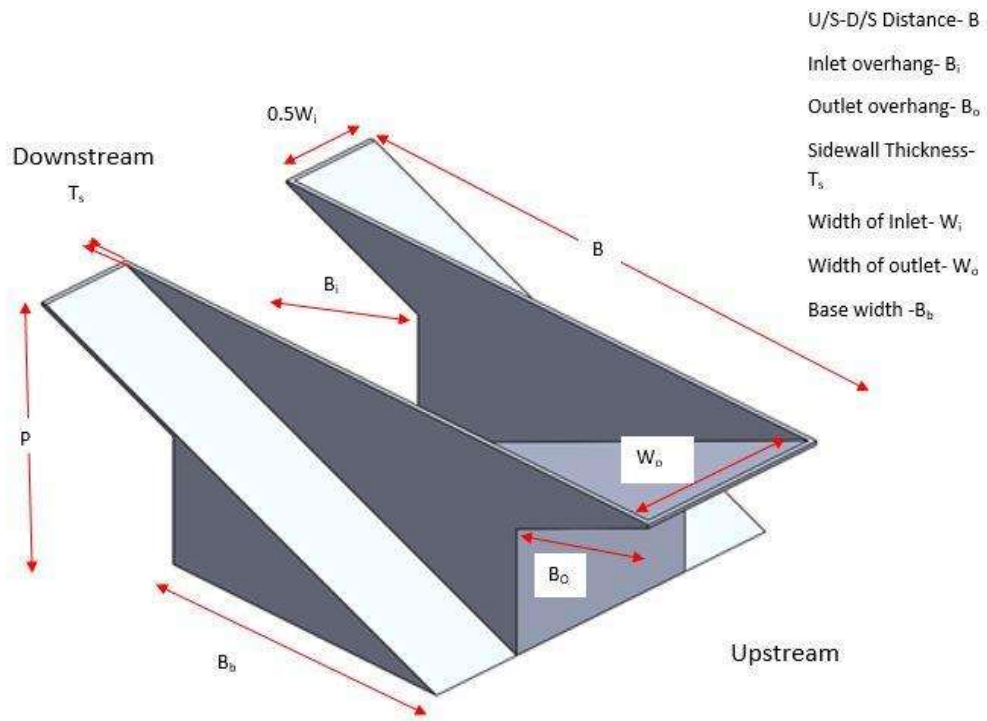


CHAPTER 5 EXPERIMENTAL AND NUMERICAL STUDY OF DISCHARGE CAPACITY AND SEDIMENT PROFILE UPSTREAM OF PIANO KEY WEIRS WITH DIFFERENT PLAN GEOMETRIES

5.1 Introduction

Weirs are hydraulic structures built across a river (or stream) to raise the water level upstream and to release the excess discharge downstream efficiently. Weirs have been classified according to the shape of openings, the shape of crest or discharge conditions. Piano Key Weir is an excellent alternative to its counterparts in dam rehabilitation and river and streamflow conditions. PKWs are free-flow weirs allowing the excess floodwater to pass downstream with a lesser upstream level than for a gated dam when the reservoir is lower than the natural level of an extreme flood (Lempérière et al. 2011). A naming convention for a PKW was proposed by Pralong et al. (2011) (Fig. 5. 1(a)). Leite Ribeiro et al. (2011) established the width of the inlet key (W_i) as the most critical parameter instead of the developed length ratio (L/W) for a given value of H/P ratio, affecting the flow where 'W' is the total width of the weir/channel (m), 'H' is the head upstream at sufficient distance from PKW and 'P' is the height of PKW.

Kabiri-Samani and Javaheri (2012) conducted extensive experiments on rectangular PKW for both free and submerged flow. After regression analysis, they proposed a relation for discharge-coefficient, which is a function of H/P , L/W , W_i/W_o , B/P , B_o/B and B_i/B and valid within experimental limits. Ribeiro et al. (2013) found L , W , H and P to be the key parameters controlling the discharge through PKW. All these experiments were done with a rectangular plan of PKW.



(a)

U/S-D/S
 Distance- B

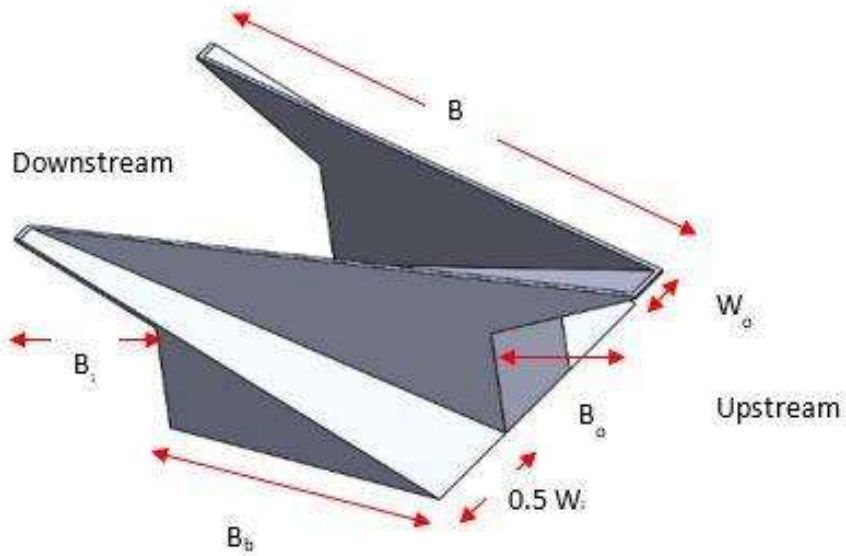
Width of Inlet-
 W_i

Width of outlet-
 W_o

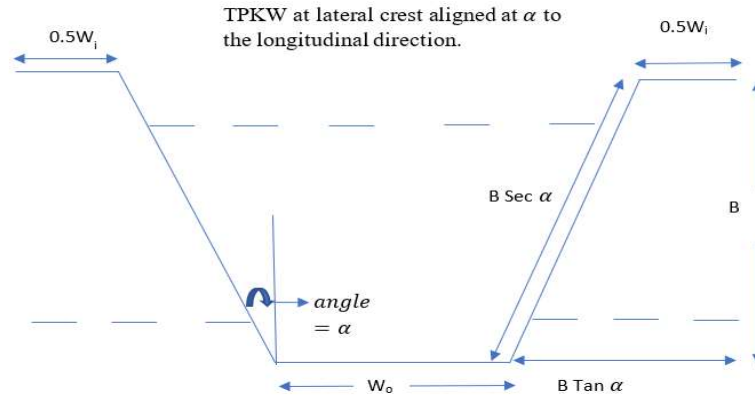
Base Width- B_b

Inlet overhang-
 B_i

Outlet
 overhang- B_o



(b)



(c)

Figure 5. 1 (a) Geometric parameters of an RPKW, (b) Trapezoidal PKW nomenclature & (c) A single TPKW unit plan in terms of the net decrease in the developed length (L).

Later PKWs with different plan shapes such as Trapezoidal PKW (TPKW) or Arced PKW (Allahdadi et al. 2021; Karamvand et al. 2020) were studied for their hydraulic characteristics. Trapezoidal Piano key weir (TPKW) is a type of PKW with a Trapezoidal plan shape instead of the Rectangular plan shape. The basic unit of TPKW has been discussed by Mehboudi et al. (2016). They presented a naming convention for the TPKW unit, as shown in Fig. 5. 1(b) and suggested a 22% increase in the discharge capacity with the same developed length (L) as of RPKW. Khassaf and Al-Baghdadi (2015) studied different non-rectangular geometry of PKWs with varying angles to find associated discharge coefficients.

For the same number of cycles in a PKW with constant channel width (W), the discharge in RPKW is higher due to a higher value of the developed length (L) than TPKW. TPKW cannot compensate for a decrease in development length due to a decrease in the width of inlet and outlet keys. This decrease in the width of the inlet and

outlet keys of TPKW is due to the alignment of the lateral crest at an angle α from the longitudinal direction. (Fig. 5. 1(c)).

The increased discharge is because for the same no. of cycles' n' in a PKW with constant channel width (W), aligning the lateral crest of PKW changes its developed length (L). The increase in the lateral crest length for one-unit PKW due to angle α if the upstream-downstream length is fixed as B is given by:

$$\Delta Increase = 2B(\sec\alpha - 1) \quad (5.1)$$

The decrease in the corresponding width of inlet-outlet keys contributing to the developed length (L) of the TPKW is

$$\Delta Decrease = 2BTan\alpha \quad (5.2)$$

Hence the net decrease in the Developed length (L) for a single unit PKW is given by

$$Net\ decrease\ in\ developed\ length = 2B(Tan\alpha - Sec\alpha + 1) \quad (5.3)$$

The discharge capacity of PKWs is often compared with a linear weir because at increased heads, it tends to behave like a linear weir. Therefore, the discharge capacity of PKWs is often expressed by relative ratio $r = Q_{PKW}/Q_W$, where Q_{PKW} and Q_W are discharges through PKW and a linear weir with the same channel width (Ribeiro et al. 2007).

$$r = Q_{PKW}/Q_W \quad (5.4)$$

where P_i is the height of the inlet of PKW.

Increasing water depth upstream and the accompanying decrease in the flow velocity near an obstruction like a weir causes sediments to settle down upstream of the weir.

The self-cleaning capacity of weirs as such plays a critical role in ascertaining the life of a reservoir. Hence the question arises which type of weir is more self-cleansing in nature. Falvey (2003) gave a comprehensive overview of the hydraulic investigations on different weir plan geometries. Belzner et al. (2016) focused on the hydraulic

comparison between triangular, trapezoidal and rectangular labyrinth weirs under the same boundary conditions. Rectangular and trapezoidal Labyrinth weirs were also studied for their self-cleaning nature experimental studies (Gebhardt et al. (2018); Herbst et al. 2018). Their study revealed that the Froude number is the dominant parameter affecting the scouring action. The self-cleaning process for the rectangular plan started at a lower discharge as compared to the trapezoidal plan.

Sharma and Tiwari (2013) have established in their study that as the flow approaches PKW, the vertical component of velocity in the region close to bed increases, which helps in upward lift generation, thereby lifting the sediments and helping them pass over the weir. Jüstrich et al. (2016) have studied the scour formation and ridge generation downstream of PKW and presented a prediction model for the same. Nosedá et al. (2019) studied the upstream erosion and sediment passage over PKW and observed 88% removal just after two hours of flow. However, all three models had a rectangular plan geometry.

Kumar et al. (2021a) studied the discharge characteristics of Piano Key Weirs with and without upstream siltation with Type-A PKW models with noses below the upstream apexes. They suggested that the upstream siltation had no impact on the discharge efficiency of submerged PKW but observed a maximum reduction of 4% under free-flow conditions. They even proposed equations for free-flowing PKWs with errors well within permissible limits.

Kumar et al. (2021b) further investigated the mechanics of movement of singular quartz gravel and coarse riverbed particles upstream and over the inlet key of three Type-A PKWs. Rolling and saltation regimes were observed over the key, and the CFD simulations showed a rapid increase in shear stress at the key end.

Kumar and Ahmad (2020) conducted an experimental investigation on a three-cycle

PKW to study the scour pattern downstream of inlet and outlet keys with and without a solid apron. The study suggested that falling and impringing jets originating from inlet and outlet keys were liable for the formation of dip and ridge downstream. Scour formation was negligible for high submergence downstream, and the presence of a solid apron downstream led to a significant reduction in scour.

It has already been observed that PKW is a highly self-cleaning weir. They are excellent in transporting sediments over to the downstream side and are better than labyrinth weirs and weirs of other plans and shapes like linear weirs. Much research has been done on Rectangular PKWs, but only a few have been dedicated to Trapezoidal PKWs. In the present work, experimental and numerical studies have been carried out for studying the head-discharge relationship of both RPKW and TPKWs (TPKW 6 & TPKW 13). The results have been compared for finding the hydraulically superior plan form. Further, the sediment transport capabilities of PKW of two different plan shapes (RPKW & TPKW6) are investigated by studying the bathymetric profile upstream of the weir through experiment and the study of vertical velocity component through CFD. Critical locations have also been identified where the scouring mechanism is highest.

5.2 Experimental Setup

Experiments were performed in a straight reach channel at the IIT (BHU) Hydraulics lab, Varanasi. A photographic view of the experimental setup for studying the weirs' discharge capacity is shown in Fig. 5. 2 (a) & Fig. 5. 2 (c). The channel was 0.4 m wide and 3.5 m long. The channel sidewalls were fabricated with perplex glass, and the bed was rigid. The channel width was fitted with two PKW units in each experimental run, sufficient to provide representative results independent of the number of keys (Ribeiro et al. 2012).

The water was first collected in a tank, which was then allowed to flow in the channel

using gates. The discharge was calculated from a 35 cm wide rectangular weir at a sufficient distance from downstream of PKW. The experiment was run for about eighteen discharges for all three plan geometries (RPKW, TPKW6 & TPKW13), with discharge rates varying from 1.1 L/s to 45 L/s.

For comparing the sediment transport capability of PKW with rectangular and trapezoidal shapes in river flow conditions, fine Ganga sand was filled up to the height of PKWs as shown in Fig. 5. 2(b). The considered sediment bed length was 2 m with a 0.5-meter ramp provided at the channel inlet, hydrodynamically shaped to avoid model effects. Three discharges of 3.38 L/s, 7.06 L/s & 15.36 L/s to study the sediment carriage capacity of these PKWs have been carried out.

The models were tested for free overflow. The sand granulometry analysis was done in the IIT(BHU) soil mechanics lab, Varanasi, and has been given in Table 5.1.

Table 5. 1 Properties of sand used in the study

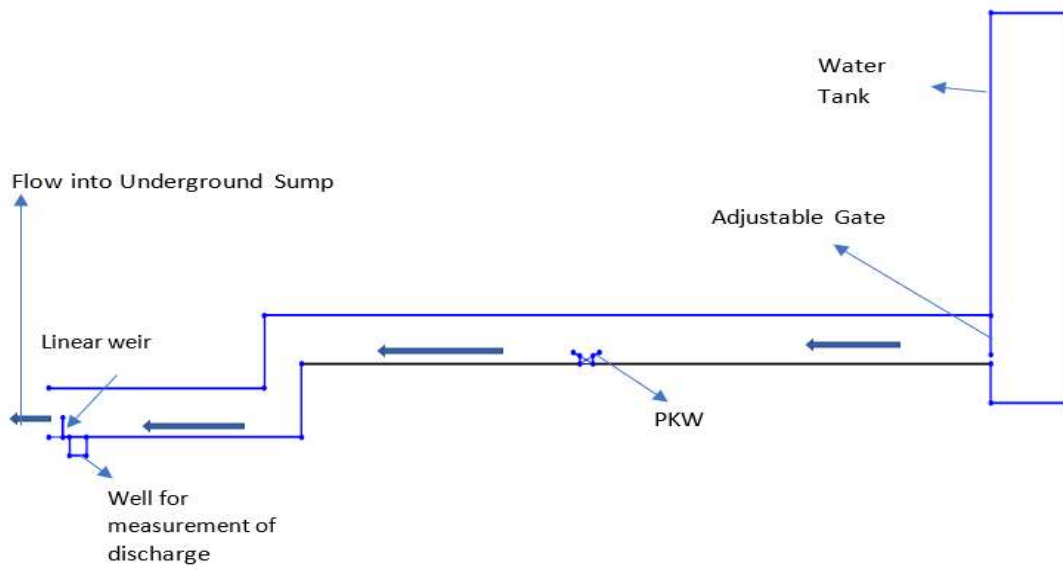
Sl. No.	Particle size (mm)			Source
	D ₁₀	D ₃₀	D ₉₀	
1	0.1	0.138	0.195	River Ganges

The point gauge was used to measure the water surface depth and bathymetric profile at one and two hours from the experiment's start with an accuracy of ± 0.1 mm. The vertical profile was measured along the longitudinal length and transverse length at four points up to a distance of 1.3 meters. Table 5.2 summarizes the geometric parameters of the basic units of RPKW and TPKW used in this study. The weir geometries are PKW 'A' type, which has an equal overhang in the upstream-downstream side.



(a)

(b)



(c)

Figure 5. 2 Experimental setups for (a) free flow and (b) sediment carriage study & (c) Experimental Layout of Lab

Table 5. 2 Geometric parameters of PKWs

PKW Type	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	121	325	81	81	163	97	97	0	2
TPKW 6	121	325	81	81	163	114.5	63	6	2
TPKW 13	121	325	81	81	163	135	23	13	2

5.3 Numerical Setup

Numerical simulations using the ANSYS-Fluent software platform have been performed to compare with the experimental results. This code has been used to solve the Reynolds-Averaged Navier Stokes Equation using the Finite Volume Method. ANSYS FLUENT makes use of the conservation of mass and momentum to solve equations for all flows.

The simulations were performed on a 20 core CPU using a parallel solver option and double precision. Half PKW unit was used to model the flow in a channel with a channel height of 0.5m. The upstream length of 2.5 m and a downstream length of 1.0 m of PKW has been adopted in numerical modeling. The mesh was refined for the PKW unit. Mesh of 3 mm has been adopted for PKW, while upstream and downstream portions near PKW have been meshed with a 6 mm mesh size. The rest of the channel has been meshed with 10 mm grids. The meshing resulted in 1.5 million elements for all the above three geometries. The same meshing technique was adopted for all geometries to ensure a standard reference.

A good technique for approximating turbulence is using the turbulent viscosity ratio, which is the ratio of molecular viscosity to turbulent viscosity. This is often used along

with turbulence intensity in turbulent flows. To define the right turbulent boundary condition, the initial conditions must be considered in the inlet. Recommendation for setting this to 10 times the inlet values is often suggested as the system's turbulence is much greater than the inlet. Setting this too high will allow the system to settle instead of continually increasing the conditions until they are correct. The turbulence intensity is defined as the root-mean-square ratio of the velocity fluctuation to the mean flow velocity. A turbulence intensity of 1% or less is considered low, while greater than 10% is considered high. A turbulence intensity of 5 % is hence taken, suggesting medium turbulence.

The top portion of the channel and outlet portion was given a pressure outlet condition with no water backflow. The wall boundary condition was used for PKW while the inlet, which was 0.2m in height, was kept as velocity-inlet. The wall boundary was given a no-slip boundary condition, while the standard wall surface function was used to model the areas near the wall. The sides of the channel were given a symmetry boundary condition. SIMPLE algorithm was used to model the pressure-velocity coupling inside the channel. The second-order upwind for momentum while the first-order discretization scheme was chosen for the turbulent kinetic energy. The standard k- ϵ model was selected for the study as per the references available. The time step varied from 0.001 to 0.01 seconds. The number of iterations was kept at 20 per time step. Each model was patched with water up-to-the PKW height, and flow was run for ten seconds. The numerical study was done at five discharge points for the discharge-head study for each of the three PKW geometries. For sediment study, the numerical model was run at the three experimental discharges for RPKW and TPKW6.

5.4 Results and Discussions

5.4.1 Discharge Coefficient

Head at four locations was measured in the middle of the lateral crest for all three plan geometries of PKW. Head at Linear weir was also measured for comparison purposes. Fig. 5. 3(a) shows a comparison between the head measured at the lateral crest of PKWs (h) and the corresponding 'r' values for different geometries where 'r' is the relative ratio of discharge through PKW to that of a Linear weir at same head.

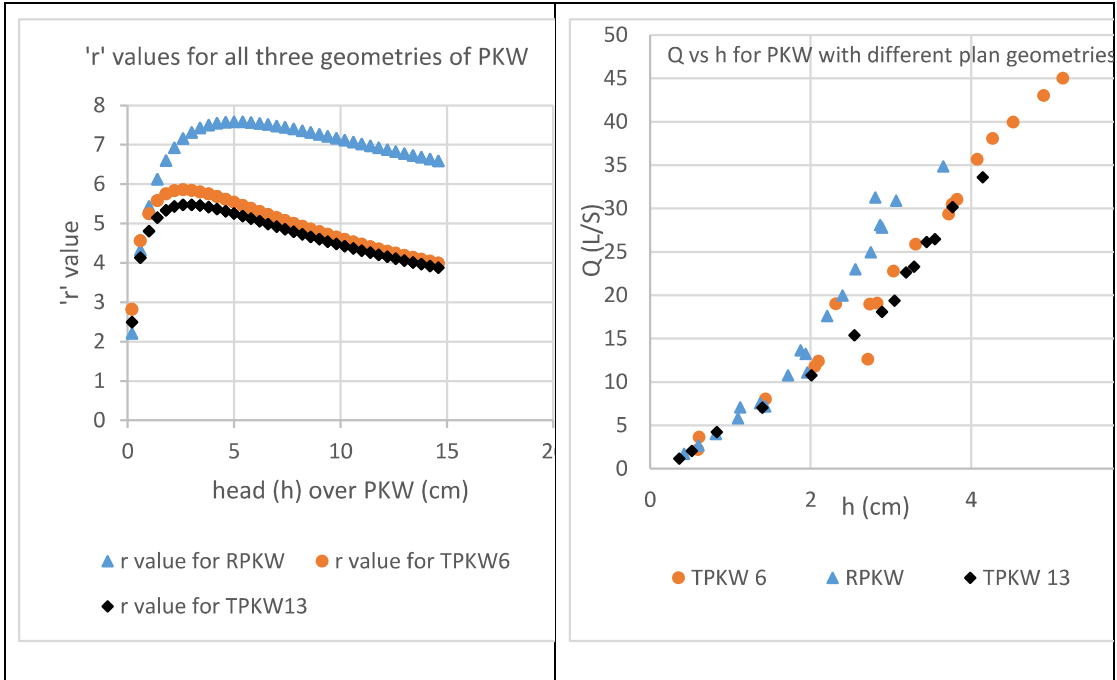
The graph shows that the 'r' value for RPKW is the highest of all three geometries for a given head and constant channel width. 'r' values decrease with increasing heads for all three geometries suggesting that the efficiency of PKWs decrease with increasing heads.

Discharge (Q) vs. head at the lateral crest of PKWs with different plan geometries (h) have been shown in Fig. 5. 3(b). Fig. 5. 3(b) shows that the RPKW has a higher discharging capacity than TPKW 6 and TPKW 13. The R² values are 0.9804, 0.9684 and 0.9952 for RPKW, TPKW 6 and TPKW 13 respectively.

The discharge coefficient (C) of a PKW can be found as below, taking 'h' as the head over the lateral crest of PKW:

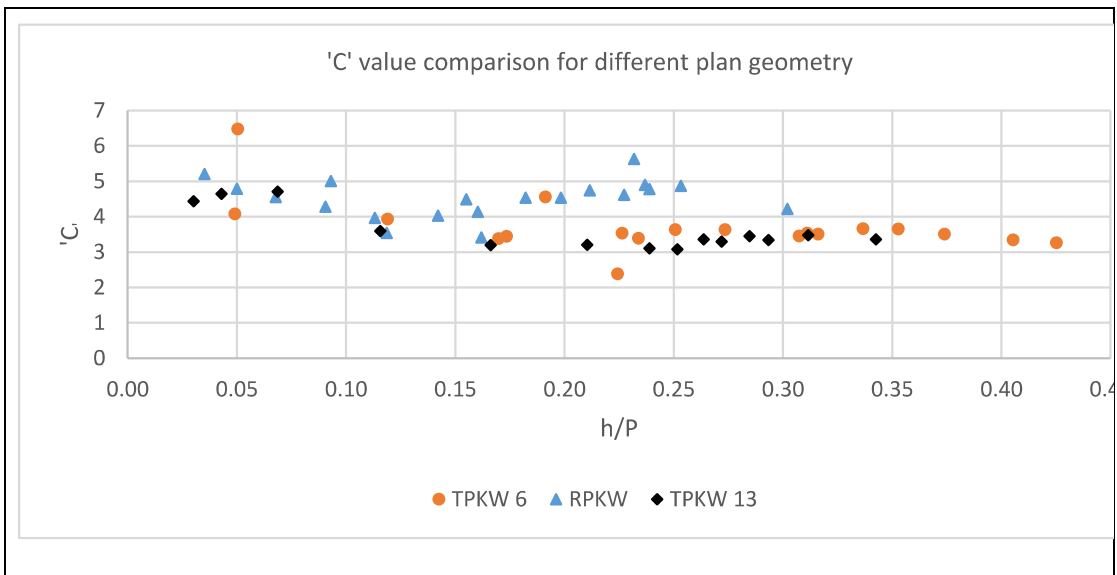
$$Q = \frac{2}{3} C \sqrt{2g} W h^{3/2} \quad (5.5)$$

Where Q is the discharge over the weir, C is the coefficient of discharge, g acceleration of gravity, W total width of the weir and H upstream head at sufficient distance upstream of PKW. 'C' for different 'h/P' values has also been plotted for all three geometries in Fig. 5. 3 (c), taking 'h' as the head over the middle of the lateral crest of PKW rather than upstream of PKW.



(a)

(b)



(c)

Figure 5.3 (a) Plot between head at the crest of the weir (h)(cm) vs. r values for different plan geometries of PKW (b) Discharge (Q) vs. head at the crest (h) for different plan geometries of PKW & (c) C vs. h/P for PKW with different plan geometries.

The 'C' values of RPKW change very slowly with the head and remains higher than TPKW6 and TPKW 13 at increasing heads.

RPKW shows a higher coefficient of discharge than TPKW 6 and TPKW 13. Further, the coefficient of discharge of PKWs decreases as the head increases. Crookston (2010) had presented in their study that the discharge capacity of a labyrinth weir with nearly parallel sidewalls ($\alpha = 6^\circ$) is up to 7 times higher than the discharge capacity of a straight linear weir for minimal upstream head ratios ($H_u/P = 0.05$). For higher sidewall angles α and higher upstream head ratios H_u/P , the capacity decreases considerably and converges to the capacity of a straight linear weir. 'C' value for TPKW 13 is substantially lower than TPKW 6. In general, RPKW has a higher discharge carrying capacity than other plan geometries of PKW. This is mainly due to the increased crest length in RPKW than TPKW for the same number of PKW cycles in a channel, as seen in Fig. 5. 1 (c). The aligning lateral crest reduces the developed length ratio (L/W) from 4.22 in RPKW to 3.88 for TPKW 6 and 3.56 for TPKW 13.

As many geometrical parameters influence the flow, constructing different physical models for PKW for estimating the optimal geometric parameters required for any project design can be tedious. The present Numerical study suggests that CFD can be used as a guiding and analysis tool for investigating the hydraulic need of the various PKW projects, thus drastically lowering the time required for the project's planning. A numerical study using ANSYS FLUENT has been carried out at five discharge points and compared with the experimental results (Fig. 5. 4).

The results show that when the water head is extremely low ($h/P = 0.05$) and high ($h/P=0.3$), the error is relatively high. This may be due to unstable pump discharge. The results show that CFD simulations can reproduce flow depths near PKW with reasonably good accuracy and errors within permissible limits, as shown in Fig. 5. 4.

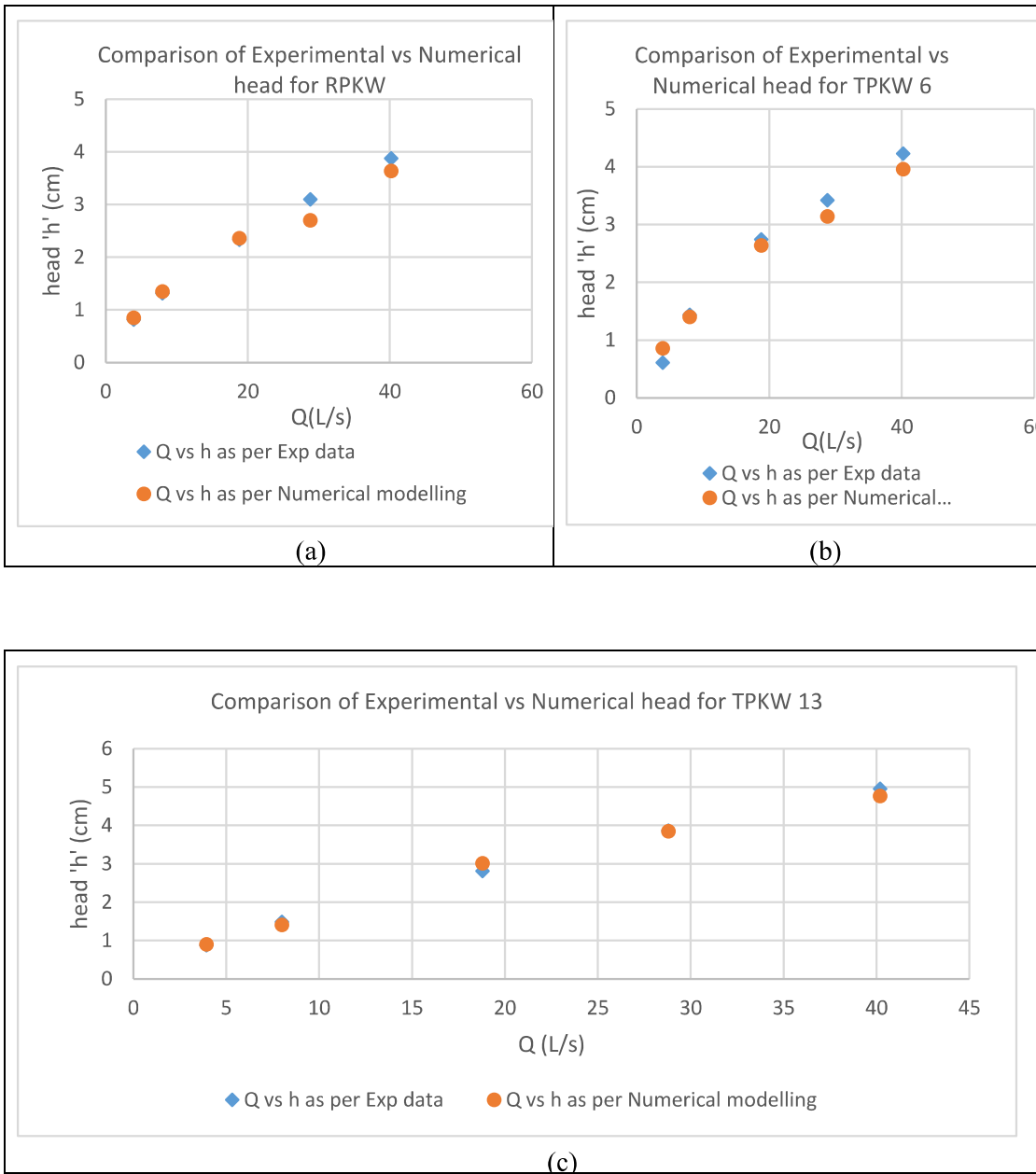


Figure 5. 4 Comparison of experimental and numerical study results for (a) RPKW (b)TPKW6 (c)TPKW13.

5.4.2 Sediment Profile and Self-Cleaning Capacity

TPKW 6 and RPKW have been studied for three discharges experimentally (Table 5.3), and their bathymetric profile are compared. The three discharges are taken into account as they represent the change in the flow regime over PKW. The flow regime over PKW is often characterized in terms of the h/P ratio, where h is the head over PKW and P is

PKW height. Each of the three discharges represents the change in the value of h/P from 0.05 to 0.1 to 0.15, suggesting a change in nappe of flow regime over PKW (Machiels et al. 2011b; Mehboudi et al. 2016; Mehboudi et al. 2017). The sediment carriage study was intended to study the variation in the vertical component of velocity due to a change in the Piano Key Weir plan form. As such, only two models, RPKW and TPKW6, were studied.

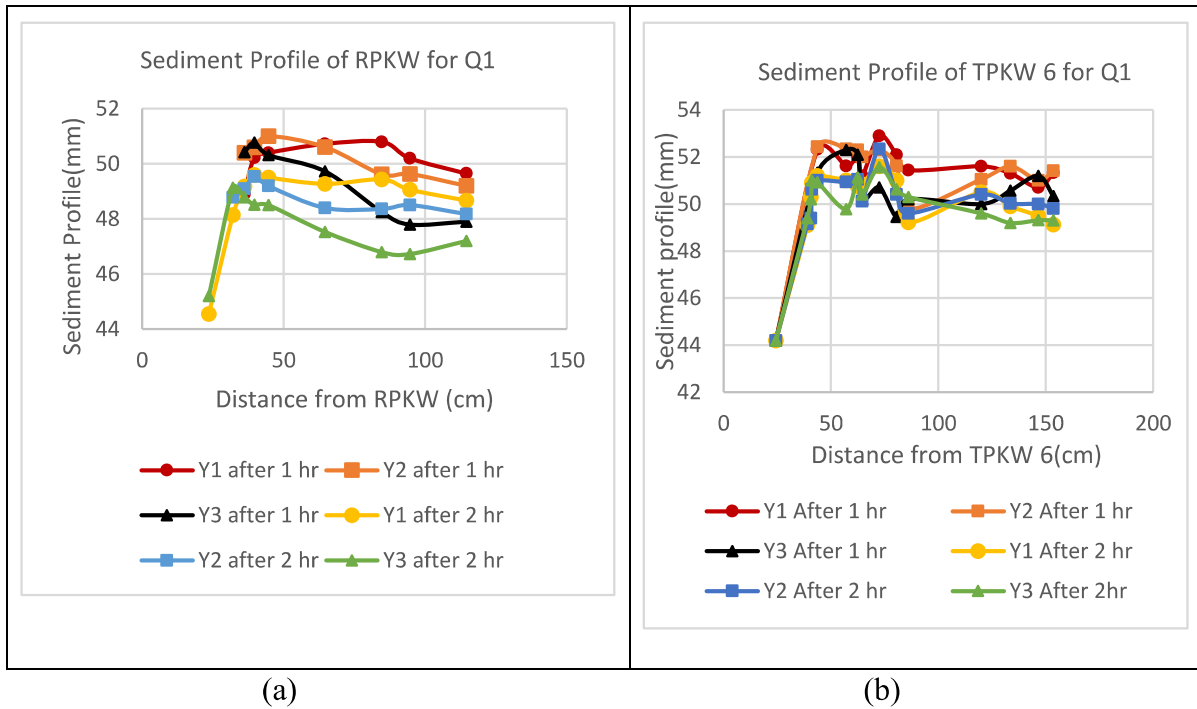
Table 5. 3 PKW plan types and discharges for experimental study of sediment carriage property

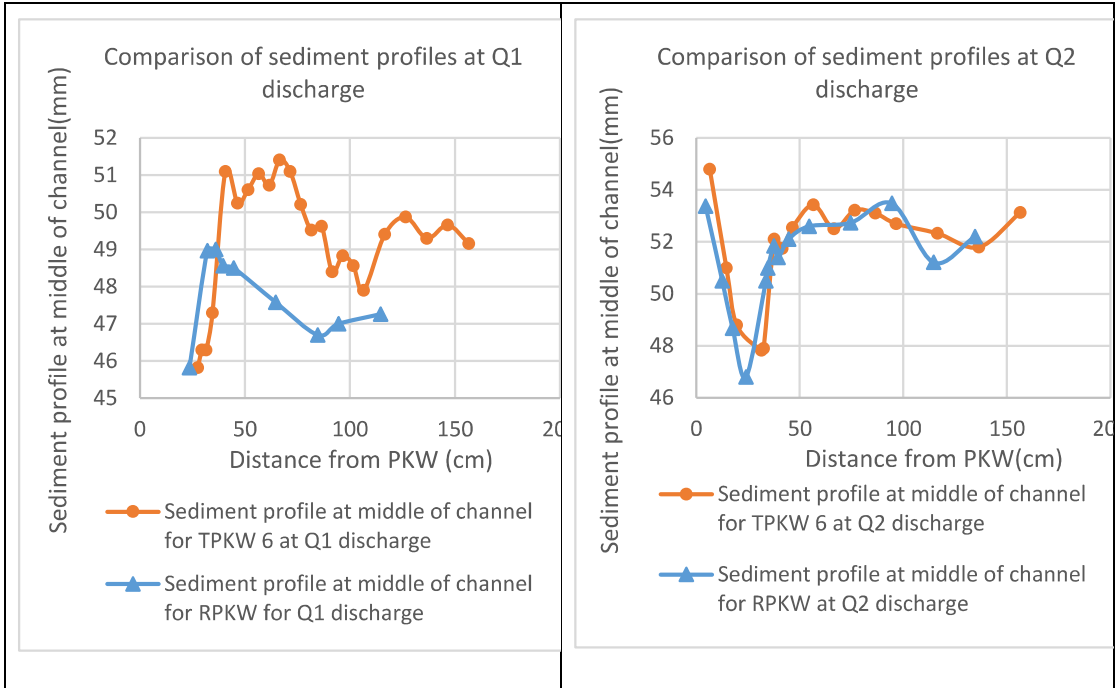
PKW Types -	RPKW & TPKW6
Discharges (Q1, Q2 & Q3)	15.36 L/s, 7.06 L/s, 3.38 L/s
Locations (Y1, Y2 & Y3)	52mm, 135 mm, 115 mm from the perplex glass.

The bathymetric profile has been shown for TPKW6 and RPKW for a single discharge Q1 at three different locations after one hour and two hours of channel flow (Fig. 5. 5 (a) and 5. 5 (b)). Nosedá et al. (2019) have inferred in their study that 2 hours of flow time is sufficient for getting an equilibrium condition in which 95 percent of scouring has already taken place. Figs. 5 (c) to 5 (e) compares the sediment profile in the middle of the channel for all three discharges. The lower discharges take more time for the equilibrium to be established. There is not much difference between the Sediment profile after 1 hour and 2 hours for higher discharges. The equilibrium is reached within one hour. However, for lower discharges, the equilibrium is attained after 1 hour.

5.4.3 Vertical Velocity Component 'v' for PKW with Different Plan Geometries

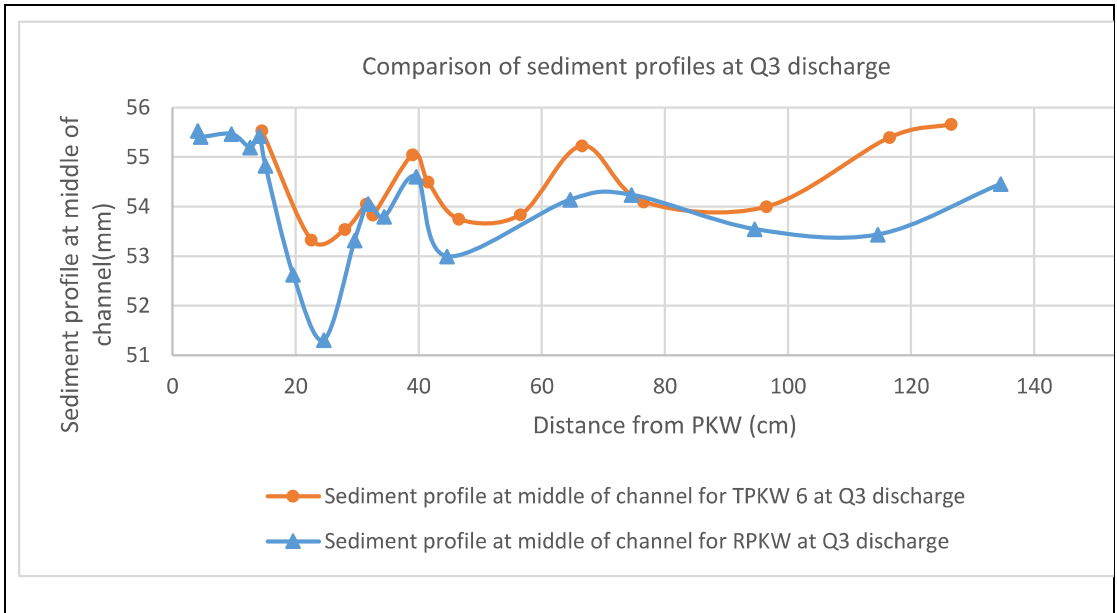
Experimental study of PKWs with different plan geometries suggests that RPKW has a greater sediment passage degree than TPKWs. Breusers and Raudkivi (1991) concluded in their study that the vertical velocity gradient of the flow is transformed into a pressure gradient. As such, the resulting downward flow swept around the corner and formed a highly turbulent vortex system. This vortex system is also called a horseshoe vortex and is well known for the flow around bridge piers. These turbulences set in motion the sediments, which rolled along the slope to the end of the inlet key, where it was finally transported over the weir (Herbst et al. 2018).





(c)

(d)



(e)

Figure 5.5 (a) Sediment profiles for RPKW at Q1 discharge, (b) TPKW 6 at Q1 discharge, (c) Comparison of sediment profile between RPKW and TPKW 6 for Q1 discharge, (d) Comparison of sediment profile between RPKW and TPKW 6 for Q2 discharge & (e) Comparison of sediment profile between RPKW and TPKW 6 for Q3 discharge

The vertical velocity component's role, as such, becomes quite eminent.

The study of vertical velocity 'v' has been carried out by numerical study for three experimental discharges as mentioned in Table 5.3 to study how it is affected by the plan geometry.

For this numerical study, nine locations have been taken, which were earlier observed experimentally. Since most of the scouring occurs within the overhang reach of the outlet in the upstream direction, these nine points vary from the upstream base B_b and the outlet key's upstream overhang. The locations are the middle of the inlet key, middle of the sidewall and the outlet key, primarily at three X locations. The Y value varied from 0 to 0.2 m, and twenty sample points were considered for each location along the Y direction. The locations and their positions are specified in Table 5.4 below.

Table 5. 4 Locations of various study points for the two PKW geometries

Locations	X (m)	Y (m)	Z (m)	Position
11	0.244	0-0.2	0	At upstream of base B_b and middle of outlet.
12	0.244	0-0.2	0.05 (RPKW) 0.041(TPKW 6)	At the upstream point of base B_b and middle of lateral crest.
13	0.244	0-0.2	0.1	At the upstream point of base B_b and middle of the start of the inlet key.
14	0.284	0-0.2	0	At the upstream point of the middle of outlet overhangs at a distance of 0.04 m(X) from base B_b and middle of the outlet key

15	0.284	0-0.2	0.05(RPKW) 0.037 (TPKW 6)	At an upstream distance of 0.04 m from base B _b and middle of lateral crest.
16	0.284	0-0.2	0.1	At a distance of 0.04 m(X) from the start of the middle of the inlet key.
17	0.325	0-0.2 m	0	At the start of outlet overhangs and middle of the outlet key
18	0.325	0-0.2	0.05 (RPKW) 0.033 (TPKW 6)	At 0.081m (X) from base B _b and at the middle of the lateral crest
19	0.325	0-0.2	0.1	At 0.081 m (X) from the start of Inlet key

From the experimental study, we had seen that scouring and passage of the sediment start from the upstream apex of the outlet overhang, which is carried over the middle of the inlet portion. As such, locations 13 and 18 are quite interesting. Three critical points (13, 15 & 18) are observed for all three plan geometries and at three different discharges and presented in Table 5.5.

A detailed analysis at a different location for the lowest discharge of 3.38 L/s have been presented below:

For RPKW (Fig.5. 6 (a)), the vertical component of velocity (v) at location 11 remains zero-till 0.07 m, which is just below the point where the overhang emerges in the upstream direction. This is due to the sudden stoppage of water by the vertical wall of the outlet key. After that, the ' v ' decreases rapidly to -0.90 m/s since the point depicts the water flow in the outlet section now and thus the high negative vertical velocity.

For location 12, the vertical velocity component 'v' is zero till the height of RPKW. This is because the location line is at the vertical face of the sidewall. For location 13, we can see how high the vertical velocity is at such a small discharge of 3.38 L/s, roughly at an h/P ratio of 0.05 for RPKW. The vertical velocity component rises drastically from 0 to 0.0295 m/s at 0.02 m from the bottom of RPKW. It decreases slightly at 0.045 m and again rises to 0.037 m/s at 0.09 m from the channel's bottom. This high vertical velocity can be attributed to the significant sediment passage at RPKW. The inlet key's slope does not restrict the sediment particles due to its slope but facilitates their passage along with it. From the experimental study, we can see that most of the sediments are transported through the inlet key itself. The crowning is formed below the overhang of the outlet key upstream, and the sediment is carried away through the inlet part. This location 13 is such an exciting point concerned with sediment passage.

For location 14, we can see that the v is negative throughout, unlike at location 11, where the change occurred at 0.07 m. We can infer that the sediments are pulled down below the upstream overhang of the outlet key, as seen in the experiments.

At location 15, the v non zero right from the start of bed level of RPKW and attains its maximum at 0.09 m from the bottom of RPKW at 0.0125 m/s. This suggests that the vertical component of velocity is positive and robust under the sidewall. We can say at position 15, 'v' is high hence facilitating the sediment passage.

For location 16, the vertical velocity component is high. A peak of 0.024 m/s is obtained at 0.0895 m from the bottom of the channel. The 'v' is, however, lower than the v just at the start of the inlet key. This suggests that the sediment is picked up mainly at the start of the inlet key, and this picking power gradually decreases as we move upstream.

Table 5. 5 Study at three critical points for different discharges and various plan geometries

PKW	Discharge (L/s)	Location 13	Location 15	Location 18
RPKW	3.38	Linear rise, then dips slightly after 0.02 m, and again maximum at Y=0.09 m at 'v' = 0.037 m/s	Linear rise with maximum at Y=0.09 m at 'v'= 0.0127 m/s	Linear rise with maximum at Y=0.115 m at 'v'= 0.027 m/s
RPKW	7.06	Linear rise up to maximum 'v' = 0.09 m/s at Y=0.021 m, then dips and again rises at Y= 0.90 m with 'v' = 0.075 m/s	Linear rise after an initial negative 'v' with maximum at Y= 0.09 m at 'v' = 0.02 m/s	Linear rise with maximum at Y= 0.112 m at 'v' = 0.048 m/s
RPKW	15.36	Linear rise up to maximum 'v' = 0.235 m/s at Y=0.025 m, then decreases and again rises with maximum at Y=0.09 m at 'v' = 0.15 m/s	Linear rise after an initial negative 'v' with maximum 'v' of at Y= 0.09 m at 'v' = 0.038 m/s	Linear rise with maximum at Y = 0.115 m at 'v' = 0.06 m/s
TPKW 6	3.38	Linear then parabolic rise with a maximum at Y=0.07 with 'v' =0.026 m/s.	Linear rise, with maximum at 0.085 m at 'v'= 0.0125 m/s	Linear rise with maximum at 0.112 m at 'v'= 0.028 m/s

TPKW 6	7.06	A linear curve with a maximum at $Y=0.02$ m with ' v ' = 0.064 m/s then dips but remains above zero-till TPKW6's height.	Linear rise with maximum at $Y=0.085$ m at ' v ' = 0.02 m/s	Linear rise with maximum at 0.11 m at ' v ' = 0.046 m/s
TPKW 6	15.36	Linear rise up to maximum ' v ' = 0.20 m/s at $Y=0.021$ m.	First, ' v ' dips below zero and then rises above zero after $Y=0.05$ m. Then rises again with maximum at $Y = 0.09$ m at ' v ' = 0.03 m/s	Linear rise with maximum at $Y=0.11$ m at ' v ' = 0.06 m/s

For location 17, ' v ' is almost zero-till 0.9P, then increases sharply to 0.01 m/s at 0.111 m from the bottom. It then turns negative after $Y=0.115$ m and decreases.

For location 18, we can see high ' v ' as we move along the vertical direction, with values touching 0.0263 m/s at 0.115 m from the bottom. This supports our experimental study.

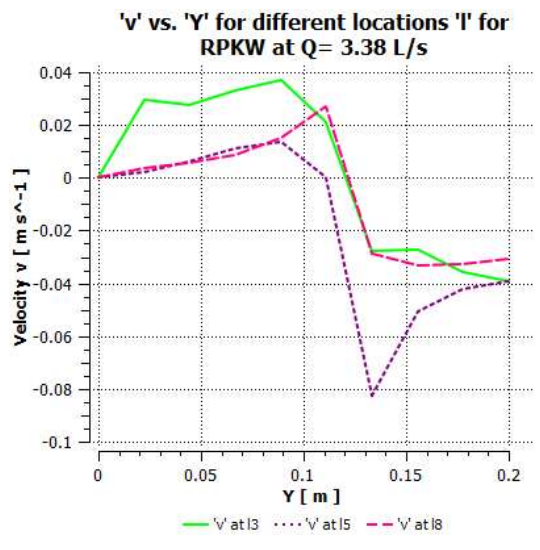
The sediment passage begins by the sediment gradually moving away into the inlet portion right under the outlet key's upstream overhang at the sidewall. The sediment is pulled away as such from below the overhang upstream outlet key and transported downstream. For location 19, v is less than v at 13 and 16 with maximum ' v ' attained as 0.01m/s at $Y=0.069$ m.

For TPKW 6 (Fig.5. 6 (d)), there is not much difference at a discharge of 3.38 L/s. ' v '

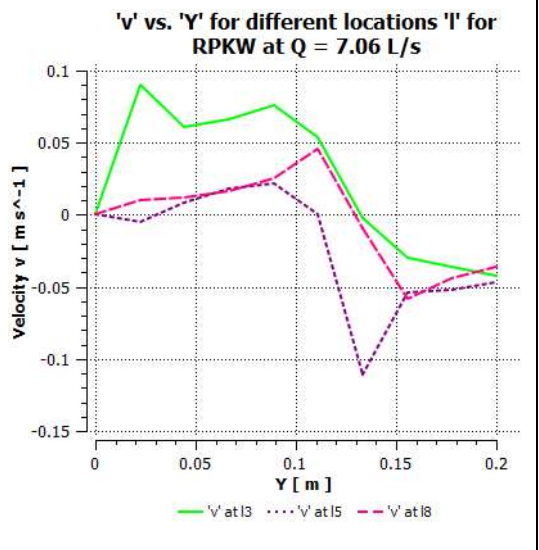
at locations 11 and 12 is zero as expected. The vertical component of velocity 'v' at the three critical points is shown in Table 5.6. 'v' at 13 compared with RPKW is smaller. Hence, the sediment passage is less, as confirmed by experiments. 'v' at location 14 is always below zero like RPKW, suggesting sediment pulled down towards the bottom below the outlet upstream overhang. We see that the 'v' decreases as the plan form are changed from rectangular to trapezoidal at 15. 'v' at 18 is non zero for the entire height of TPKW. And the peak is roughly the same as in RPKW.' v' at 19 is positive till 0.09 m and then becomes negative.

Vertical velocity (v) is utilized for deposition or suspension of sediment particles in open channel flow. Results show that the vertical velocity attains a higher value as the distance from the bed increases (Fig. 5. 7). Another interesting observation is that the vertical velocity close to PKW and nearer to bed level (13) is small but higher than the vertical velocity near the bed level but farther from PKW (16 & 19).

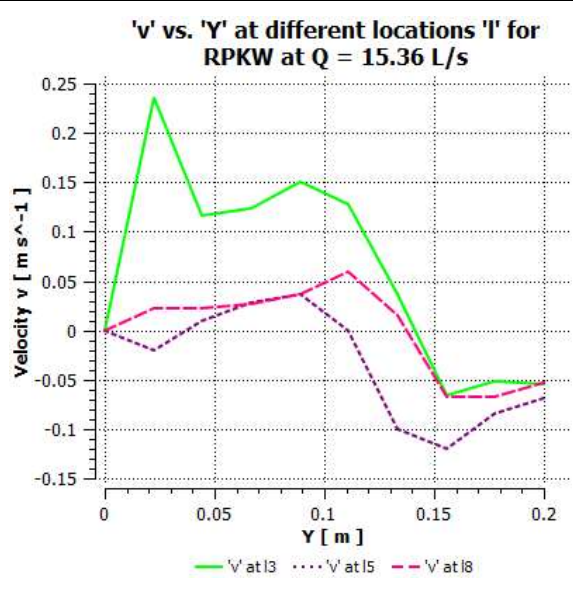
The sediment passage begins at locations 13 and 18, as depicted in Fig. 5. 8. This observation helps to understand why PKWs are self-cleaning, i.e., PKWs help in sediment passage over them through the inlet, unlike other weirs. Vertical velocities were observed to be higher at the middle portion of keys compared with in front of the sidewall.



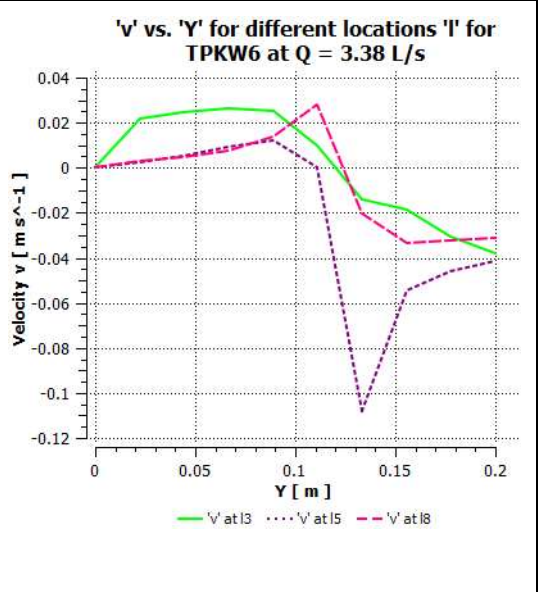
(a)



(b)



(c)



(d)

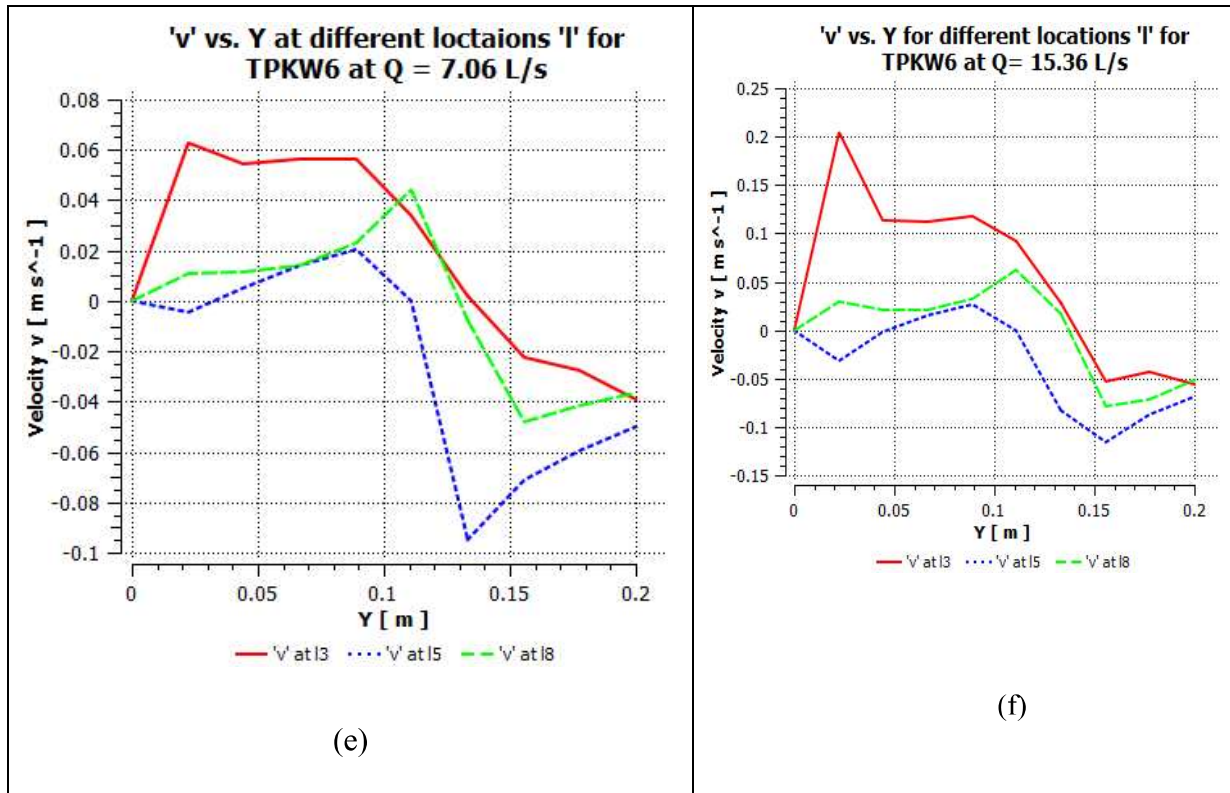
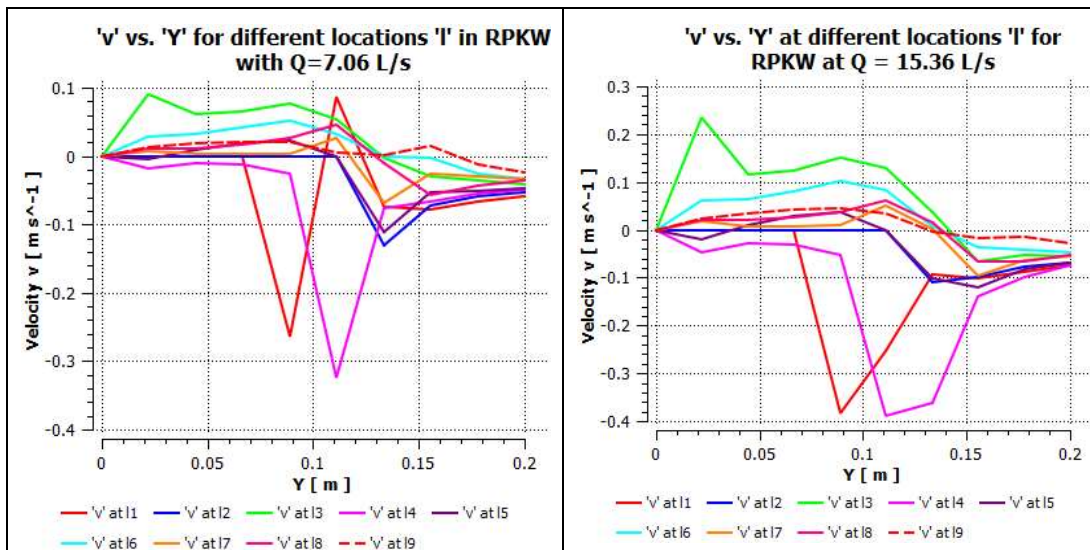


Figure 5. 6 Vertical velocity component 'v' vs. 'Y' at different locations for three different discharges for RPKW & TPKW6



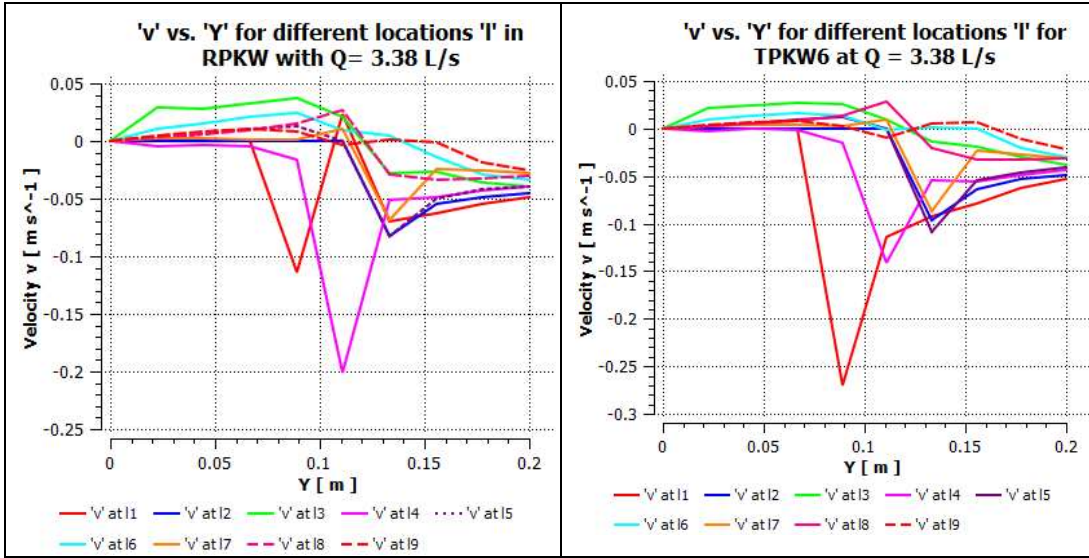


Figure 5. 7 Vertical velocity component ('v') at all locations for RPKW and TPKW6 for different discharges



Figure 5. 8 (a) High degree of sediment uplift near the start of the inlet key and (b) Sediment passage beginning under the upstream overhang near the lateral crest

5.5 Conclusions

This study aimed to determine the head discharge relationship among PKWs of different plan geometries to find the hydraulically superior plan-form of PKW. Further, a sedimentation study was also conducted to find which plan form offers the better self-cleaning ability. The study was conducted both experimentally and by CFD. CFD study

was carried out to assess if the CFD tool can be safely applied instead of experimental models, thereby saving cost and time. The experimental study of the head discharge relationship was carried out for three plan geometries (RPKW, TPKW6 & TPKW13) at eighteen discharges, while the numerical study was conducted on five of these experimental discharges. The five discharges are taken into account as they represent the h/P value of the PKW weir at 0.07, 0.1, 0.2, 0.25 & 0.3. The flow regime over PKW is often characterized in terms of h/P ratio, where h is the head over PKW and P is PKW height. Each of the five discharges represents the change in the value of h/P value and studying the change in flow regime over PKW. Also the numerical study gives good results at varying h/P values of flow over PKW, which further suggests applicability of CFD techniques in studying flow over PKW. The sediment passage over PKW with a rigid bed with three different discharges has been carried out for two plan geometries (RPKW & TPKW6) for accessing which plan geometry is showing more significant sediment passage downstream. The vertical velocity component ' v ' in sediment passage at nine critical locations for the three experimental discharges has been studied using CFD. The following conclusions can be drawn from the experimental and numerical study:

- With the same no. of cycles in a fixed-width W of any channel, aligning the lateral crest from the longitudinal direction decreases the developed length (L) of the PKW. As we have observed, the developed length (L) reduced from 4.22 to 3.88 from RPKW to TPKW 6 and further reduced to 3.56 for TPKW13.
- The RPKW shows a higher discharge coefficient than TPKWs owing to greater crest length for the same no. of cycles of PKW in a fixed channel width (W). As the h/P ratio increases, we can see that the discharge coefficient decreases for all geometries.

- Comparing the three PKW plan geometries, it has been observed that sediment transport is higher for RPKW at the same discharges compared to the TPKW. This confirms the self-cleaning ability of RPKW to be higher than TPKW for a constant channel width (W) and the same number of cycles (N).
- Vertical velocity (v) has been studied by the use of ANSYS-FLUENT. ' v ' at the start of the inlet key, under the outlet key just below the lateral crest and at the upstream overhang of the outlet key is high, suggesting the scouring and sediment transport happens primarily from these locations. ' v ' plays a vital role in lifting the sediments and helping them pass downstream. The study will contribute to studying the correlation between ' v ' and the sediment uplift upstream of the PKW.
- Vertical velocity (v) is utilized for deposition or suspension of sediment particles in open channel flow, and results show that the vertical velocity attains a higher value as the distance from the bed increases. Another interesting observation is that the vertical velocity close to PKW and nearer to bed level (13) is small but higher than the vertical velocity near the bed level but farther from PKW (16 & 19). This observation helps to understand why PKWs are self-cleaning, i.e., PKWs help in sediment passage over them through the inlet, unlike other weirs. Vertical velocities were observed to be higher at the middle portion of keys compared with in front of the sidewall.
- The study suggests the use of the CFD tool to study flows around complex geometries like PKWs.
