Original Research Article

An Experimental Study of Fish Movement with Turbulent Kinetic Energy along The Pools of A Vertical Slot Fish Pass

ABSTRACT

Bangladesh is a land of river which is situated in the delta of the Ganges-Brahmaputra-Meghna (GBM) Rivers which are three of the largest rivers of the world. These rivers provide an arterial transportation network for fish movement. Fish migration depends on flow characteristic and surrounding flood plain connected to rivers. In recent time for flood control in monsoon and water storage in lean period a lot of structure has been built along and across the river (Rajaratnam, N., Katopodis, C. and Solanki, S., 1992). As a result the natural sequence of flooding in floodplain of Bangladesh, food chain and life cycle of natural fish and other aquatic species has become under sever threat (NWMP, 2001). In this research an experimental approach has been carried out to understand the turbulence structures of the flow inside a laboratory flume with different local fish species. The structural set up consists of an adverse slope of 6% followed by a mild slope of 3.4%. The adverse slope is 2.54 m in length and the mild slope is 4.45 m in length. Total nine sets of experiments have been conducted. For each set of experiments, data points were distributed on a 10 cm (in the longitudinal direction) x10 cm (in the transverse direction) grid at 0.6 hydraulic depth and 10 cm (in the longitudinal direction) x20 cm (in the transverse direction) grid at 0.4 and 0.8 hydraulic depth.In this experimental setup turbulent kinetic energy and fish movement in all four pools will be observed. This experimental study consists of three types of fish species; Rui (*Labeorohita*), Catla (*Giberlioncatla*) and Mrigel (*Cirrhinusmrigala*) of fry size (1-2 cm body length), fingerline size (7-10 cm) and juvenile size (10-20 cm) have been selected for studying. The flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. There are similarities with turbulence characteristics in each case. Fishes have avoided high turbulent kinetic energy area in the contour map. The comparison shoes the area with low turbulent kinetic energy was most suitable for fishes to pass the pools or taking rest inside the pools.The results may be useful insight on the turbulence characteristics of flow in the vertical slot fish pass and can be used to study fishes characteristic and also for guidance in the design of fish pass in the future.

Keywords: Fish pass; Turbulence;Hydraulic structures; Fish habitats; Water flow.

1. INTRODUCTION

Fish migration upstream and downstream or in the floodplain depends on flow characteristics and surrounding flood plains connected to rivers. The floodplains in the monsoon play primary role of reproduction and increase the fish biomass in open water fishery system. During floods fish migrates into the floodplain for feeding, grazing, growth and reproduction. Fishes return to the river from floodplain at the end of the flood (FAP-20, 1998). The construction of embankments, sluice gates and weirs parallel to the river for monsoon flood results in an interruption of main river flow with floodplains. On the other hand, construction of hydraulic structures such as dams, rubber dams and barrages across the river for storage purpose of water for lean period causes an interruption of flow across the river (Hassan, 2002). As a result the natural sequence of flooding in floodplains of Bangladesh and life cycle of natural fish and other aquatic species has become under sever threat. It has become necessary to make an adjustment of the existing hydraulic structure, to enable the fish to pass upstream or downstream. Otherwise the migratory fish have been found to be striking against the water current or swept away in flow (Ali, 1990). Fish friendly structures are defined by as hydraulic structures which can facilitate upstream and downstream or in the floodplain migration of fish species in rivers where natural and man-made obstructions prevent a free migration. If simply an open gap is left in the hydraulic structure for fish migration, the velocity of flow through such an opening will be too high. Therefore, even the strongest fish will not be able to travel through the structure (Rahman, 2015).

Many vertical slot fishpasses, particularly of the more economical single slot versions, are used in Canada, U.S.A., Norway, Australia, France, Germany and many other countries. Several of the older ones were designed with salmonid criteria and, not surprisingly, produced rather poor results in passing non-salmonids (e.g. Mallen-Cooper and Brand, 2007). Comprehensive hydraulic studies of various designs with single slots, most of them summarized by Katopodis (1992), have assisted in adapting this fishway type to meet the needs of a variety of species, particularly potamadromous species (Barton., 2009; Bermúdez., 2010; Katopodis, 2005; Khan, 2006; Larinier, 2008; Mallen-Cooper and Brand, 2007; OTA, 1995; Rajaratnam, 1992; Wang., 2010; Wu, 1999). White, (2010) report on the use of a vertical slot fish-way by three native potamodromous species of the Murray River in Australia. The Torrumbarryfishway has a slope of 5.5%, instead of the more common 10% for salmonids, pools of 2.9 m long × 2.0 m wide, and slot widths of 300 mm. The three species and corresponding maximum standard lengths for those fish which moved through the fishway were: bony herring (*Nematalosaerebi*) (Clupeidae) ≤260 mm, silver perch (*Bidyanusbidyanus*) (Terapontidae) ≤320 mm and golden perch (*Macquariaambigua*) (Percichthyidae) ≤520 mm. It was found that for lengths of ≥120 mm, ascent rates related primarily to species behaviour, not fish size.

Fisheries sector requires urgent attention to tackle the challenges occurred from unplanned flood control structures. Capture fishing on the floodplains and the haorbasins, a traditional activity of the poor, is declining rapidly and will disappear altogether unless proper measures are taken. Due to interruption in the natural sequence of flooding in floodplain of Bangladesh, food chain and life cycle of natural fish and other aquatic species have become vulnerable (NWMP, 2001). The impact on fish migration for flood control embankment and regulator appears to be of major concern to the perpetual survival of the natural fish stocks utilizing rivers and floodplain in many parts of Bangladesh (FAP-6, 1993; 1994; and 1998; FAP-17, 1994).

The water regulatory structures like barrage, rubber dam, sluice gate and weirs causing river fragmentation and plays a major role in declining the freshwater fisheries (Lucas and Frear, 1997; Cowx and Welcomme, 1998). The fish that complete their migrations within the river system are mostly affected by structural arrangements (Nicola et al., 1996; Poulet, 2007). If no adjustment is made in the hydraulic structure, to enable the fish to pass upstream or downstream, then such migratory fish have been found to be striking against the water current or swept away in flow. Non-provision of an arrangement for fish to pass upstream or downstream, may thus lead to large scale destruction of fish life. If simply an open gap is left in the hydraulic structure for fish migration, the velocity of flow through such an opening will be very high. Therefore, even the strongest fish will not be able to travel through the structure (Garg, 2008).

A fish pass is a fish friendly structure that enables fish to overcome obstructions in the passage to the spawning grounds and other upstream or downstream migrations and is built when it is required for ecological, economical or legal considerations. Also this can provide an area in the-pool where fish might be able to rest to gain energy to pass the next obstacle. Most commonly used fish pass in the world can be four types namely: pool and weir, Denil, vertical slot and culvert fish passes (Bell 1973; Clay 1995; Katopodis 1990).

Fish passages typically consist of a series of stepped pools, ramps, or other mechanisms that assist fish in navigating around obstacles. They provide a pathway for fish to move upstream or downstream, mimicking natural river conditions to the extent possible. By restoring connectivity and providing fish with access to previously inaccessible areas, fish passages play a crucial role in mitigating the impact of hydraulic structures on fish populations and restoring their natural migration patterns. The implementation of fish passages requires careful planning and engineering to ensure their effectiveness and minimize potential negative impacts on fish and other aquatic species. Ongoing monitoring and evaluation are also important to assess the success of fish passage projects and make any necessary adjustments to improve their functionality. Overall, fish passages are an essential tool in the restoration and conservation of river ecosystems, helping to maintain healthy fish populations and preserve the biodiversity and ecological balance of rivers impacted by hydraulic structures.

The concept of fish pass was introduced in Bangladesh in the 1990s and since then four Fish Friendly Structure (FFS) and fishpass have been built. These are: i) Kashimpurfishpass in Kushiyra River in Maulvibazar District, ii) Sariakandifishpass in Jamuna River in Bogra District, iii) Jugini fish friendly regulator in Lohajong River in Tangail District, and iv) Morichardana fish friendly regulator in Jamalpur District. Among them Sariakandifishpass and Kashimpurfishpass were designed as a vertical slot fishpass. A vertical slot fishpass consists of a rectangular channel with a sloping or stepped floor, which is divided into a number of pools of regular lengths. The main advantages of vertical slot fishpass are: i) tolerate reasonably large water level difference between upstream and downstream ends (Clay 1995); ii) flow patterns inside the pools and water velocities in the slots are almost independent on the water depth in the fishpass (Liu et al., 2006); and iii) provides an area in the-pool where fish can take rest to gain energy to pass the next obstacle (Kamula, 2001; Rajaratnam et al., 1992 and 1986). From the literature review studies it has been found very few experimental work based on local fish species has been conduct out in vertical slot fishpass. Based on the above discussion an experimental study on vertical slot fishpass with local fish species will be carried out.

2. EXPERIMENTAL ARRANGEMENT AND EXPERIMENTS

The experiment has been performed in a 70 feet (21.34 m) long, 2.5 feet (0.762 m) wide and 2.5 feet (0.762 m) deep rectangular tilting flume. The side walls of the flume are made of clear glass and they are vertical. The water resistant color has been used to pain the flume bed to avoid the development of any unnecessary bed friction. In the upstream and downstream end of the flume two wire mesh screens were placed to stop the fish to go inside the pumps and reservoir of the flume. An adverse slope of 1:16.67 was placed at the upstream portion and a mild slope of 1: 29.17 was placed at the downstream portion of the physical model. The entire model structure including the sloping portion was painted with protective coating to prevent the decomposing of wood from the effect of hydraulic flow.

Flume bed has been maintained as horizontal and it is supported on an elevated steel truss system. Two pumps were used to supply the head tank from the laboratory sump and the discharges were measured by means of magnetic flow meters located in the supply lines. Necessary steps were taken to prevent any unnecessary damage in the flume structure while conducting the experiment.

The structural design that has been applied in this study is the design 1 (Rajaratnam et al., 1992) which is widely used for designing vertical slot fish pass all over the world. The physical model of the structure was developed as a vertical slot fish pass. The structural set up consists of an adverse slope of 6% followed by a mild slope of 3.4%. The adverse slope is 2.54 m in length and the mild slope is 4.45 m in length. The fish pass is constructed on the mild slope which contains four pools. Each of the pool is approximately 1 m long, 0.762 m wide and 0.60 m high. The width of the opening of each pool was 0.127 m. Each component of the overall structure was built with wooden sheets. Schematic diagram of the physical model set up is shown Figure 1 and Figure 2.

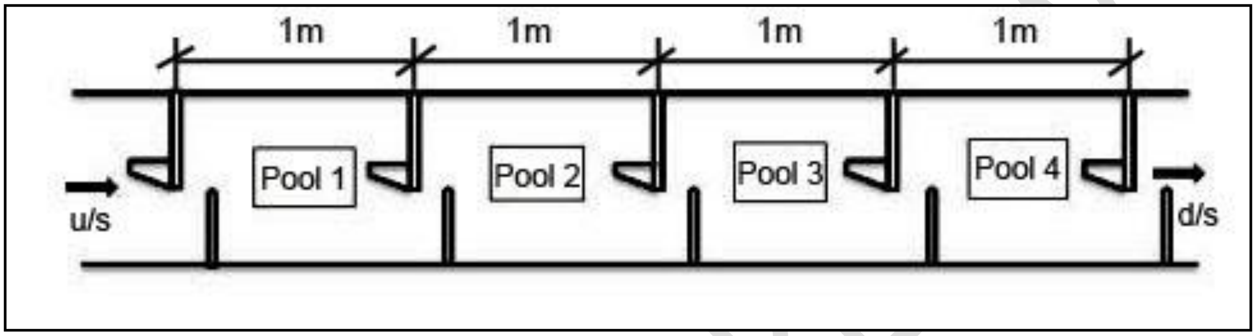


Figure 1: Plane view of the schematic diagram of the physical model

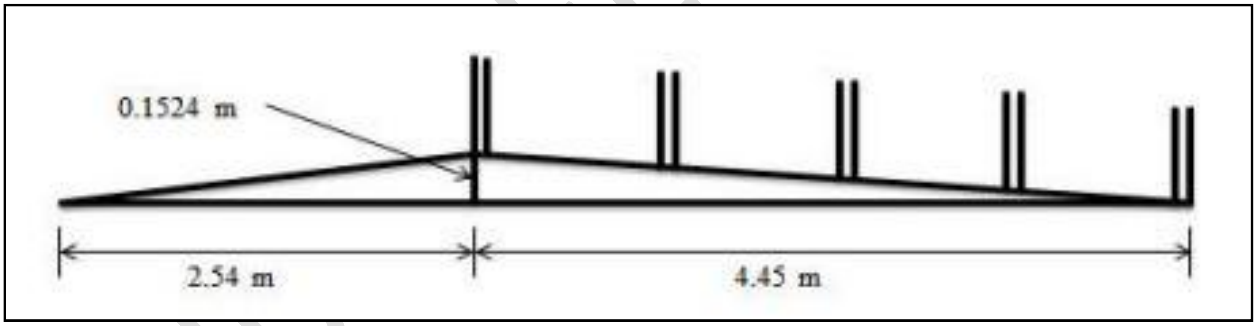


Figure 2: Side view of the schematic diagram of the physical model

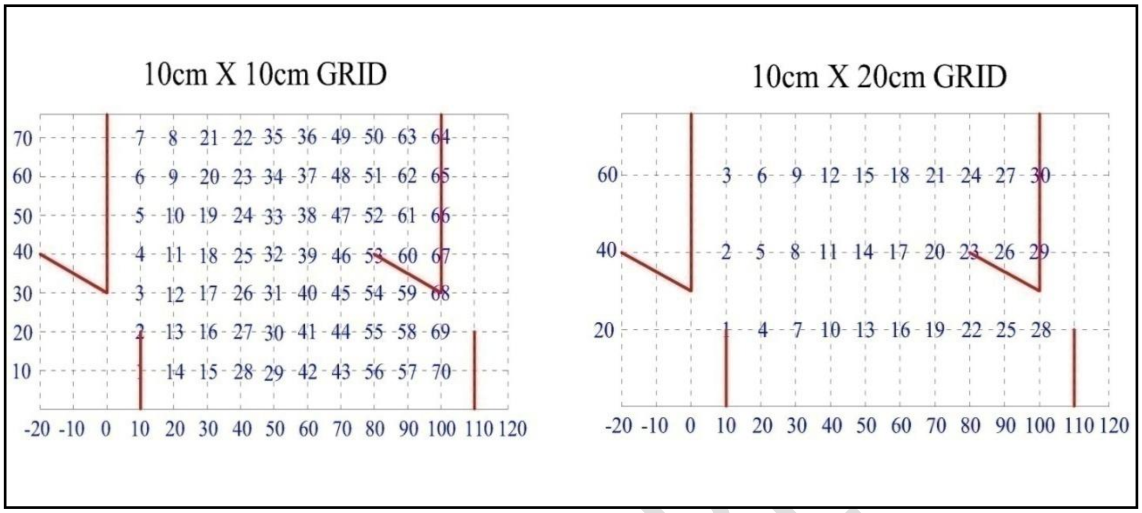
A down-facing acoustic Doppler velocimeter (ADV) was used to investigate the velocity field. The SonTek 10-MHz ADV (Acoustic Doppler Velocimeter) is a versatile, high-precision instrument used to measure 3D water velocity. The ADV is designed to record instantaneous velocity components at a single-point with a relatively high frequency. ADV has become a useful instrument in point wise measurement of 3D velocity fields in laboratory and field environments by recording the Doppler shift produced by acoustic targets in the flow (Kraus et al., 1994; Lohrmann et al., 1994; Son Tek, 1997). Velocities are measured in a sampling volume located 5 cm away from the probe head. The probe head is made up of a single transmitter located in the center of the probe head and either two or three receivers mounted on arms. The transmitter generates a narrow beam of sound that is projected through the water. Reflections from particles or "scatterers” (such as suspended sediment, biological matter, or bubbles) in the water are reflected and sampled by the highly sensitivity receivers. The intersection of the receiver axes designates the location of the sampling volume. Son Tek ADV specifications state that the shape of the sampling volume is a cylinder of diameter of 0.6 cm and height of 0.9 cm. Data has been acquired at a sampling rate of 50 Hz. It can measure flow velocities from about 1 mm/s to 2.5 m/s with an accuracy of ±1% of the measurement range (Sontok Horizon ADV User Guide, July 2007).

Total 9 sets of experiments have been conducted. Specifications of the experiment sets are shown in Table 1. For each set of experiments, data points were distributed on a 10 cm (in the longitudinal direction) x10 cm (in the transverse direction) grid at 0.6 hydraulic depth and 10 cm (in the longitudinal direction) x20 cm (in the transverse direction) grid at 0.4 and 0.8 hydraulic depth as shown in Figure 3. Since ADV measures velocity in a sampling volume located 5 cm away from the probe head, measurement at 0.2 hydraulic depth is very difficult. It has been found that the flow pattern and the head drop per pool remain almost same in most of the pools (Wu et al., 1999). Again measurements have been carried out in all the four pools for the critical and good conditions to obtain the velocity fields and contours.

Table 1: Specifications for Experiment Runs

Experiment Run No.	1	2	3	4	5	6	7	8	9
Discharge, Q (m^3/hr)	96	65	37	118	81	55	145	100	70
U/s Water Level (cm)	40	40	40	50	50	50	60	60	60

Total Head Loss, Δh (cm)	19.17	6	1	19.5	6	1.75	15.75	5.75	2



(a) (b)

Figure 3: Data points distribution (a) 10 cm (in the longitudinal direction) x10 cm (in the transverse direction) (b) 10 cm (in the longitudinal direction) x20 cm (in the transverse direction)

3. RESULTS AND DISCUSSION

Turbulence strength has been calculated from: Tx= $\sqrt{\overline{(u')^2}}$; T_y = $\sqrt{\overline{(v')^2}}$ and T_z = $\sqrt{\overline{(w')^2}}$ respectively. Where u', v' and w' are the fluctuating components of velocities [cm/s] in the down-stream, cross-stream, and vertical directions respectively; an overbar is used to denote a time average. In theory, the velocity record is continuous, and the mean can be evaluated through integration. Three-dimensional velocity measurements showed the isotropic turbulence strength in the (x, y) plane with and the non-isotropic turbulence strength in the (x, z) plane. While turbulence is generated by the shear, stronger shear appears at the channel bed. This is evident in profiles of turbulence strength within a boundary layer, as shown figure is greater. Turbulence distribution changed in the vicinity of the pool entrance. It increased the closer to the middle of the pool, forming a profile similar to turbulent velocity measured across a jet (Mih and Hooley 1972). The mainstream continues through the center of the pool to the next slot while one recirculation regions of higher turbulent are created on either side of the mainstream. And these recirculation regions with low turbulent provide resting places for fish.

Total 9 sets of experiments have been conducted. Among them, comparison between two experimental runs; run 6 (Lowest discharge, Q = 55 m3/hr) and run 7 (Highest discharge, Q = 145 m3/hr) have been represented here.

3.1 Results from Experiment Run 6

The distribution of the turbulent kinetic energy contour at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 6 in all 4 pools have been shown in figure 4, 5 and 6 respectively. From the velocity contour map analysis it is found that in most of the case maximum magnitude of turbulent kinetic energy occurs in between pools with two circulation pattern. In this figures the high turbulent kinetic energy is represented by red color which is ranged between 140 to 210 cm^2/s^2. The low turbulent kinetic energy zone is represented by blue color ranged 0 to 70 cm^2/s^2. These low velocity zones represents the resting place of fish to gain energy before entering the high velocity zone or crossing the pools. Table 2 shows Maximum Turbulent Kinetic Energy (cm^2/s^2) at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 6 in all 4 pools. Where maximum turbulent kinetic energy occurs at 0.8H at pool 3.

In natural settings, fish are subject to the influence of a complex water environment that impacts their movement behavior. The local velocity field plays a crucial role in shaping fish movement patterns. The alteration in fish movement orientation could serve as a mechanism to enhance the effectiveness and efficiency of fish locomotion.

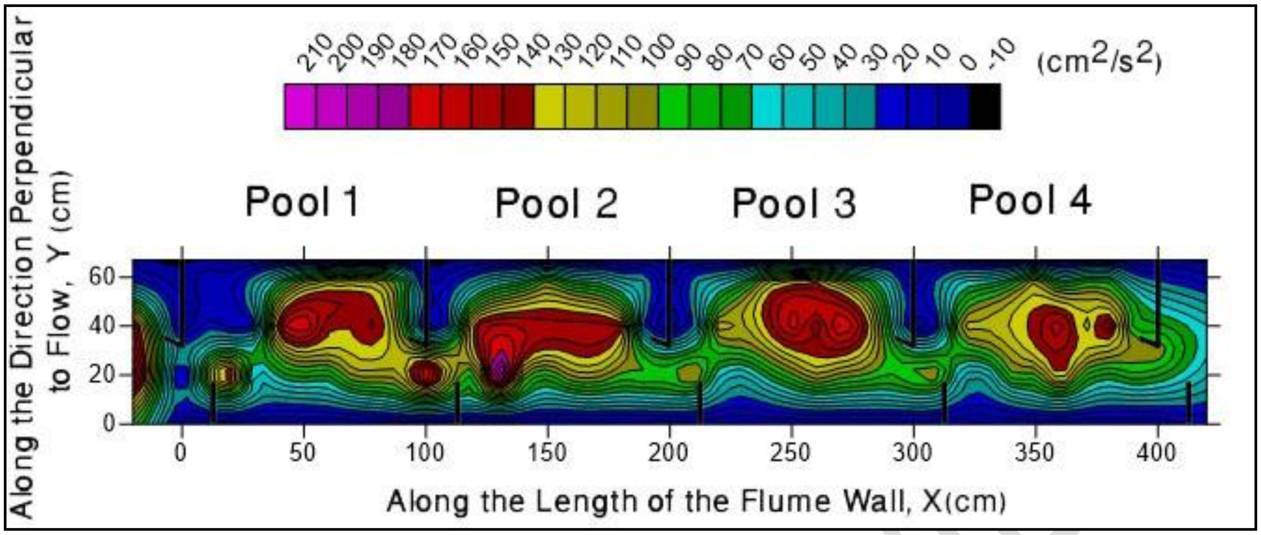


Figure 4: Turbulent Kinetic Energy contour map at 0.4 hydraulic depth in all 4 pools for experiment run 6

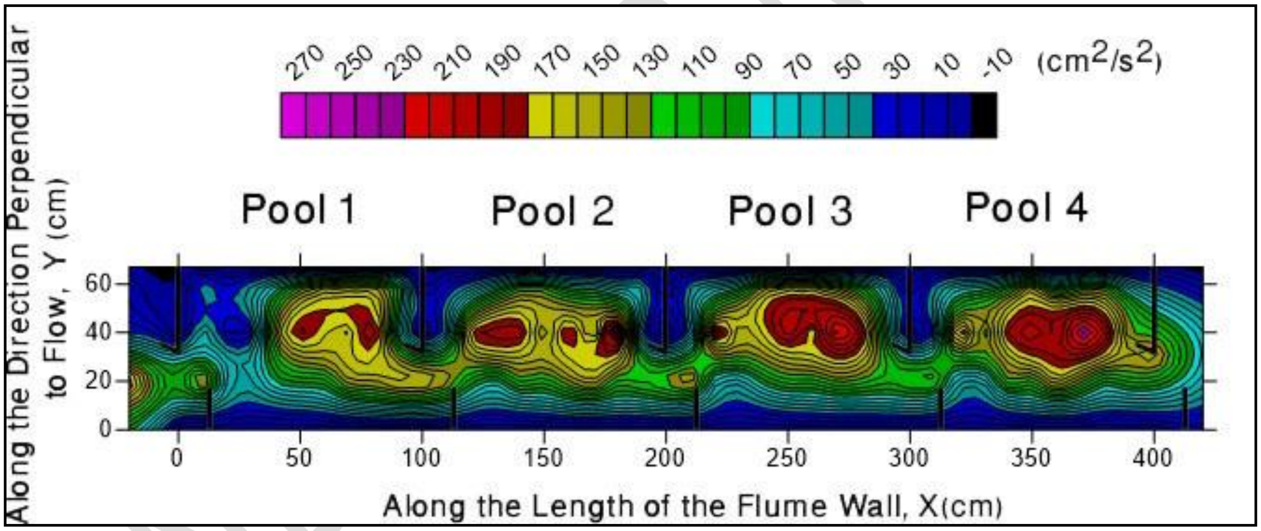


Figure 5: Turbulent Kinetic Energy contour map at 0.6 hydraulic depth in all 4 pools for experiment run 6

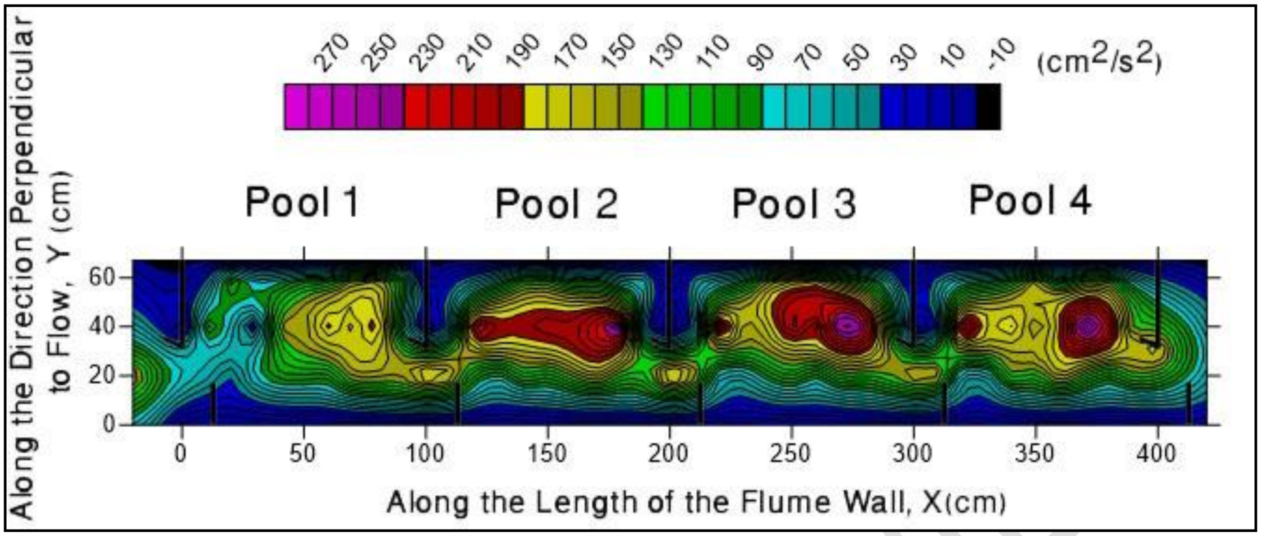


Figure 6: Turbulent Kinetic Energy contour map at 0.8 hydraulic depth in all 4 pools for experiment run 6

Table 2: Maximum Turbulent Kinetic Energy (cm^2/s^2) at a depth of 0.4H, 0.6H and 0.8H in all 4 pools for experiment run 6

Pool	Hydraulic Depth	Maximum Turbulent Kinetic Energy (cm^2/s^2)
Pool 1	0.4 H	182.598
	0.6 H	161.548
	0.8 H	166.958
Pool 2	0.4 H	163.02
	0.6 H	177.842
	0.8 H	174.658
Pool 3	0.4 H	185.82
	0.6 H	188.247
	0.8 H	194.754
Pool 4	0.4 H	170.658
	0.6 H	177.956
	0.8 H	184.956

3.2 Results from Experiment Run 7

The distribution of the turbulent kinetic energy contour at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 7 in all 4 pools have been shown in figure 7, 8 and 9 respectively. From the velocity contour map analysis it is found that in most of the case maximum magnitude of turbulent kinetic energy occurs in between pools with two circulation pattern. In this figures the high turbulent kinetic energy is represented by red color which is ranged between 360 to 520 cm^2/s^2. The low turbulent kinetic energy zone is represented by blue color ranged 0 to 160 cm^2/s^2. These low velocity zones represents the resting place of fish to gain energy before entering the high velocity zone or crossing the pools. Table 3 shows Maximum Turbulent Kinetic Energy (cm^2/s^2) at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 7 in all 4 pools. Where maximum turbulent kinetic energy occurs at 0.4H at pool 2.

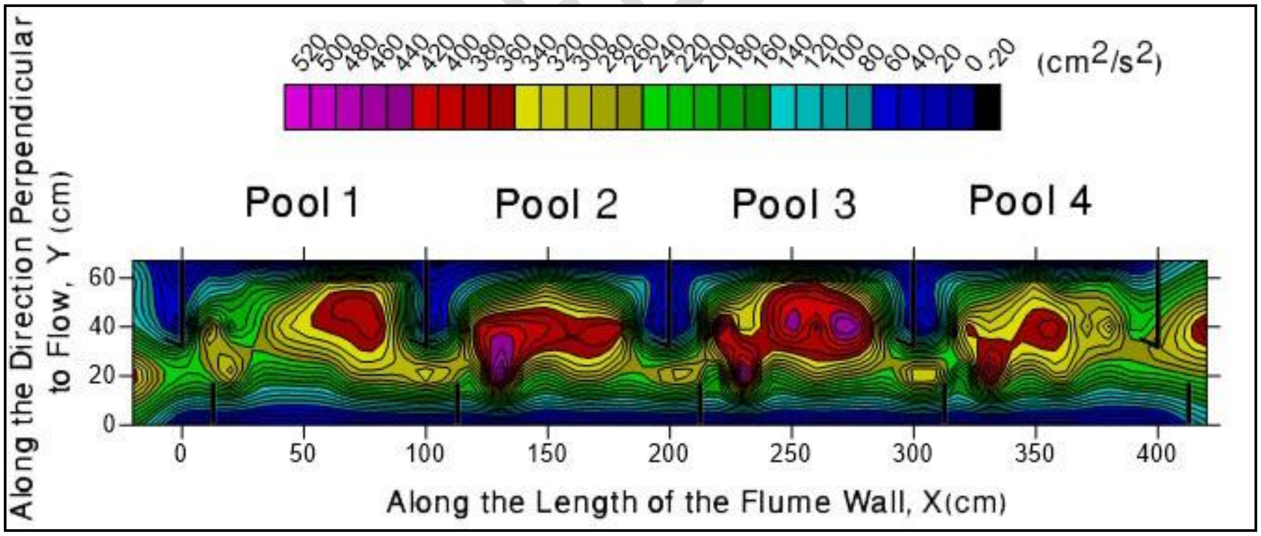


Figure 7: Turbulent Kinetic Energy contour map at 0.4 hydraulic depth in all 4 pools for experiment run 7

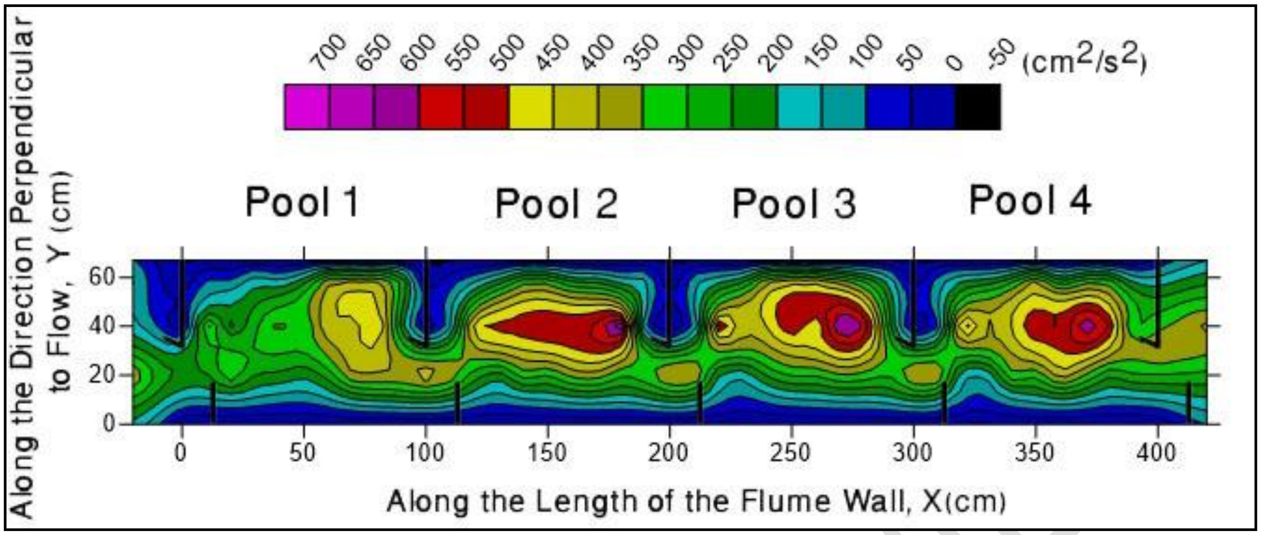


Figure 8: Turbulent Kinetic Energy contour map at 0.6 hydraulic depth in all 4 pools for experiment run 7

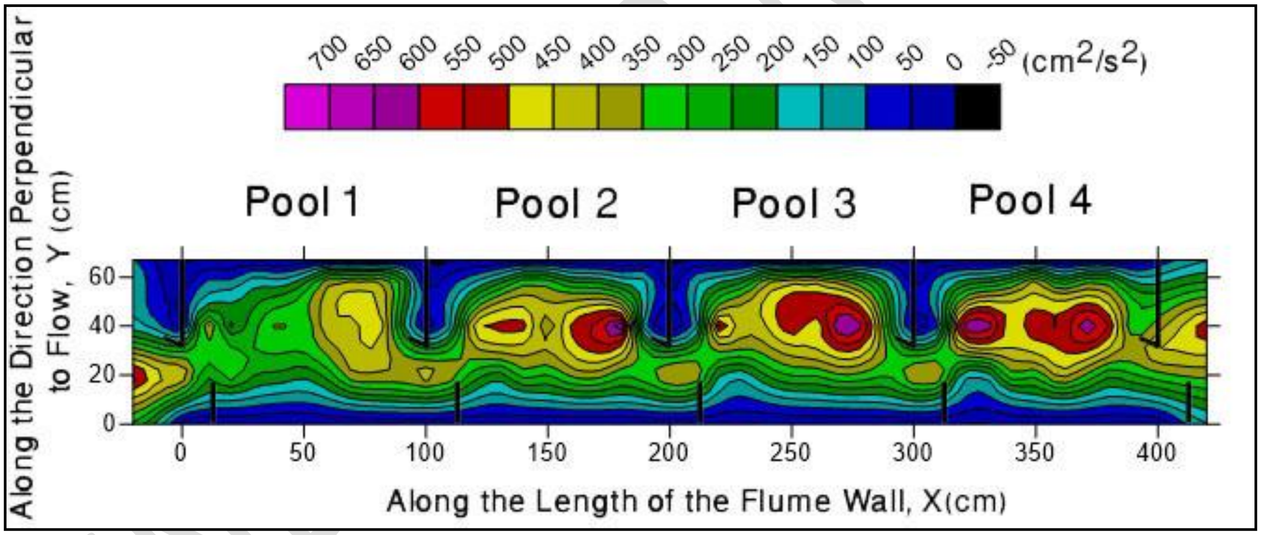


Figure 9: Turbulent Kinetic Energy contour map at 0.8 hydraulic depth in all 4 pools for experiment run 7

Table 3: Maximum Turbulent Kinetic Energy (cm^2/s^2) at a depth of 0.4H, 0.6H and 0.8H in all 4 pools for experiment run 7

Pool	Hydraulic Depth	Maximum Turbulent Kinetic Energy (cm^2/s^2)
Pool 1	0.4 H	402.487
	0.6 H	406.986
	0.8 H	422.658
Pool 2	0.4 H	564.451
	0.6 H	550.148
	0.8 H	562.478
Pool 3	0.4 H	499.968
	0.6 H	513.486
	0.8 H	477.628
Pool 4	0.4 H	501.689
	0.6 H	488.587
	0.8 H	481.293

4. FISH SWIMMING AND RESTING BEHAVIOR IN FISHPASS

1. Fishes have survived hundred percent in this fishpass , no mortality or fish injury occurred due to high turbulence.
2. The contour map of turbulent kinetic energy at different hydraulic depth in all 4 pools for experimental runs 1 have been observed from Figure 4 to Figure 6. Comparing the figures of all contour map of turbulent kinetic energy with Figure 7: fish movement and resting patter in the pools for different turbulence condition, it can be said fishes have avoided high turbulent kinetic energy area (red) in the contour map. The comparison shoes the area with low turbulent kinetic energy (blue) was most suitable for fishes to pass the pools or taking rest inside the pools.
3. They could enter into the fish pass opening with water flow and reached up to downstream without any injury.

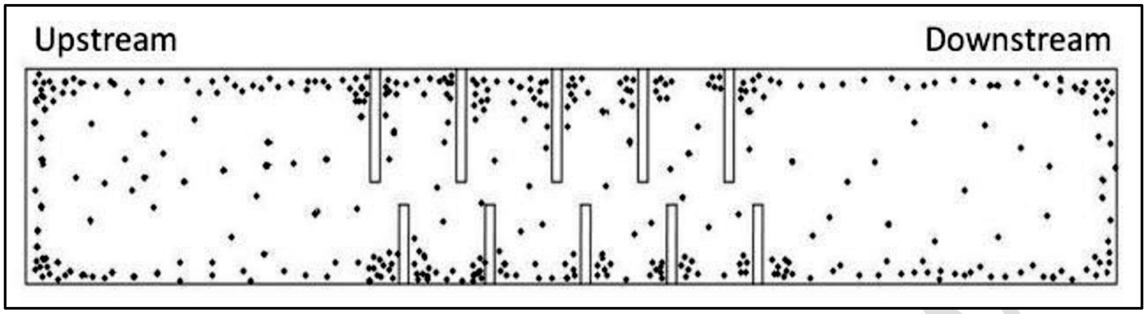


Figure 10: Fish movement and resting patter in the pools for different velocity and turbulence condition.

4.1 Group Swimming Behavior of Fishes

Migration of fishes typically occurs by group movements (Figure 8 and 9). In this experiment, the number of major fishes migrating together tended to increase water velocity, forming groups. When theycame to enter of fish passage (pool 1), the give the tail in front and passing with the water current. And when they enter from downstream (pool 4) they give the mouth or face to the chamber, and keep themselves free with the current. Water velocity was high, low and medium but it did not create any barrier for fishes. Mixed fishes moved with the water current and also moved against the water current. It can be said that fish size can be a barrier when fishes are alone, but when they are in group they can pass barrier without less straggle. Their speed were cruising and sustained. Survival of fishes increased with the size of the group of migrating fishes.

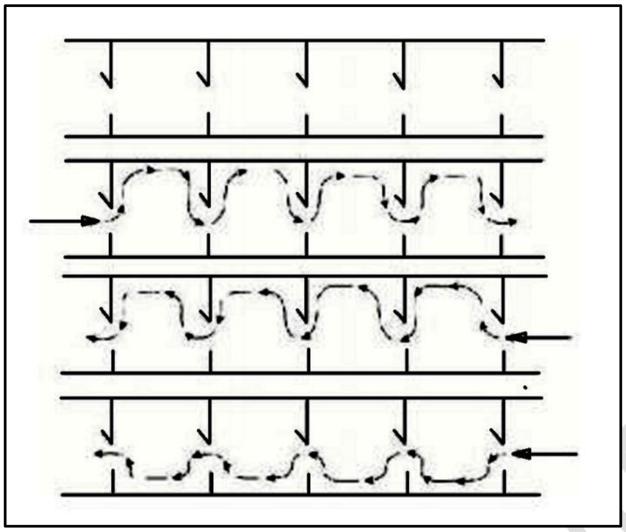


Figure 11: Path of fishes in individual movement to cross the fish pass.

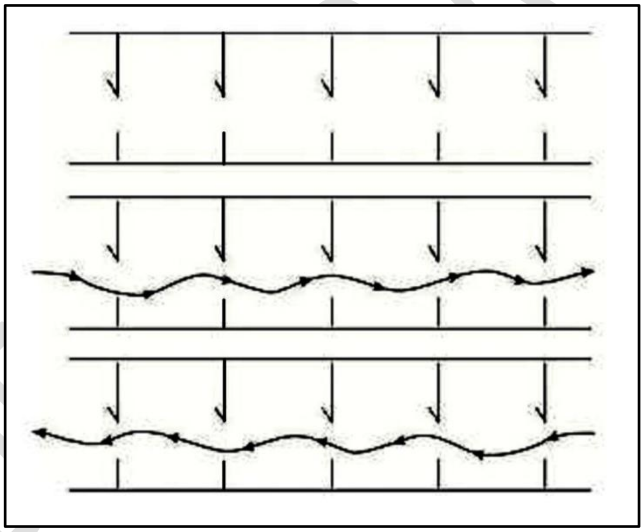


Figure 12: Path of fishes in group movement to cross the fish pass.

The primary objective of a fishway is to provide suitable swimming paths for fish, with the aim of facilitating their migration. Therefore, it is crucial to identify movement zones that are energetically favorable for fish migration. However, due to the absence of physiological experiments, the integration of physiological indices to better understand the interaction between fish behavior and hydraulic metrics remains an area for future research. It should be noted that the energy expenditure of fish in these studies may be conservative, and the conclusions drawn may not directly correspond to real-life fish passage scenarios. Nevertheless, this approach can still be valuable in the operation and management of fish passage systems, including those implemented in hydropower reservoirs and other fish bypass structures. By considering the energetic demands of fish during migration, these findings can inform decisions related to the design and optimization of fish passage facilities, enhancing their effectiveness in facilitating fish movement and conservation.

5. CONCLUSION

The growth rate of the jet in the pool is greater than that of a plane turbulent jet and the jet grows wider at planes close to the bed of the fishpass.Fish movement and resting patter in the pools for different turbulence condition, it can be said fishes have avoided high turbulent kinetic energy area (red) in the contour map. The comparison shoes the area with low turbulent kinetic energy (blue) was most suitable for fishes to pass the pools or taking rest inside the pools The results published in this article also provide helpful information about the eddy length scales and distribution within the jet and recalculating flow regions. These findings are important for understanding the potential effects of fish passage flow structure and would be useful to fish biologists and fishway developers.

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