avoid using a ratio of Wi/Wo less than 1 and higher than 1.5 in the design of PKW.
- v. The obtained results can be used as a good reference for validation of numerical model and the practical application for real hydraulic structure since the value of correlation analysis for each model close to unity.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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