THREE-DIMENSIONAL MODELLING OF FLOW IN A WEIR AND POOL TYPE FISHWAY WITH ORIFICES FOR DESIGN OPTIMZATION

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ABSTRACT

Anthropogenic obstacles across the water bodies which slow down and obstruct fish migration causes a high fish population shrinkage in natural water bodies. Appropriately designed fishways with suitable hydraulic conditions, contribute to mitigate these adverse effects by bypassing these anthropogenic obstacles. In the present study, flow in a weir and pool fishway with orifices was investigated by experimental and numerical modelling approaches to optimize the fishway design. The 3-D model was calibrated and verified using measurements obtained by laboratory experiments. The numerical model was then applied to compute the variation of water depth, velocity, turbulent kinetic energy and energy dissipation rate distributions for four fishway slopes ranging from 7% to 13% and for seven baffle arrangements. Experiments were conducted for the slopes, 11% and 13% by varying the downstream water depth to investigate the effect of tail water condition on fishway flow. The mild slope of the fishway geometry was shown to result in a fishway hydraulically suitable for fish passage, overcoming the fish fatigue. The maximum velocities in the fishway can be reduced by controlling the depth at the downstream of the fishways to further increase the fishway slope to economize the design while maintaining a suitable velocity pattern. Moreover, the study compares the hydrodynamics and assess the hydraulic suitability of eight baffle arrangements of weir and pool fishways. For this purpose, a computational fluid dynamics (CFD) model was used to examine the flow field characteristics and turbulence structure of flow maintaining constant discharge, slope, pool volume and size of orifices and weir.

Keywords: Weir and pool fishway, optimize, velocity, turbulent kinetic energy, energy dissipation rate

1. INTRODUCTION

Anthropogenic obstructions constructed across rivers cause a significant impact on the fish populations which seasonally undergo upstream and downstream migrations within the waterways to spawn, to feed, and to protect from predators and unfavorable environmental conditions. Fishways are the hydraulic structures integrated to these anthropogenic obstructions to mitigate their adverse impacts on fish migration and thereby to facilitate restoring the migratory fish populations in rivers to healthy levels. Fishways are sloped channels with intermediate in-channel devices called baffles, which act hydraulically together to produce flow conditions that are suitable for fish navigation (Katapodis, 1992). Fishways are broadly classified as weir and pool, Denil and Vertical slot according to the arrangement and geometry of these in-channel devices.

As found in Larinier (2008), currently, the most common fishways built at the small hydropower plants are weir and pool fishways which consists of a sequence of pools organized in a stepped pattern detached by cross walls called baffles. The baffles are equipped with overflow weirs and submerged orifices at the bottom which has two main objectives, i.e., to ensure adequate dissipation of the energy of water, with no carryover of energy from one pool to another and to offer resting areas for fish (Larinier and Marmulla, 2004). Notches are provided in the cross-walls for the passage of middle and surface swimmer fish while orifices can be provided in the weirs for lower depth swimming fish and to accommodate fish movement during dry seasons. The fish move from pool to pool by jumping or swimming depending on the water depth. Movement between pools require the burst swimming speed of fish and they can rest and gain energy at the pools for further ascending (Katapodis, 1992). The transportation of fish along the channel relies on the velocity in the fishway not exceeding the swimming ability of fish. These types of fishways are simple to construct, responsive to flow regime variations with oscillating water levels and it is the least expensive compared to other types (Katapodis, 1992).

An effective fishway attracts fish, allow them to enter, pass through and exit safely with minimum time and spending least amount of energy (Katapodis, 1992). Fish generally uses cruising (resting) speed for movement with less efforts, sustained speed which is moderately high for passage through difficult areas and burst speed to overcome high velocity regions. Biological requirements such as fish behavior, motivation, preferences, migration timing and swimming ability derive design and construction criteria of fishways (Katapodis, 1992). The proposed fishway at the Moragolla Hydropower Project (MHP), Sri Lanka has been designed using biological parameters of rare fish species; volume required for rare species, fish pass capacity and speed of fish (Nippon Koei and Fichtner, 2017). The optimal design for the upstream migration fish is reported as the straight type rectangular weir with both notch and orifice among three different designs for weir and pool fishway: Trapezoidal weir with notch, straight and zigzag type rectangular weir (Kim, 2001). Overall low slope of fishway is useful to overcome non optimal design dimensions and produce a fishway with hydraulics suitable for the fish passage (Marriner et al., 2016).

Fish normally tend to avoid strongly turbulent regions, because these regions reduce their critical speed and increases their energy expenditure (Enders et al., 2004). Low values of turbulent kinetic energy would be good for the passage of fish because fish normally avoid entering areas of high turbulence at sustained swimming levels (Bell. 1973). According to Quaranta et al (2017), based on fish swimming behavior, resting areas should maintain lower turbulent kinetic energy than in slot areas. Higher the energy dissipation rate, harder it is for fish to swim. Efficiency of fishway depends on the turbulence and aeration in the pools (Umeda et al., 2017).

Number of experimental and numerical studies on hydraulic performance of weir and pool fishways have been reported. Fishway hydraulics mainly depend on fishway geometry, channel slope and water depth. Among the reported studies, dimensionless discharge equations for weir and pool fishways, effect of slope, weir spacing and weir height on flow regimes, design configurations to develop a relationship between rock weir hydraulics and fish passage (Baki et al., 2017, Ead et al., 2004 and Quaresma et al., 2018) are noted, and findings are useful to develop prototypes. A comparison of hydrodynamics in two widely used vertical slot fishways (VSF) configurations and three multi slot fishway (MSF) configurations is also reported (Quaresma et al., 2018) .

Construction of fishway requires additional cost for a development projects, and the overall slope of a given fishway type matters the cost of the fishway (Marriner et al., 2016). The main objective of this study is to economize the fishway design by investigating the effect of fishway overall slope and tail water conditions on its hydraulic efficiency based on the lowest values of maximum velocity, maximum turbulent kinetic energy and average energy dissipation rate. Moreover, the study compares the hydrodynamics and assess the hydraulic suitability of eight baffle arrangements of weir and pool fishways. For this purpose, a computational fluid dynamics (CFD) model was used to examine the flow field characteristics and turbulence structure of flow maintaining constant discharge, slope, pool volume and sizes of orifices and weir.

2. METHODS

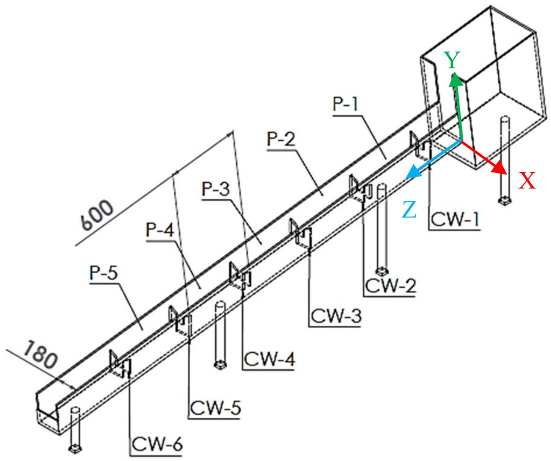
2.1 Experimental Setup

The impact of the fishway overall slope on its efficiency was tested in the experimental setup of weir and pool type fishway built in the Fluid Dynamics Laboratory, University of Peradeniya, Sri Lanka. The experimental setup was built to 1:5 geometric scale of the proposed fishway of Moragolla Hydropower Plant (MHP) with a slope of 11% (Nippon Koei and Fischtner., 2017). It's a flume of 4 *m* in length, 180 *mm* width and 250 *mm* height with five pools separated with six cross-walls. The slope of the fishway was adjustable, discharge and water depth at the downstream was adjustable. A constant discharge of 5.35 *l/s* which was determined using Froude similarity (Fr = 0.33) was maintained in all the experimental test cases in Table 1.

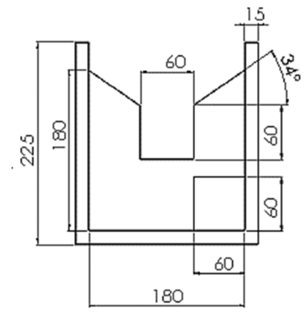
Table 1: Laboratory test cases

Test case	**I-1**	**I-2**	**I-3**	**I-4**	**II-3**	**II-4**
Slope	7%	9%	11%	13%	11%	13%
Downstream condition	With downstream control				Without downstream control	

Mean velocity point measurements at the orifice and notch were carried out using Model 801 Electromagnetic Flat Type Flow meter at 1.5 *cm* lateral spacing at a sampling frequency of 60 *Hz* to 0.001 *m/s* accuracy. Velocity measurements at a total of 100 points were recorded in this study for each slope of the fishway. The depth gauge was placed at the mid vertical plane of the experimental set up and water depth was measured at 40 *mm* intervals along the fishway to 0.1 *mm* accuracy.



(a)



(b)

Figure 1: (a) Experimental setup (P-Pool, CW-Cross-Wall) (b) Cross-wall dimensions (All dimensions are in millimeter)

2.2 Computational modelling

2.2.1 Governing equations

The multi-phase flow simulations were adopted using commercial software ANSYS-CFX, which uses finite volume method to solve the three-dimensional transport equations (1) and (2). It used the VOF (Volume of fluid) model to resolve the interface between water and air (Free surface).

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \left\{ (\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3}\rho k \delta_{ij} \right\}}{\partial x_j} + (\rho - \rho_a) g_a \tag{2}$$

Where i and j denotes 1, 2 or 3, x_1, x_2, x_3, denotes the longitudinal x, vertical y and transversal z directions respectively , u_1, u_2, u_3 are the average velocities in x, y, z directions respectively, δij is the kronecker delta, g is gravitational force, k is turbulent kinetic energy, μ is the molecular viscosity of the fluid, μt is the turbulent viscosity of fluid, p is the static pressure, ρ and ρ_a are the densities of fluid and air respectively. These equations use volume fraction of water and air for calculation of bulk density and viscosity terms as in (3) and (4) where, the subscript w and a used for water and air respectively and α for volume fraction.

$$\rho = \alpha_w \rho_w + \alpha_a \rho_a \tag{3}$$
$$\mu = \alpha_w \mu_w + \alpha_a \mu_a \tag{4}$$

The standard *k-ε* model, where ε is the turbulent kinetic energy dissipation rate is used to calculate turbulent viscosity. *k-ε* model is based on eddy viscosity concept so that,

$$\mu_{eff} = \mu + \mu_t \tag{5}$$

Where, μ_{eff} is the effective viscosity accounting from the turbulence. The *k-ε* model assumes the turbulence viscosity is linked to the turbulent kinetic energy and dissipation by the equation (4), where, C_μ is a constant

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{6}$$

2.2.2 Calculation domain, computational mesh and boundary conditions

The geometry of the fishway was developed using SOLIDWORKS 2013 and the calculation domain was extracted using ANSYS space-claim. Boundary conditions were defined at all the boundaries of calculation domain. Mass flow rate was specifies at the upstream inlet and the downstream was specified as a pressure boundary (hydrostatic pressure at the water region and atmospheric pressure at the air region). A turbulence intensity of 10% was defined at the inlet due to the strong turbulence and recirculation observed at the inlet. The free surface was treated as an open boundary with the atmospheric pressure. The bottom and cross-walls of the fishway was assumed as smooth and no-slip condition was applied.

The model used high resolution scheme for advection. Simulations were run under steady state conditions as a standard free surface model. The numerical iterations are continued until the residual of each parameter is less than 0.0001. Hex- dominant mesh of size 0.01 *m* was used to mesh the fluid domain. In order to check the mesh sensitivity, different mesh sizes ranging from 0.008-0.012 *m*, were used to simulate velocity field selecting one case - Case II-2. The changes observed in velocities were within 1%, and thus, mesh size of 0.01 *m* was used in the simulations. Water depths and velocities at orifices and slots were obtained from the simulation for the validation of model results. The maximum values of mean velocity, turbulent kinetic energy and energy dissipation rate were used for the evaluation of the effect of fishway overall slope and downstream water depth on fishway hydrodynamics.

2.2.3 Design modifications and evaluation

Numerical modelling was done for the existing geometry and Case (II-2) was selected as the optimum design. For optimizing the geometry further, seven modifications of the cross-wall arrangement were tested (effect of inclination to the horizontal and vertical). Figures 2(a)-2(e) show the plan view and 2(f) and 2(g) show the channel longitudinal cross section. Boundary conditions imposed were similar as in the section 3.2.1. In the arrangements (a)-(e), the cross-walls are inclined 15º to the horizontal, while in arrangement (f) and (g), they are inclined 15º to the vertical.

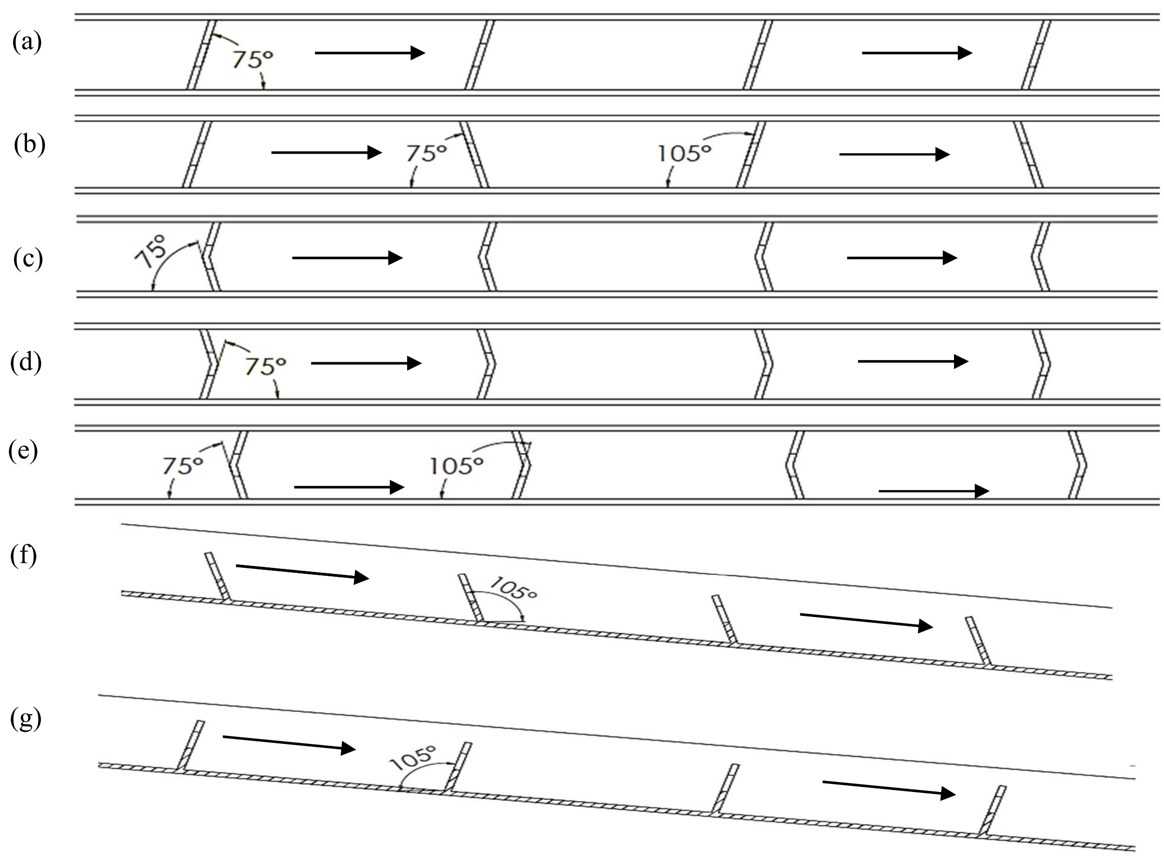


Figure 2: Cross-wall arrangements in design modifications (a)-(e) Plan views of the arrangements where the cross-walls are inclined 15º to the horizontal (f) and (g) Longitudinal sections of arrangements where cross- walls are inclined 15º to the vertical

The average pool volume, discharge, slope and size of orifice and notch were kept constant and the design alterations in the study are evaluated based on the maximum velocity of jet flow through orifice (V_{M0}), maximum velocity of flow over notch (V_{MN}), maximum turbulent kinetic energy (TKE_M), maximum turbulent kinetic energy dissipation (ε_M) and percentage of low velocity fishway volume ($PV_{L\%}$). Typically the low values of maximum velocity and turbulent kinetic energy are favourable for fish passage. The low velocity pool volume is obtained by considering the sustained speed of fish, which is the resting speed with less efforts.

3. RESULTS AND DISCUSSION

3.1. CFD model validation

The free surface profile at middle vertical plane parallel to Y-Z and the water velocities at the notches and orifices in cross-walls 02-06 at the depths of 2 *cm*, 3 *cm*, 10 *cm*, 12 *cm* and 13 *cm* from the pool floor level were compared in all the six cases. The velocity comparison of flow over the weir in Case II-3 and the water depth comparison in the Case II-4 are in Figures 3(a) and 3(b) respectively. According to the comparisons, there is a good agreement between experimental and numerical model results.

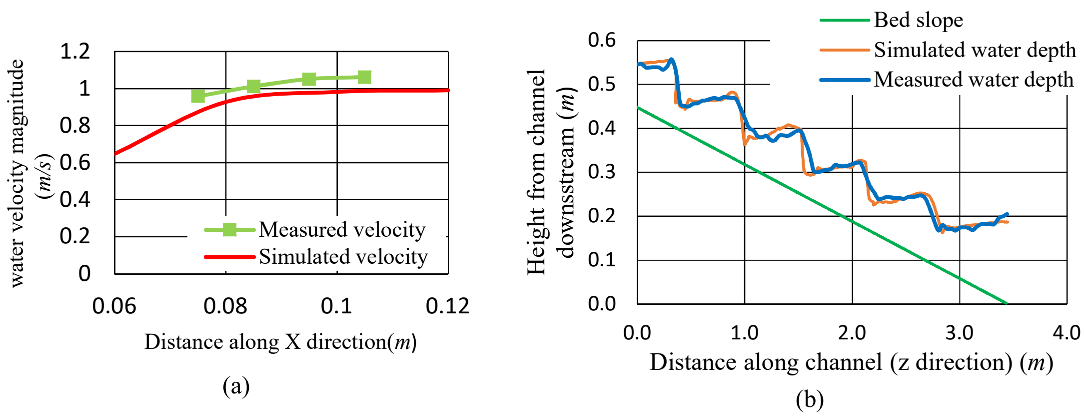


Figure 3: CFD model validation results (a) Velocity comparison in y-z plane at 10 cm above channel at the downstream of baffle No. 02 in Case II-3 (b) Comparison of experimental and simulated water surface profile in Case II-4

3.2. Computation results

Tables 2 indicates the values of hydrodynamic parameters that affect the fishway efficiency, maximum mean velocity (U_M), the maximum turbulent kinetic energy (TKE_M) and maximum average energy dissipation rate (ε_M) for the six simulated test cases (Table 1). Results show that the U_M, TKE_M and ε_M increases with the increasing slope. Therefore, lower overall slopes are favourable for fish passage. However, these increases can be reduced by increasing the tail-water depth and thus to maintain high fishway efficiency even at higher slopes. The calculated U_M of the prototype base on Froude similarity is given in the Table 3. The burst speed of river water fish prescribed by Central Inland Fisheries Research Institute, (CIFRI) Kolkata is ranging from 4 *m/s* to 7 *m/s* (Das and Hassan, 2008). Thus, even the 13% slope was acceptable with a raised tail-water depth (Case II-4). Therefore, fishway designs can be economized by increasing the slope and controlling the downstream water depth so that the U_M does not exceed the burst speed, which is the maximum attainable swimming speed by ascending fish. The estimated maximum velocities in the prototype are below this range. Therefore, the fishway of slope 13% was found to be acceptable.

Table 2: Maximum values of velocity, turbulent kinetic energy and energy dissipation rate in simulation test cases

Test Case	I-1	I-2	I-3	I-4	II-3	II-4
U_M (*m/s*)	1.04	1.10	1.96	2.0	1.23	1.40
TKE_M (m^2/s^2)	0.17	0.17	0.21	0.26	0.19	0.24
ε_M (m^2/s^3)	1.60	1.84	3.05	3.98	2.24	3.04

Table 3: Calculated maximum velocities in prototype

Test Case	I-1	I-2	I-3	I-4	II-3	II-4
U_M (*m/s*) -model	1.04	1.10	1.96	2.0	1.23	1.40
U_M (*m/s*) -prototype	2.33	2.45	4.38	4.47	2.74	3.12

3.2.1 Velocity field and flow patterns

According to the velocity contour plots derived from the results, all the cases studied here show similar flow patterns with maximum velocities at the orifices and notch while preserving some low velocity recirculation zones as resting areas for the ascending fish. Case (II-4) which is the most economical design, was selected for further analysis.

Two major flow patterns were observed in the upper and lower water depths of fishway (Figs.4 & 5). Fig.4 depicts the flow pattern I at lower depths through the orifice. Submerged jet flow through the orifice moves from one side of the pool to the next orifice on the opposite side of the pool. Beside the jet flow through pool, a large flow recirculation region with low velocities is observed. Therefore, alternating orifices allow water to skip to the next pool, preserving some of the pool volume as resting areas for fish ascending the fishway. Fig. 4 also show that the flow pattern I exists in all design modifications with different baffle orientations.

The flow pattern II is the flow over the weir (Fig. 5). The nappe from the upstream notch with high velocity bends towards the side of the pool where the baffle's orifice is located and flows through that side of the pool to the next notch. Recirculation area is formed at the other side similar to the flow pattern I. Therefore, the alternating orifices cause weir flow to form recirculation regions with low velocities for the fish to rest. According to these flow patterns, there is a large resting area on alternating side of pools throughout the flow depth. Flow pattern II over the notch is similar in all the design modifications as shown in Fig. 5.

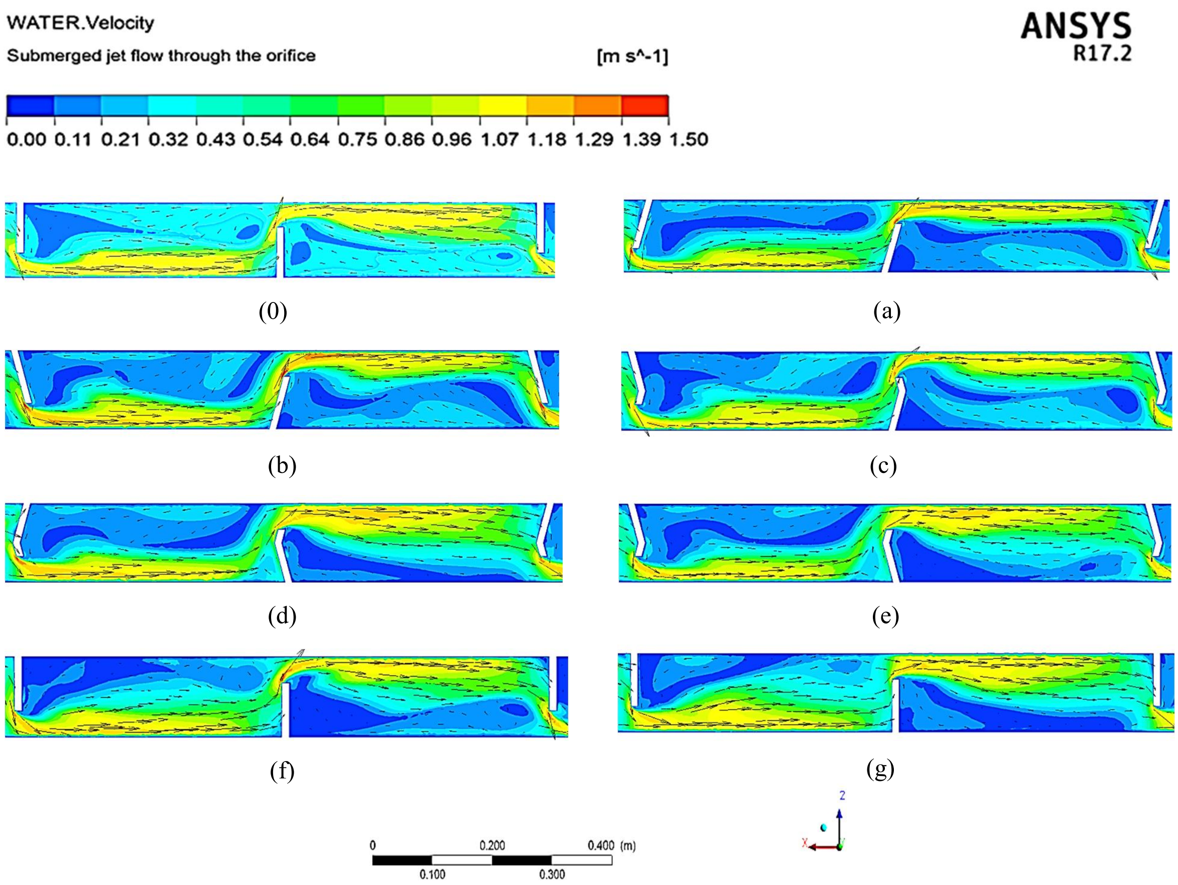


Figure 4: Flow pattern I – submerged jet flow through the orifice in the pools 3 and 4 at 2 cm from the pool bottom
(0) Baffle arrangement of proposed fishway at Moragolla Hydropower project (a)-(g) Studied baffle arrangements as in the section 2.2.3

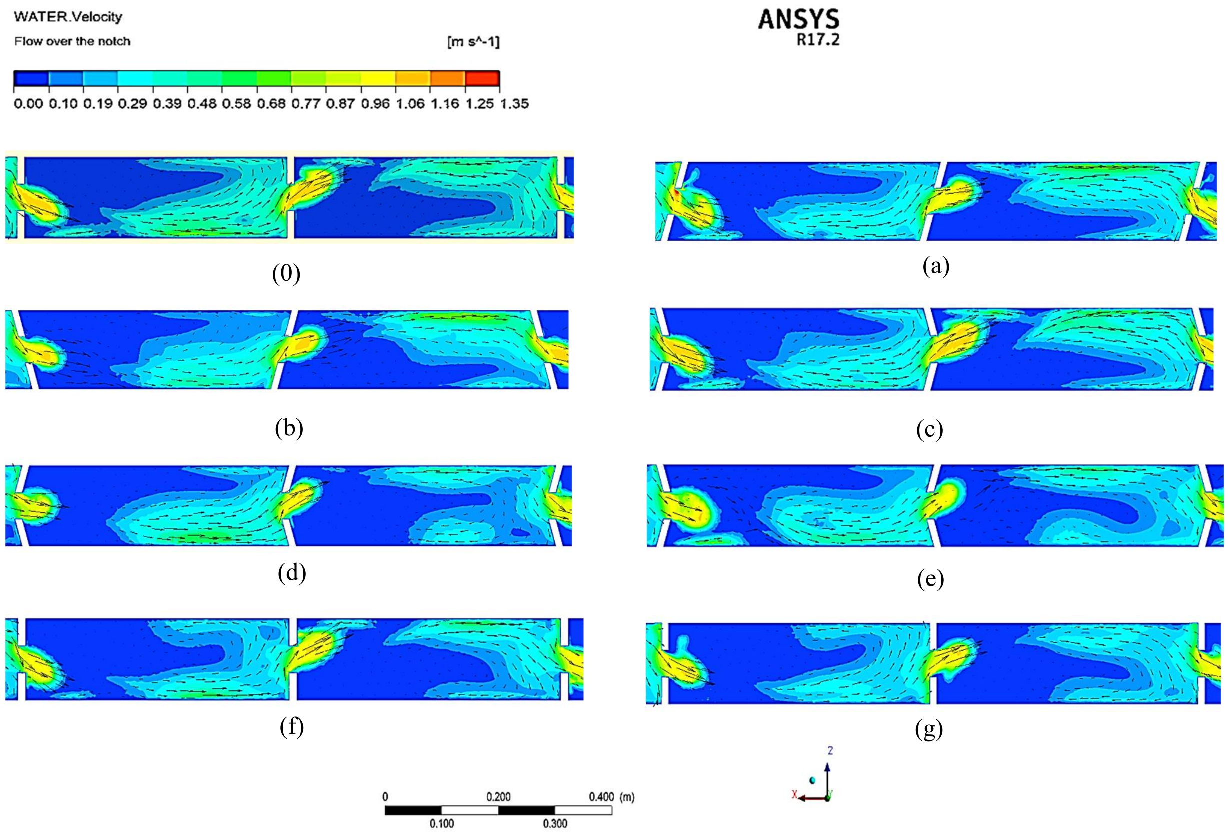


Figure 5: Flow pattern II –flow over the notch in the pool 3 and 4 at 10 cm from the pool bottom (0) Baffle arrangement of proposed fishway at Moragolla Hydropower project (a)-(g) Studied baffle arrangements as in the section 2.2.3

The values of V_{M0}, V_{MN}, TKE_M, ε_M and $PV_{L\%}$ changes in different design considerations according to the Table 4. In all the configurations, submerged jet flow through the orifice presents higher maximum velocity magnitudes compared to the flow over the notch. More than 60% of fishway volume has mean velocity magnitudes less than 0.67 *m/s* in prototype, which is the maximum sustained speed (Resting speed with less efforts) (Das and Hassan, 2008). The lowest V_M, lowest ε_M and maximum $PV_{L\%}$ is observed in the design configuration, ‘d’, making it the best configuration among the studied designs. The lowest TKE_M was observed in the configuration, ‘f’ while, ‘d’ has the third lowest maximum TKE which is 12% higher than TKE_M in ‘f’. The calculated maximum velocity for the prototype based on Froude similarity is shown in Table 4. Burst speed range of target river water fish in the proposed fishway in the MHP is 4 *m/s* to 7 *m/s* (Nippon koei and Fichtner, 2017). The obtained maximum velocities in all design configurations are below this range. Therefore, all the fishway designs with 13% slope was found to be acceptable.

Table 4: Variation of V_{MO}, V_{MN}, TKE_M, ε_M, and $PV_{L\%}$ in different fishway design configurations (V_{MO} - Maximum velocity of jet flow through orifice, V_{MN} - Maximum velocity of flow over notch, TKE_M - Maximum turbulent kinetic energy, ε_M - Maximum turbulent kinetic energy dissipation and $PV_{L\%}$ - Percentage of low velocity fishway volume)

Design Configuration	**V_{MO} (*m/s*)**	**V_{MN} (*m/s*)**	**TKE_M (*m^2/s^2*)**	**ε_M (*m^2/s^3*)**	**$PV_{L\%}$**		**V_M (m/s) (model)**	**V_M (m/s) (prototype)**
					% of Total Volume	**% of Water Volume**		
0	1.40	1.28	0.25	11.22	30.83	62.62	1.40	3.12
a	1.47	1.45	0.30	20.35	32.22	65.31	1.47	3.29
b	1.50	1.35	0.30	12.57	32.50	66.00	1.50	3.35
c	1.49	1.32	0.37	14.32	31.73	66.06	1.49	3.32
d	1.34	1.32	0.28	10.74	32.58	66.04	1.34	3.00
e	1.36	1.23	0.35	13.05	27.34	63.30	1.36	3.03
f	1.46	1.25	0.25	10.99	30.93	65.42	1.46	3.25
g	1.44	1.40	0.34	19.77	31.66	65.48	1.44	3.22

The configuration ‘d’ is the most suitable design for lower depth swimming fish and to accommodate fish movement during dry seasons because it has the lowest V_{MO} while, the configuration ‘f’ is the most suitable design for surface and middle swimmer fish and to accommodate migration in wet seasons since it has the lowest $V_{MN.}$

4. CONCLUSIONS

1. The computed velocity fields show the occurrence of two distinct flow patterns at lower and higher depth levels in the pools of weir and pool type fishways with bottom orifices. Moreover, there exists a region of low velocity required for ascending fish to rest although high velocities occur at the orifice and the notch.
2. The model is a useful tool for selecting the optimum slope and baffle arrangement for an economical construction of orifice and weir type fishway while satisfying the flow conditions conducive for the target fish to ascend through it.
3. Economic design of steeper weir and pool type fishways with high fishway efficiency is feasible by controlling the depth at the downstream of the fishway. For the proposed fishway of the MHP, where the burst speed of target fish is in the range of 4 *m/s* to 7 *m/s*, the fishway slope of 13% is found to be acceptable with downstream depth control.
4. The design configuration ‘d’ was found to be the most optimum baffle arrangement compared to the other seven arrangements. Also it is the best arrangement for lower swimmer fish and to accommodate fish movement during dry seasons.
5. The design configuration ‘f’ was found to be the most optimum baffle arrangement for middle and surface swimmer fish and to accommodate fish movement during wet seasons.

6. REFERENCES

Baki, A., Zhu, D., Harwood, A., Lewis, A. and Healey, K. (2017). Rock-weir fishway II: design evaluation and considerations. *Journal of Ecohydraulics*, 2(2), pp.142-152.

Bell, M. (1973). Fisheries Handbook of Engineering Requirements and Biological Criteria. Portland, Oregon: Fisheries-Engineering Research Program, Corps of Engineers, North Pacific Division.

Das, M.K. and Hassan, M.A. (2008). Statutes of Fish Migration and passes with Special Reference to India (Central Inland Fisheries Research Institute Bulletin no.156)

Ead, S., Katopodis, C., Sikora, G. and Rajaratnam, N. (2004). Flow regimes and structure in pool and weir fishways. *Journal of Environmental Engineering and Science*, 3(5), pp.379-390.

Enders, E., Boisclair, D. and Roy, A. (2005). A model of total swimming costs in turbulent flow for juvenile Atlantic Salmon (Salmo salar). *Canadian Journal of Fisheries and Aquatic Sciences*, 62(5), pp.1079-1089.

Katopodis, C. (1992). Introduction to fishway design. Freshwater Institute, Central and Arctic Region, Department of Fisheries and Oceans, 501 University Crescent, Winnipeg, Manitoba, Canada, pp. 3-6.

Kim, J. (2001). Hydraulic characteristics by weir type in a pool-weir fishway. *Ecological Engineering*, 16(3), pp.425-433.

Larinier, M. (2008). Fish passage experience at small-scale hydro-electric power plants in France. *Hydrobiologia*. 609, pp.97–108

Larinier, M., Marmulla, G. (2004). Fish passes: types, principles and geographical distribution - an overview. In *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries*, Phnom Penh, Kingdom of Cambodia, volume II.

Marriner, B., Baki, A., Zhu, D., Cooke, S. and Katopodis, C. (2016). The hydraulics of a vertical slot fishway: A case study on the multi-species Vianney-Legendre fishway in Quebec, Canada. *Ecological Engineering*, 90, pp.190-202.

Nippon Koei & Fichtner (2017). Fish Ladder, Moragolla Hydropower Project, Ministry of Power and Renewable Energy, Ceylon Electricity Board, Democratic Socialist Republic of Sri Lanka

Quaranta, E., Katopodis, C., Revelli, R. and Comoglio, C. (2017). Turbulent flow field comparison and related suitability for fish passage of a standard and a simplified low-gradient vertical slot fishway. River Research and Applications, 33(8), pp.1295-1305.

Quaresma, A., Romão, F., Branco, P., Ferreira, M. and Pinheiro, A. (2018). Multi slot versus single slot pool-type fishways: A modelling approach to compare hydrodynamics. *Ecological Engineering*, 122, pp.197-206

Umeda, C., Lima, G., Janzen, J. and Salla, M. (2017). ONE- AND THREE-DIMENSIONAL MODELING OF A VERTICAL-SLOT FISHWAY. *Journal of Urban and Environmental Engineering*, 11(1), pp.99-107.