CHAPTER 6 STUDY OF FLOW OVER PIANO KEY WEIR OF DIFFERENT PLAN SHAPES WITH FREE AND PARTIALLY SUBMERGED OUTLET CONDITIONS

6.1 Introduction

Any transverse structures constructed in the rivers or any flowing water body like dykes, bridges, weirs etc., tend to affect the natural flow (Yu et al. 2015) and hence create turbulence in the channel. The turbulence created in the open channel flow is also dependent on the shape of the channel, i.e., rectangular, compound or trapezoidal etc. (Pandey et al. 2019a; Pu 2019; Pu et al. 2020) and plays a vital role in the sediment transport within the channel (Singh et al. 2020)(Singh et al. 2020). The effect of Sediment scouring around hydraulic structures like bridges, piers, dykes has been studied by various researchers (Nhu et al. 2020; Pandey et al. 2020; Pandey et al. 2019b; Pandey et al. 2018). Weirs are also transverse hydraulic structures used extensively for water level moderation, channel stabilization, flow discharge measurement and control and environmental improvement. For achieving these goals, the weir must have high hydraulic functioning, structural feasibility and social sustainability. Since extensive studies of flow over weirs have established that weir's discharge capability depends mostly on the crest length, efforts to achieve the same have been carried out by various researchers over time. Optimizing the shape to achieve a hydraulically efficient design with less cost has to be studied to arrive at a solution.

Weir's self-cleaning ability is also an essential factor to be considered while evaluating a weir's life. Studies to achieve all such favorable outcomes have been carried out in the past, leading to different weirs' evolution.

Experimental and Numerical Studies on Labyrinth weirs continue to better understand the flow around these structures (DANESHFARAZ et al. 2020; Ghaderi et al. 2020a). Labyrinth weirs were also studied for their different plan geometries (Ghaderi et al. 2020b) and their use as a side weir (Abbasi et al. 2021). PKW is considered to be a modified form of labyrinth weirs. A review of the piano key weir has shown to be quite efficient compared to its counterparts (Abhash and Pandey 2020). It has higher discharge capacity as compared to improved labyrinth weir (Anderson and Tullis 2012c; Anderson 2011; Blancher et al. 2011; Lempérière et al. 2011), it is very economical (Noui and Ouamane 2011; Ouamane 2011; Paxson et al. 2013) as well as much higher self-cleaning ability (Abhash and Pandey 2021a; Noseda et al. 2019; Sharma and Tiwari 2013). PKW has also been shown to allow for recovery of global storage volume and risk of non-opening of gates in spillway use (Lempérière and Ouamane 2003). The gated piano key weir's discharge coefficient has also been studied (Akbari et al. 2019; Paxson et al. 2013).

The discharge coefficient of an RPKW & TPKW can be found from the standard weir equation:

$$Q = \frac{2}{3} Cd\sqrt{2g}\, LH^{1.5} \tag{6.1}$$

Where $C_d = f(\frac{H}{P}, \frac{L}{W}, \frac{Wi}{Wo}, \frac{B}{P}, \frac{Bo}{B}, \frac{Bi}{B})$

Researchers have tried to find and refine empirical equations that can be used to find the discharging capacity of PKW.

Crookston et al. (2018) examined two design approaches (a) empirical equations (simple and complicated) and (b) CFD studies used by researchers to estimate the discharge from PKW. They have further contributed to the already available empirical equations and co-related the CFD data using forty simulations. Submergence of a weir is defined when the tailwater exceeds a specific limit above the weir's creat to increase the upstream head for a given discharge. Submergence relationships have been studied by researchers (Borghei et al. 2003; Maghsoodi et al. 2012; Thornton et al. 2011; Villemonte 1947). Labyrinth weir was also studied for submergence criteria (Carrillo et al. 2020; Tullis et al. 2007).

Khassaf and Al-Baghdadi (2018) experimentally studied the behavior of piano key weir under submerged flow conditions. They concluded the discharge reduction factor (Cs) to be mainly influenced by the submergence factor ('S'). The discharge reduction factor (*Cs)* is influenced negligibly by the parameters L/W, Bi/B & P_d/P, where P_d is the dam height.

Kabiri-Samani and Javaheri (2012) also performed an experimental study on free and submerged flow in PKW conditions and gave analytical formulas. They conducted a submergence test on each weir configuration, and by sensitivity analysis, the relevant parameters for free (C_d) and submerged flow conditions (C_s) were analyzed. The submergence studies of Piano Key Weirs have also been carried out in the past(Dabling and Tullis 2012; Javaheri and Kabiri-Samani 2012; Maghsoodi et al. 2012; Sharma and Tiwari 2013; Shemshi and Kabiri-Samani 2012)

Various researchers in this field have always pondered the advantages of numerical study. A numerical study has the advantage of lower cost and time savings incurred in evaluating each physical prototype. However, this does not necessarily obliviate the need for physical modeling. Physical modeling is required for the validation and verification of the results of CFD. Complex flow geometry of PKW, sediment transport capability, aeration requirements, site conditions, downstream energy dissipation etc., presents limitations along with the scaled physical models used in Labs. Hence, the growing need to combine the CFD and physical models has become necessary to combat the limitations and present a thorough understanding of factors involved in the study of flow around PKW. Various numerical study to determine the effects of physical parameters on discharge efficiency of PKW has been studied by researchers (Abhash and Pandey 2021b; Abrari et al. 2015; Bremer and Oertel 2017; Chahartaghi et al. 2019; Cicero et al. 2013; Eng and Lennart 2018; Erpicum et al. 2012; Ghasemzadeh et al. 2015; Hu et al. 2018; Oertel 2015).

The side weir flow characteristics of PKW, Labyrinth and Linear weir have been compared & presented by (Karimi et al. 2018). The rectangular plan geometry of PKW has been studied most by researchers. Other plan forms like trapezoidal or arched still need further experimental research to understand their flow hydraulics.

The present study focuses on the two different plan forms of PKW, i.e., RPKW and TPKW9, for their head discharge relation in a wide channel of 0.984 m width in free-flow conditions. The study was conducted to find the hydraulic efficient plan form among the two. A numerical study was also conducted to ascertain if it can correctly predict the flow around PKWs. Further, the tailgate was closed to render the outlets of PKWs partially to fully submerged and see its effect on discharging capacity and changes in the upstream head.

6.2 Methods

6.2.1 Experimental setup

The PK weir testing was conducted in a laboratory flume measuring a magnitude of 0.984 m wide, at 0.5 m deep and 24m long. The flume bed and sides were made of bricks plastered with fine sand and punning. After being collected in a tank, water entered the flume separated by a vertical baffle wall to create a relatively uniform approach flow condition. The PKW was installed at a distance of 7 m from the tank with a baffle wall. The tailgate was positioned 8 meters beyond that. Finally, the water was made to fall into another stilling well before reaching the linear weir for the discharge measurement. The Linear weir was also positioned at a distance of 8 meters from the stilling well. After flowing over the linear weir, the water collected into the underground sump from which it was pumped back into the flume.

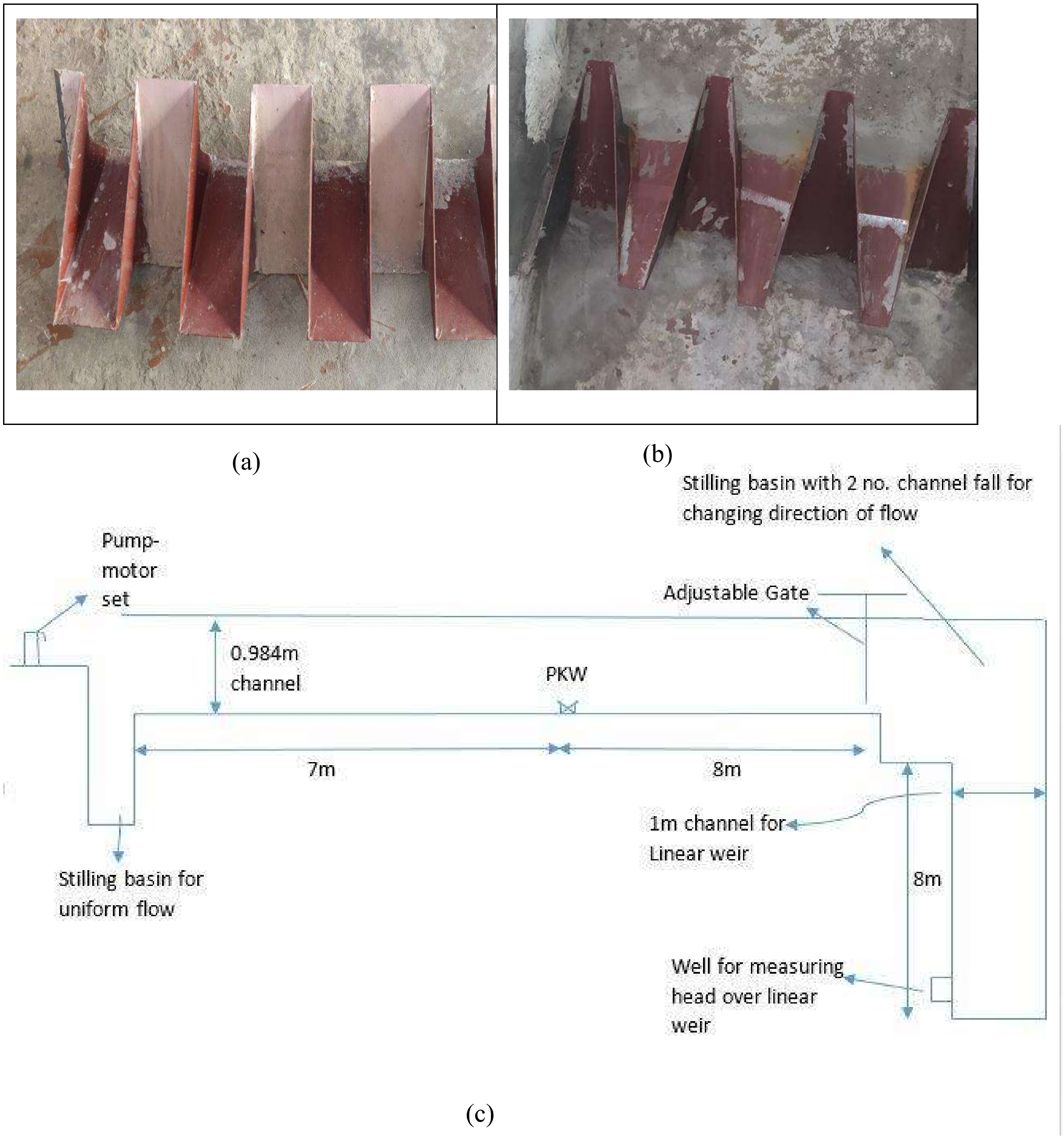


Figure 6. 1 Models used in the experimental study (a) RPKW (b) TPKW9 & (c) Experimental setup

The models used in the experimental study are presented in Figs. 6. 1(a) & 6. 1(b). The experimental setup is as shown in Fig. 6. 1(c). Table 6.1 summarizes the different models and their dimensions used for the study. Four cycles of PKW were used for all the models in the study. A total of ten discharge measurements were made for each PKW model. The water head was measured with the help of a point gauge with ± 0.1 mm reading accuracy.

The entire setup rested upon an underground sump from where water was circulated in the channel. The experiment was run for free overflow and partial closure of gates to produce partial to complete submergence of outlets of PKW. The head was measured from the well-installed near the linear weir, and the discharge was then read from the graph available in the Hydraulics lab of IIT (BHU), Varanasi. The discharge was varied from as low as 3L/s to 40 L/s.

Table 6. 1 Geometric parameters of PKWs

PKW Types	P (mm)	B (mm)	B_i (mm)	B_o (mm)	B_b (mm)	W_i (mm)	W_o (mm)	α(deg)	No. of cycles
RPKW	150	400	100	100	200	122	122	0	4
TPKW 9	150	400	100	100	200	24	78	9	4

6.2.2 Numerical Setup

Numerical simulations were performed on the ANSYS-Fluent platform, and the results were compared to the experimental results. Reynolds-Averaged Navier Stokes Equation using the Finite Volume Method was used to solve the problem numerically.

The simulations were performed on a 20 core CPU using a parallel solver option and double precision. Flow over PKW and TPKW9 were modeled on half PKW with a channel height of 0.5m. A total length of 3.0 m was created for the numerical simulations with an upstream length of 2.5 m. Mesh near PKW was refined further so that discretization error could be reduced. A total of 1.35 million mesh cells were introduced in the channel for our study. The same meshing technique was adopted for the two geometries to ensure a standard reference. The top and outlet were specified as 'pressure outlets,' while the inlet was specified as 'velocity inlet.' Both sides of the channel were taken as 'symmetry,' while the bottom and PKW were treated as 'walls.' The numerical study was carried out for four discharges (6.67 L/s, 12 L/s, 20 L/s and 29 L/s) in free-flow conditions. Each of these discharges was selected as they mark a change in the nappe flow over the PKW.

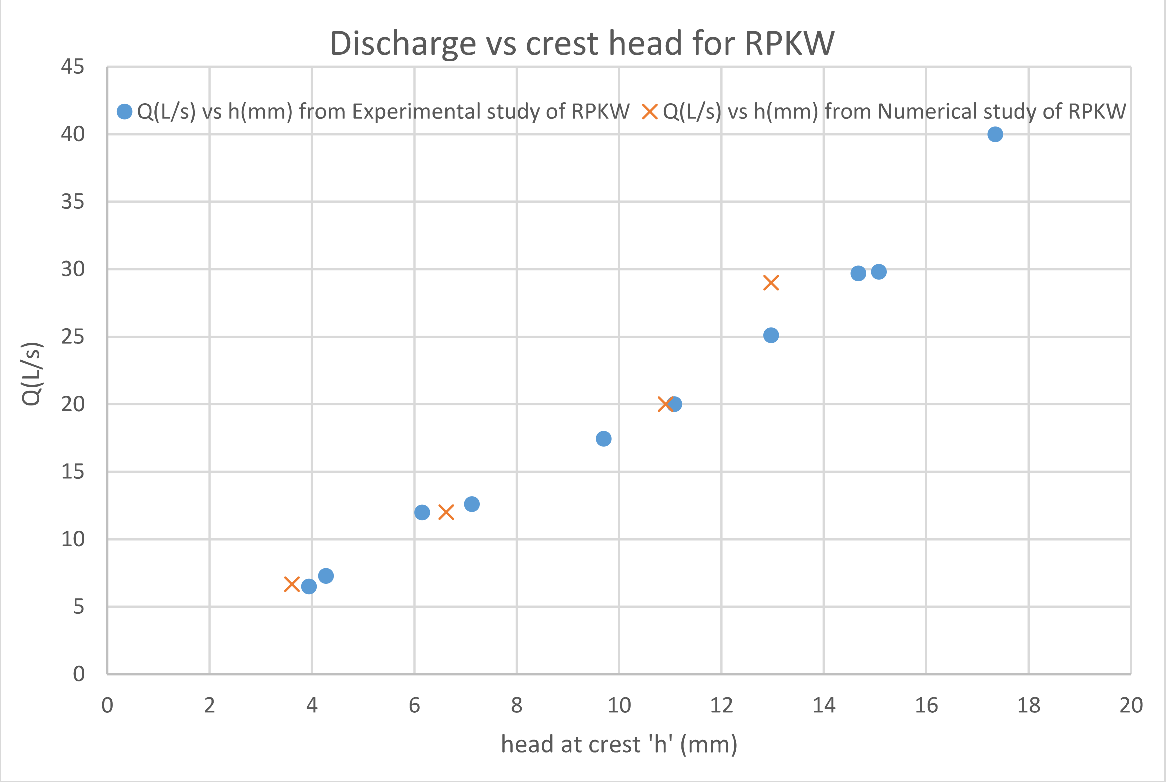
The flow over PKW has been categorized as a transition from a clinging nappe to leaping and then to a springing nappe flow for different values of the H/P ratio. Machiels et al. (2011b) had established that for H/P between 0.09 and 0.1, the nappe on the lateral crest is free, while for $0.16 \leq H/P \leq 0.17$ on the downstream crest of the inlet, the nappe is wholly aerated. Changes in nappe of flow have been observed in our experimental and numerical study.

The PISO k-Ɛ model was selected for the study as per the references available. The time step was kept small at 0.0005 and was varied to 0.005 seconds with 20 iterations to reduce the linearization error. The equations were solved numerically, making use of the conservation of mass and momentum for all flows.

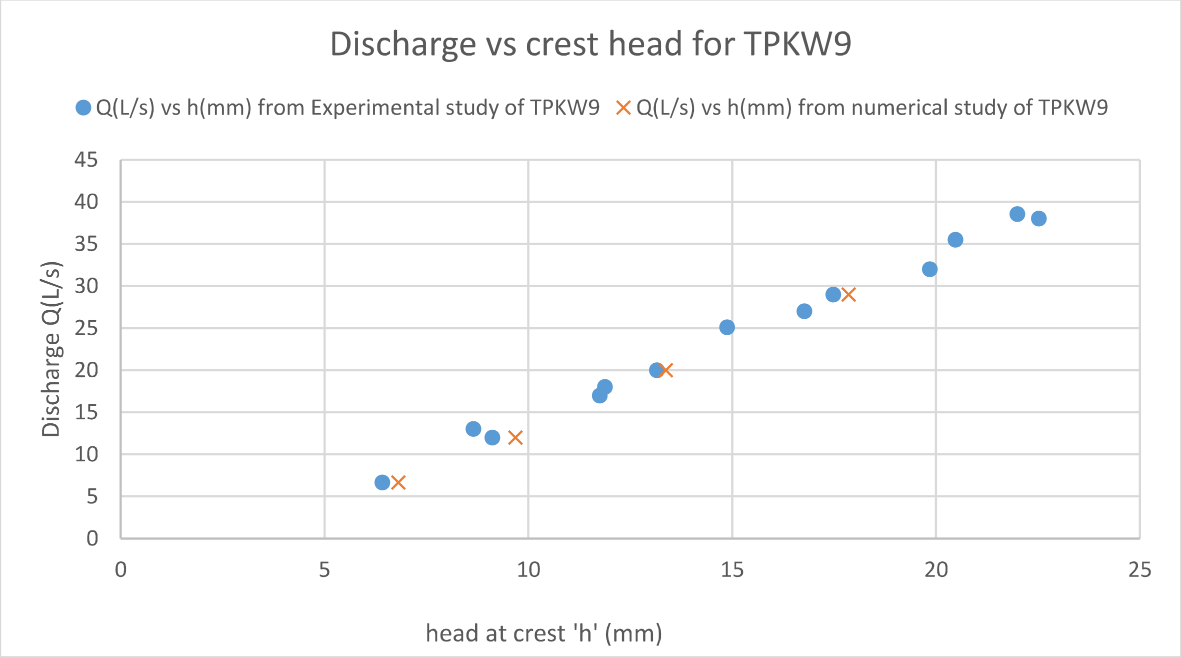
6.3 Results and Discussions

6.3.1 Discharge-Head Relationship of PKW Models

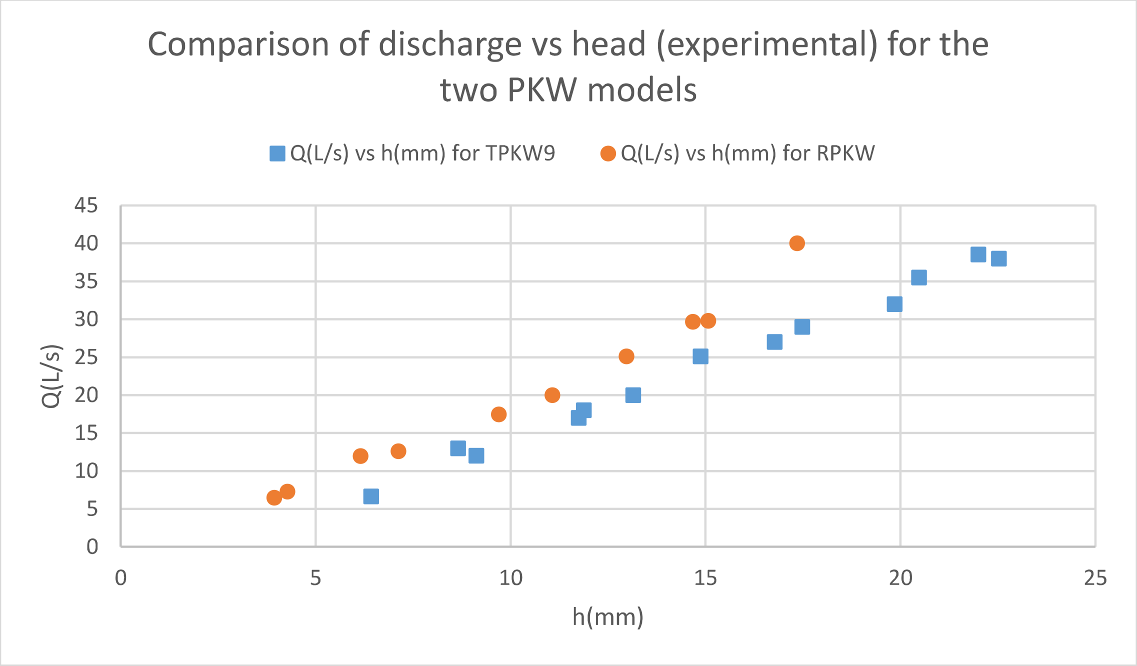
Discharge (Q) vs. head at the crest (h) for RPKW has been plotted in Fig. 6. 2 (a). The numerical results of the four discharges have also been plotted to compare the experimental and numerical results. Similarly, Fig. 6. 2 (b) illustrates the discharge-head relationship of TPKW9 and compares the numerical results with the experimental study. Both the result shows the numerical study to be in close proximity with the experimental results. The errors are well within the permissible limits.



(a)



(b)



(c)

Figure 6. 2 (a) Comparison of an experimental and numerical study of discharge vs. head at the crest for RPKW (b) Comparison of an experimental and numerical study of discharge vs. head at the crest for TPKW9 & (c) Comparison of experimental discharge vs. head at the crest for RPKW and TPKW9

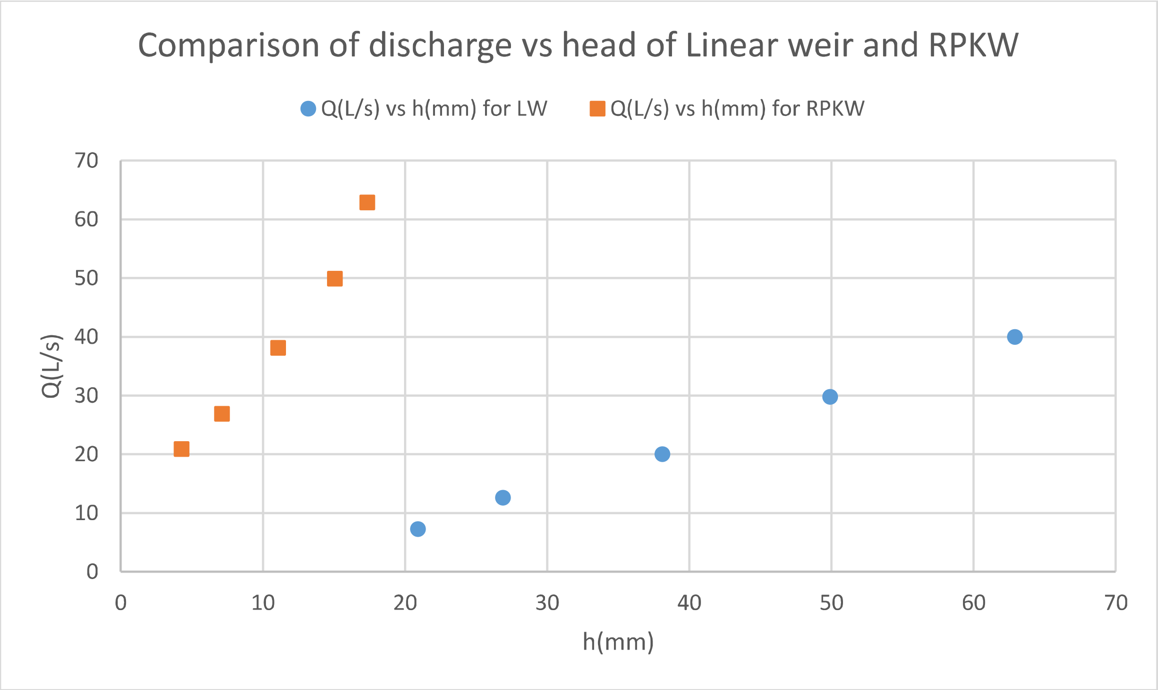
A comparison of the RPKW and TPKW9 discharge-head relationship has been plotted in Fig. 6. 2 (c). The results show RPKW to be more hydraulically efficient than TPKW9 for the same number of cycles and upstream-downstream distance (B) and the same channel width.

The efficiency of an RPKW and TPKW9 has also been compared with a linear weir. The comparison has been shown in Fig. 6. 3 (a) & 6. 3 (b), for RPKW & TPKW9, respectively. PKWs, at higher heads, tend to behave like a linear weir. Hence, the comparison of PKW(Q_{PKW}) as compared to a linear weir with the same width W(Q_W) further illustrates the superiority of PKWs

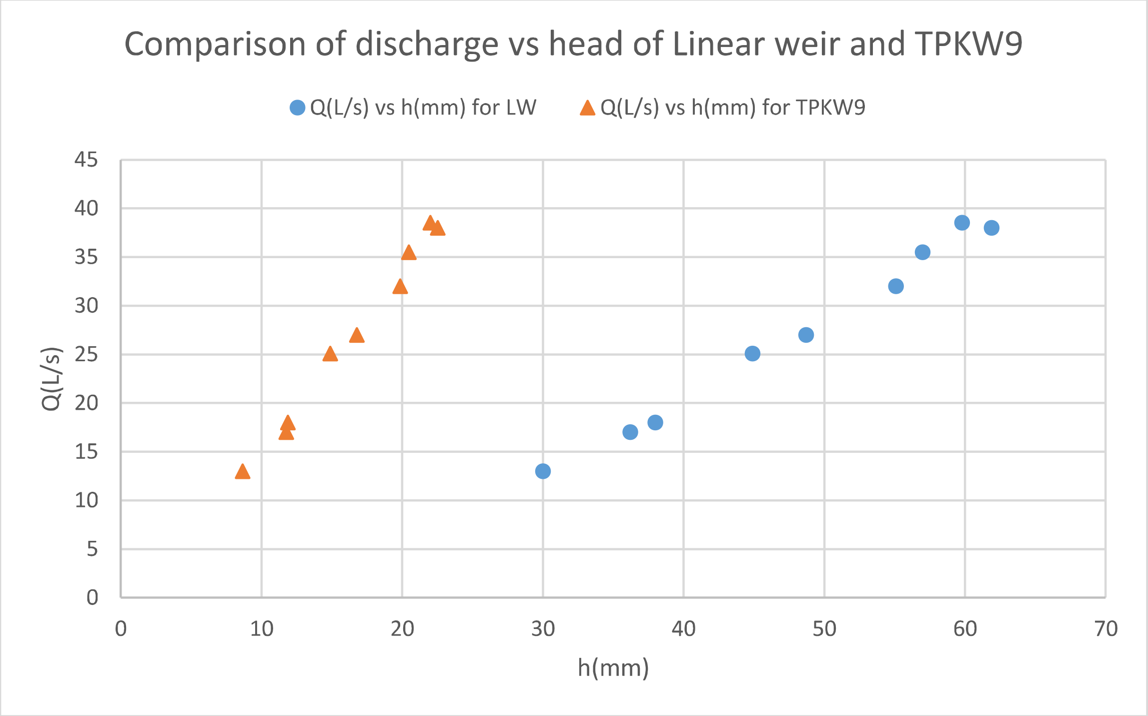
6.3.2 Observations Under Partial to Full Submergence of the Outlet of PKW

RPKW and TPKW both were observed for partial and complete submergence of outlet portions of PKWs. The gate was partially closed to create partial submergence in the outlets of PKWs. The outlet was fully submerged in three stages to observe any changes in the head over the crest of PKWs or the upstream head. The water upon raised downstream first begins to rise in the outlet slope. The rapid water falling from the outlet meets the still water downstream, and dissipation of energy takes place at the downstream outlet of PKWs (Figs. 6. 4 (a) & 6. 4 (b)). The water falling from the inlet forms a beautiful water film all along the crest length of PKW. This water film's shape is governed by the plan form of PKW as shown in Figs 6. 5 (a) and 6. 5 (b), respectively, for RPKW and TPKW9.

The water level downstream rises but without affecting the head on the crest of PKW.



(a)

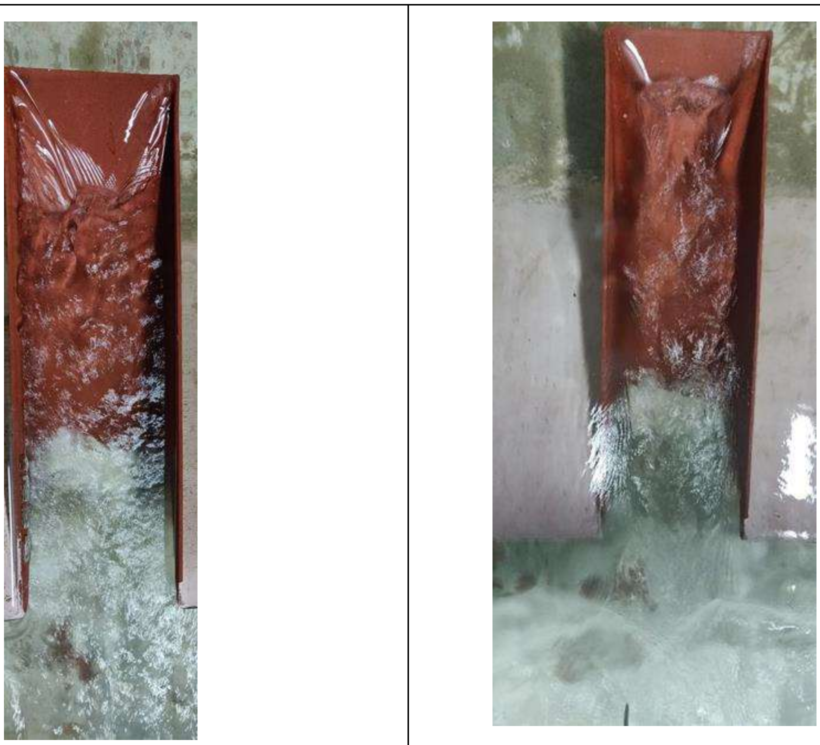


(b)

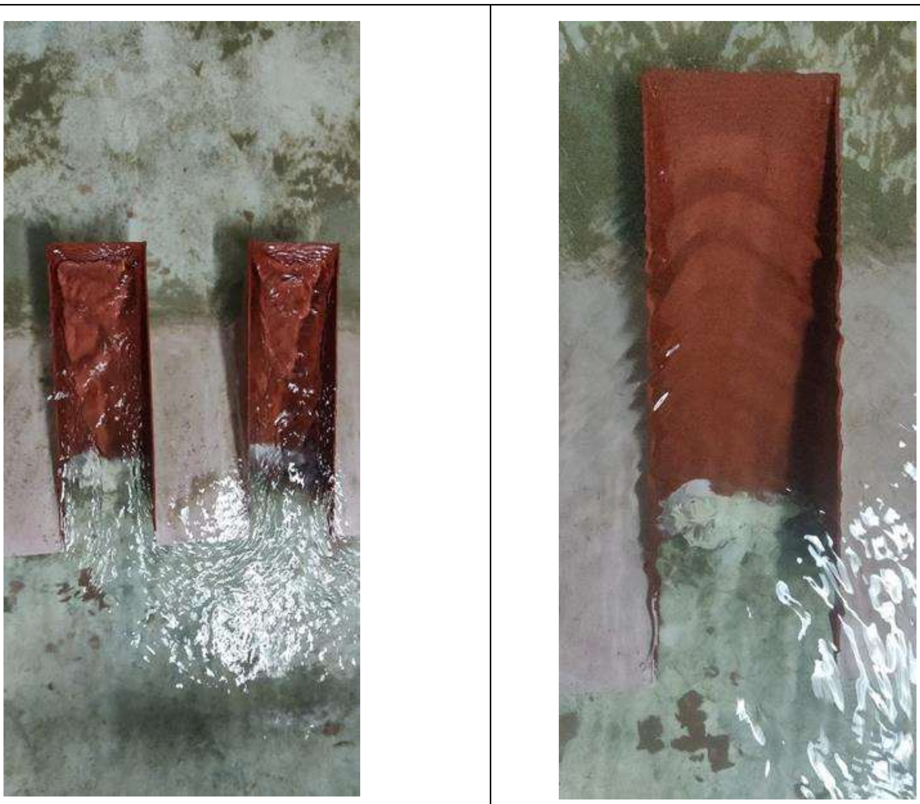
Figure 6. 3 Comparison of experimental discharge vs. head at the crest for RPKW with that of a linear weir (b) Comparison of experimental discharge vs. head at the crest for TPKW9 with that of a linear weir

The head over the crest was measured at all these stages to detect any changes. On further increasing the downstream water level by closing the gate further, the triangular wedge as seen in both RPKW and TPKW9 changes into a rectangle with a curvy boundary, as shown in Figs. 6. 4 (b) and 6. 4 (c).

We can see in Fig. 6. 4 (c) that about 80 % of the PKW outlet is submerged. The curvy rectangular boundary has a distinguish ring formation connecting one outlet of PKW to another. The rings become furthermore distinguished, as shown in Fig. 6. 4(d) when almost 95% outlet is submerged. The head over the crest, though, remains the same for both PKW and TPKW9 cases. Upon further closing the gates, we can see these rings die down. Small ripples of waves are visible, like in Fig. 6. 4 (f), which ultimately get drowned as the downstream water level fully submerges the outlets of PKW.



(a) (b)



(c)

(d)

Figure 6. 4 Different stages in submergence of the outlet of RPKW

(a) Continuous water film running around inlet-outlet of RPKW

(b) Continuous water film running around inlet-outlet of TPKW9

Figure 6. 5 Continuous water film in PKWs under partial submergence

6.4 Conclusions

PKWs are considered more hydraulically efficient than their counterparts both in new construction and in dam rehabilitation. They are structurally efficient, economical and present higher self-cleaning abilities. An experimental study was carried out on two different plan forms of PKW, i.e., RPKW and TPKW9, to determine their hydraulic efficiency. The graph of discharge vs. head was plotted for each weir geometry. Also, the head was compared with a linear weir since, at higher heads, PKW tends to behave like a linear weir. A numerical study was also done on four of these experimental discharges using ANSYS-FLUENT to study its relevance in predicting flow around complex structures like PKW. The experimental values and numerical values were compared for errors. The experimental study showed RPKW to be more hydraulically efficient than TPKW for the same number of cycles in fixed channel width. The interference wedge was more prominent in the TPKW plan. The nappe was clinging in nature for most of the discharges for both the plan geometries. The discharging capacity of both the plan forms of PKW was much higher than Linear weirs. The study using

ANSYS suggested that numerical simulations can predict the flow around PKWs accurately and within permissible error limits, thereby saving cost, time and economy. The outlets of PKW were partial to fully submerged by closing the tailgates, and patterns emerging from this closure were studied. The study showed that partial to full outlet submergence had a negligible effect on the head measured at the crest of PKW within the experimental limits of the h/P ratio. Head over the crest of PKW increased only after complete submergence of outlets of PKW and downstream water level being higher than the height of PKW (P). The present study hopes to contribute to the literature on developing and refining discharge-head empirical equations for RPKW & TPKW. Sediment passage in the upstream and scour formation in the downstream need to be studied for different plan geometries of PKW. Energy dissipation is another area that demands attention for these PKW geometries. A combination of experimental and numerical studies will lead to a better understanding of these grey areas in the future.