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NUMERICAL MODELLING OF ROCK-WEIR TYPE NATURE-LIKE FISHPASSES

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ABSTRACT

In recent years many migration barriers have been replaced by nature-like fishpasses to mitigate the effects of human development and habitat fragmentation on fish. This research study numerically investigated the complex flow characteristics in rock-weir type nature-like fishpasses for different structure geometries and channel characteristics to optimize design. Initially, the numerical model was validated with physical model results and good agreement was achieved. As part of this research, the study described herein examined the flow characteristics of rock-weir fishpasses with and without passage slots/notches. We investigated physical characteristics within rock-weirs with and without notches to determine how they affect the hydraulics within the structures, focusing on water surface profiles, local velocity fields, volumetric energy dissipation rates, fish resting zones, and fish passage performance. It is hoped that the results of this study will advance our knowledge on flow in a rock-weir fishpass and be useful to fishpass designers and fish biologists.

Keywords: - Computational fluid dynamics, hydraulics, energy dissipation, resting zone, and rock-weir fishpass.

1. INTRODUCTION

The fragmentation of the longitudinal river corridor by different hydraulic structures (e.g., weirs, dams, and culverts) represents a major global human impact on running waters (Jungwirth 1998). This fragmentation has a negative effect on fish movement and dispersal (Yamamoto et al. 2004). To mitigate these effects of human development and habitat fragmentation on fish, considerable effort has been expended in recent years to provide passage at migration barriers via construction of nature-like fishpasses (NLFs) (DVWK 2002). NLF designs generally fall into two categories: pool-weir type and rock-ramp type. Pool-weir fishpasses are constructed using a series of weirs and pools in a stepped fashion, rather than having a single large drop (Katopodis and Williams 2011). Pool-weir type structures are designed in consideration of fish passage goals and the physical setting; common structures include rock-weirs, step-pools, and crossbar block ramps (Baki et al. 2017a). Rock-weirs are composed of boulders in rows at regular intervals to form a series of pools, which provide resting zones for migrating fish (Baudoin et al. 2014). The rock-ramp fishpass consists of a long sloping channel interspersed with boulders providing resting places for fish swimming upstream (Baki et al. 2014; 2015; 2016). They are typically constructed of boulders, cobble, and other natural materials to create diverse physical and hydraulic conditions providing efficient passage to multiple species including migratory and resident fish assemblages (Turek et al. 2016).

Generally, a NLF is designed to function by providing passable conditions over a range of flows from the 95% (low) to 5% (high) flow exceedance during periods when migrating fish are normally present at the site (NMFS 2008). The target/design flow regime, determines the size of boulder that will be used in the rock-weir design: boulder size is typically uniform if the NLF is designed for a constant flow (Baki et al. 2017a; 2017b; Kupferschmidt 2015), whereas two different sizes of boulders are used if multiple design flows are contemplated (DVWK 2002; Wang and Hartlieb 2011; Oertel and Schlenkhoff 2012; Baudoin et al. 2014; Turek et al. 2016; Baki et al. 2017c). The use of both small and large boulders provides small passage openings, hereafter called notches, which guarantee a minimum water depth over the weirs and maintain connectivity between pools at low flows to allow fish to pass (Oertel and Schlenkhoff 2012). Typically, fish preferentially pass through weir openings rather than over weir crests (Turek et al. 2016). With increasing flow rates, the water overflows the larger sized boulders and the flow regime changes from a transitional flow regime to a streaming flow regime (Baki et al. 2017a).

Depending on specific project goals, researchers have proposed various configurations of pool-weir type NLF structures. Recently, several laboratory experiments, numerical modelling, and field studies have been carried out to examine the local flow patterns associated with rock/boulder-weirs (Thomas et al. 2000; Rosgen 2001; DVWK 2002; Haro et al. 2008; and Meneghetti 2009). Thomas et al. (2000) and Rosgen (2001) proposed conceptual designs for rock-vortex structures, DVWK (2002) provided some guidelines for crossbar block ramps, Baudoin et al. (2014) proposed pre-assessment procedures for rock-weirs, and Wang and Hartlieb (2011) and Oertel and Schlenkhoff (2012) investigated flow characteristics for crossbar block ramps using physical and numerical models. Recently, Turek et al. (2016) reported some guidelines for rock-weirs with passage notches specifically designed for the target fish species. Cox (2005) found that available guidelines and literature related to pool-weirs were scarce and consistently lacked investigation of hydraulic properties and/or performance.

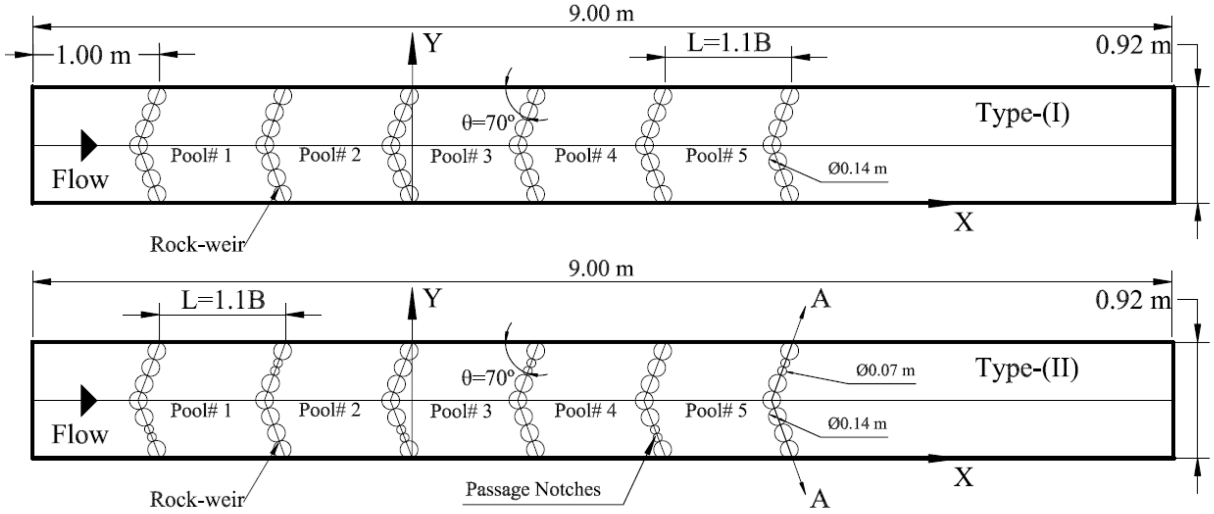
The studies conducted to date have usually focused on the hydraulics associated with a single or limited range of rock-weir geometries. None of these efforts have linked the physical/numerical processes associated with weir performance to variations in weir structure geometry. Due to the lack of reliable design guidance for the rock-weir fishpasses, this research study attempts to develop a physical/numerical model matrix to investigate the physical characteristics within rock-weirs and how variations in structure geometry affect local hydraulics. This study is part of a NSERC IRDF research project on rock-weir type NLFs, which was undertaken at Ecofish Research Ltd. in collaboration with the University of Alberta. The objective of this research study was to examine the complex flow characteristics and to optimize the design and construction of rock-weir type NLFs, so that they can be used to pass fish at run of river hydroelectric projects. Part of the outcome of this research, the numerical modeling results for the NLFs, is presented in this paper.

2. NUMERICAL MODELLING APPROACH

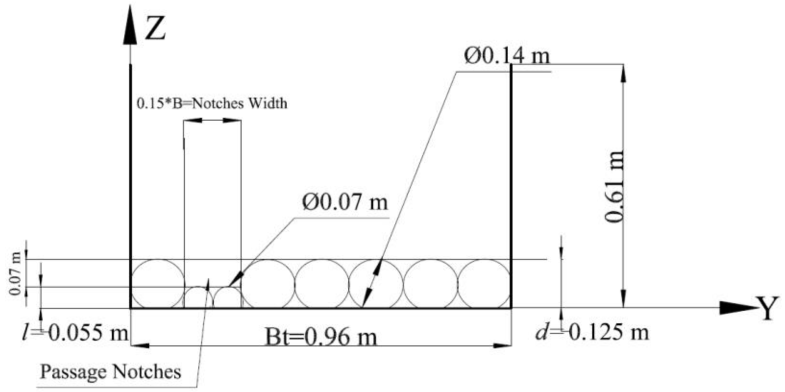
The numerical model was based on an experimental rock-weir fishpass, installed in a rectangular flume 0.92 m wide, 0.61 m tall, and 8.89 m long at the T. Blench Hydraulics Laboratory of the University of Alberta (more details in Kupferschmidt 2015). The model domain was 9 m in length consisting of six rock-weirs and five pools (
Figure **1**), with a constant bed slope of 3%. Weirs were arranged in a V-shape with the V facing in the upstream direction having an arm angle (θ) of 70 degrees, plan view angle of departure from bankline (
Figure **1**a). The domain included two different types: Type (I) - without notches and Type (II) - with notches. In (I), the rock-weirs consisted of a single size of boulder having 14 cm in diameter (*D*) and weir height of d = 12.5 cm from the bed, meaning 1.5 cm was embedded in the channel bed (
Figure **1**a). In (II), the boulders in the weirs consisted of two different sizes: larger boulders 14 cm in diameter and smaller boulders 7 cm in diameter (bringing the weirs to the height of 12.5 cm and 5.5 cm

above the bed, 1.5 cm was embedded in the channel bed), resulting in an opening height of 7 cm in the passage notches (Figure **1**a&b). Simulations were conducted varying the flow through the fishpasses (Table 1) from 0.03 m^3s^{-1} to 0.15 m^3s^{-1} in Series-A and -B.

The numerical simulations were conducted using a commercial software ANSYS-CFX. This CFD model solves the three-dimensional Reynolds-averaged Navier-Stokes equations using the finite volume approach. The standard k - ε turbulence model was used to determine the turbulent viscosity. The performance of the numerical model was validated with a series of experimental observations for water depth and velocity, and good agreement was achieved. A complete outline of the model, model development, corresponding boundary conditions, and model validation is provided in Baki et al. (2017a).



(a) Plan View



(b) Cross-sectional View (A-A)

Figure 1: (a) Plan view of CFD model domain for the Type: (I) without notches and (II) with notches, and (b) cross-sectional view of A-A in (II).

3. RESULTS AND DISCUSSIONS

1.1 Water surface profiles

The dimensionless longitudinal water surface profiles along the channel center line under the without and with notch alternatives are plotted in Figure 2 for different flow conditions in Series-A and -B. For both series from 0.03 to 0.06 m^3s^{-1} (A1-4, B1-4), a short hydraulic jump appeared immediately downstream of the weir crest and then a horizontal water surface existed. For 0.085 to 0.15 m^3s^{-1} (A6-9, B6-9), a long hydraulic jump and oscillating water surface appeared. Evaluation of the flow fields, especially the water surface profiles and hydraulic jump for 0.03 to 0.06 m^3s^{-1} compared to 0.085 to 0.15 m^3s^{-1}, confirmed two different flow regimes: weir flow regime and transitional flow regime (Chanson 1994; Dust and Wohl 2012; Baki et al. 2017a).

Table 1: Descriptions of all Simulations.

Simulation	Flow (m^3/s)	Bed Slope (%)	Boulders Diameter (cm)	C_g[*] (coefficient)	θ[^] (degrees)	Pool Spacing, L	Type
A1	0.030	3	14	0	70	1.1B	(I) Without Notches
A2	0.040						
A3	0.050						
A4	0.060						
A5	0.075						
A6	0.085						
A7	0.100						
A8	0.120						
A9	0.150						
B1	0.030	3	14, 7	0.15	70	1.1B	(II) With Notches
B2	0.040						
B3	0.050						
B4	0.060						
B5	0.075						
B6	0.090						
B7	0.110						
B8	0.130						
B9	0.150						

[*] Passage notches width = $C_g \times B$, where B is the channel width.

[^] Arm angle (θ), plan view angle of departure from bankline.

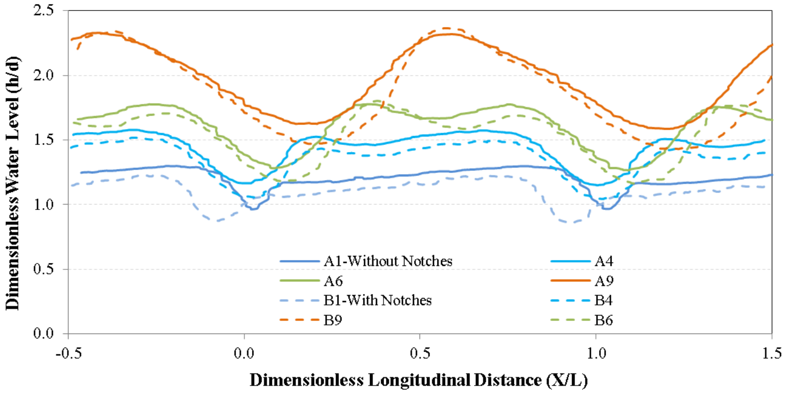


Figure 2: The dimensionless water-surface profiles along the center line of the flume in Series-A (A1= 0.03 m^3s^{-1}, A4=0.06 m^3s^{-1}, A6= 0.085 m^3s^{-1}, and A9= 0.15 m^3s^{-1}) and -B (B1= 0.03 m^3s^{-1}, B4=0.06 m^3s^{-1}, B6= 0.09 m^3s^{-1}, and B9= 0.15 m^3s^{-1}).

In general, the water level for the rock-weirs with notches is less than the water level without notches for each flow condition. The water level in Series-A without notches varied from 15.1 to 24.6 cm and in Series-B with notches 13.8 to 23.4 cm, and was ~7% higher for Series-B with notches. This result is expected as the passage notches provide additional openings to direct flow into the pool, reducing the obstruction of flow and decreasing the pool water depth due to less backwatering.

1.2 Flow pattern and velocity field

The local flow fields are important in the design of rock-weirs because they can affect fish passage and overall structure performance (Baki et al. 2017a). This study investigated the local flow patterns in a pool on the horizontal plane parallel to the bed at z = 0.5H for different flow conditions in Series-A (without notches) and -B (with notches) (Figure 3 and Figure 4, respectively), where *H* is pool averaged water depth along the center line of the channel.

In Figure 3, immediately downstream of the weir crest in the Series-A trials, the alignment of flow is directed towards the center of the downstream pool, which is similar to that observed in step-pool structures (Thomas et al. 2000). As a result, it prevents flow being directed towards the outer banks, directing scour away from the banks towards the centre of the channel and limiting bank erosion (Thomas et al. 2000). As the flow approaches the upstream side of the weir, the alignment of flow changes direction from center line and diverges towards the channel banks. The flow is spread over the weir instead of concentrated in the center line of the weir. The flow alignment in a pool, towards center line and then the channel banks, generates flow re-circulation zones along both channel banks (Figure 3). The two dimensional (transverse and longitudinal directions) extent of the high velocity zone and re-circulation zone in the pool increases with increasing flow rates, resulting in the reduction of pool low velocity zones (discussed later). In general the flow pattern in Series-B with notches is the same as that in Series-A (Figure 4).

The magnitude and extent of the high velocity zone, and re-circulation zone in the pool, varied from without notches to with notches. The maximum velocity (U_{max}) in all simulations occurred in the location of notches (Figure 4), whereas all simulations without notches U_{max} occurred along the channel center line (Figure 3). Moreover, the magnitude of U_{max} in Series-B with notches was ~20% greater than in series-A without notches due to a reduced backwatering effect. The flow recirculation zone and the slow velocity area in Series-B were larger than in Series-A due to flow being concentrated to one side of the pool.

The maximum velocity reduction, η, was calculated to quantify the effects of notches for different flow condition as follows:

[1] $\eta = (V_o - U_{max})/(V_0 * 100)$

where, V_0 is the pre-structure velocity referring to the normal depth. The results confirmed that the maximum velocity reduction η decreased from 45% to 37% when the flow rate increased from 0.03 m^3s^{-1} to 0.15 m^3s^{-1} in Series-A. Similarly in Series-B, η decreased from 30% to 25% when the flow rate varied from 0.03 m^3s^{-1} to 0.15 m^3s^{-1}. Therefore, a significant reduction of flow velocity occurred in rock-weirs without notches, which was larger than the reduction in velocity in weirs with notches.

1.1 Slow velocity zones and energy dissipation rate

The availability of fish resting areas in a pool (i.e., areas of slow velocity) was examined by calculating the relative cumulative frequency distributions of dimensionless velocities (U/U_{max}) in a horizontal plane parallel to the bed at z= 0.5H (Figure 6). The results of this analysis are independent of discharge (Wang et al. 2010); results are presented only for 0.06 m^3s^{-1} simulations in Series-A (without notches) and -B (with notches). The frequency distribution curves provide an estimate of the average percentage of areas on a plane parallel to the bed in a pool for U/U_{max} from 0 to 1. Following Baki et al. (2017b) the average percentage of areas where the velocity is lower than $0.4U_{max}$ was 30% for without notches and 46% for with notches at a flow rate 0.06 m^3s^{-1}. Therefore, the slow velocity zones under $0.4U_{max}$ are significantly altered by the opening in the weir (notches), with the areas of slow velocity in a pool increased 1.5 times in a pool with notches compared to a pool without notches (Q = 0.06 m^3s^{-1}).

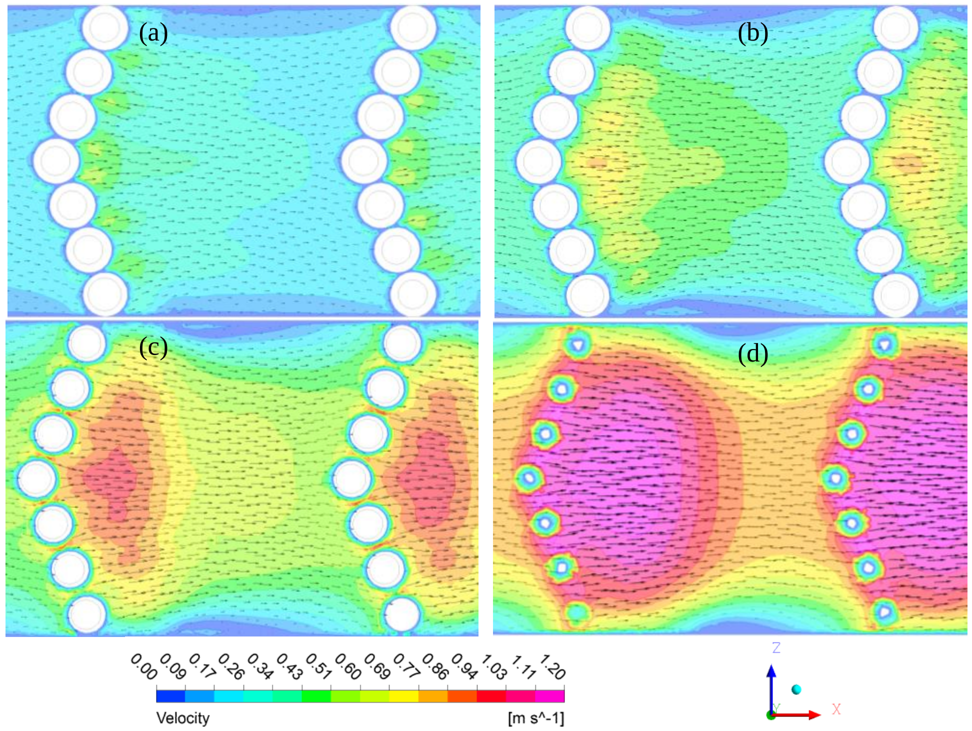


Figure 3: Spatial distributions of velocity magnitude with directions on horizontal plane parallel to bed at z = 0.5H for different flow rates in series-A (without notches): (a) 0.03 m^3s^{-1}, (b) 0.06 m^3s^{-1}, (c) 0.085 m^3s^{-1}, and (d) 0.15 m^3s^{-1} (not to scale).

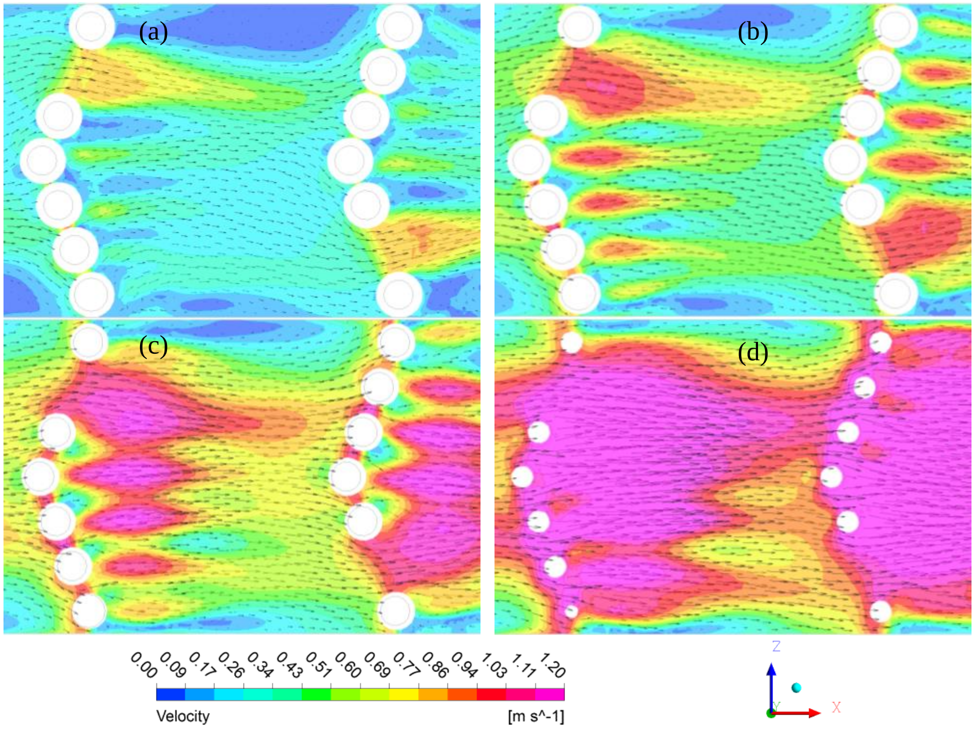


Figure 4: Spatial distributions of velocity magnitude with directions on horizontal plane parallel to bed at z = 0.5H for different flow rates in series-B (with notches): (a) 0.03 m^3s^{-1}, (b) 0.06 m^3s^{-1}, (c) 0.09 m^3s^{-1}, and (d) 0.15 m^3s^{-1} (not to scale).

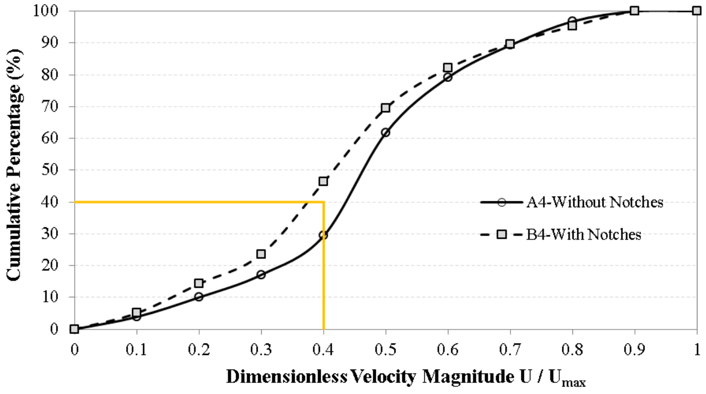


Figure 5: The relative cumulative frequency distribution curves of U/U_{max} on horizontal plane parallel to bed at z = 0.5H in the pool at 0.06 m^3s^{-1} (reference lines highlight the area for $U/U_{max} < 0.4$ and Cumulative Percentage > 40%).

Pool type fishpasses are designed to cause energy dissipation and to provide lower current velocity and higher water depth in the downstream pool section while maintaining acceptably low levels of turbulence (Towler et al. 2015). The average volumetric energy dissipation rate (E) in a pool is calculated using the following basic formula:

[2] $E = (\rho g Q \Delta h) / V_p$

where, Δh is the difference in water level between two pools (mid-point at each pool), V_p is the volume of pool excluding the volume of the rock-weir,ρ density of water, and g is the gravitational acceleration. The relationship between E and discharge per unit channel width (specific discharge, q) is presented for all series of simulations in Figure 7. E generally increases with specific discharge; which is consistent with the findings of Yagci (2010), who found E increased with increasing discharge at a constant bed slope for a pool-weir fishpass. In Series-A without notches, E increased from 63 W/m^3 to 198 W/m^3 as specific discharge increased from 0.033 m^2s^{-1} to 0.163 m^2s^{-1}. Similarly, E increased from 76 W/m^3 to 232 W/m^3 as specific discharge increased from 0.033 m^2s^{-1} to 0.163 m^2s^{-1} in Series-B with notches. On average, E increased approximately 15% from the simulation in series-A without notches to with notches (Series-B).

The average volumetric energy dissipation rates in Series-A and -B were typically within the energy dissipation criteria of 150 W/m^3 and 200 W/m^3 under specific discharge of 0.09 m^2s^{-1} (except simulation B8 and B9, Figure 7). Larinier (2008) recommended that the average volumetric energy dissipation rate should not exceed 200 W/m^3 for large salmon and sea trout, and 150 W/m^3 for smaller shad and riverine species. For a small stream on a 1:1 Froude model scale, these results could be applied *in-situ*. For a full-scale structure (prototype), where the model-to-prototype scale is 1:4, the average volumetric energy dissipation rates for the Series-A (without notches) were below the upper limit of 200 W/m^3 at a specific discharge of 0.054 m^2s^{-1} or less. In Series-B (with notches), *E* was below the upper limit of 200 W/m^3 at a specific discharge of 0.043 m^2s^{-1} or less. The average volumetric energy dissipation rates were mostly above the lower criteria of 150 W/m^3 in all series of simulations, except the A1 simulation.

1.1 <u>Fish swimming performance</u>

The effectiveness of fishpass hydraulics depends on both fish swimming speed and endurance (i.e., the length of time during which the fish can maintain a specific speed) (Puertas et al. 2012). This study analyzed swimming performance of salmonids or cyprinids fish species for a full scale prototype structure (where the model-to-prototype scale is 1:4) based on the velocity fatigue restriction as recommended by Puertas et al. (2012). The restriction states that the maximum flow velocity cannot exceed the fish burst speed (assumed to be 10 body lengths per second, or 10 L_B/s), i.e., U_{max} ≤ burst speed. This restriction limits the value of $S_0 \times L$ (bed slope × pool spacing) using dimensionless maximum velocity,

[3] $U^*_{max} = U_{max} / \mathrm{sqrt}(2gS_0L)$

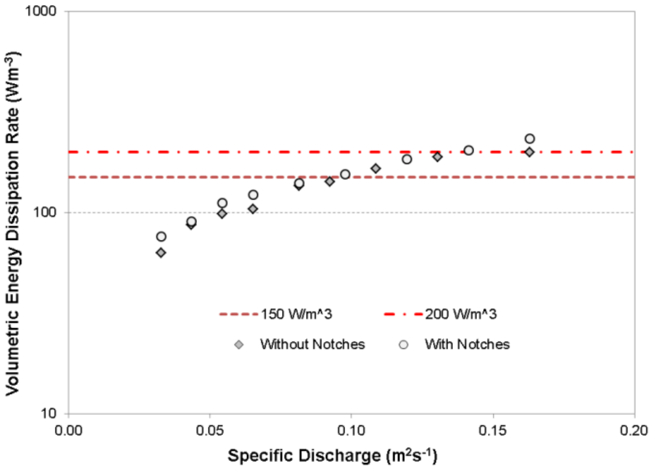


Figure 6: Relationship between average volumetric energy dissipation rate *E* and flow rate per unit channel width (specific discharge) for all simulations in Series-A and -B.

The effort that the fish must exert to traverse the fishpass was evaluated by comparing the maximum velocity $U_{max} \leq 2.5$ ms^{-1} (equivalent to the burst swimming speed of 250 mm salmonids or cyprinids) and allowable pool spacing L ≥ B (at least channel width) in Figure 7. In Series-A without notches, the maximum flow velocities in the simulations at flow rate ≤ 3.2 m^{3}s^{-1} in prototype (equivalent to 0.10 m^{3}s^{-1} in the model) achieved the above requirements (Figure 7). In Series-B with notches, the maximum flow velocities in all simulations at a flow rate of 1.92 m^{3}s^{-1} (equivalent to 0.06 m^{3}s^{-1} in the model) or less in the prototype achieve the above requirements (Figure 7). The increased flow velocity in the fishpass with notches did not produce hydraulic conditions compatible with the fish swimming performance of salmonids or cyprinids at higher flow rates (Q > 1.92 m^{3}s^{-1}).

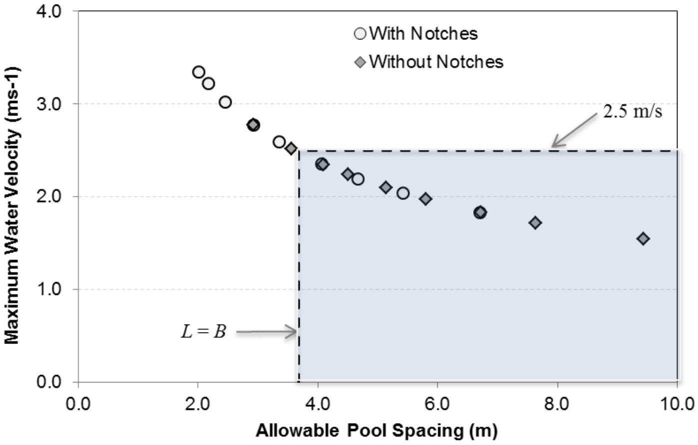


Figure 7: Relationship between maximum water velocity and allowable pool spacing at a prototype scale for 250 mm body length of salmonids or cyprinids. The dashed lines show $U_{max} \leq 2.5$ ms-1 (horizontal) and L ≥ B (vertical).

4. CONCLUSIONS

This study numerically investigated the hydraulic characteristics associated with rock-weirs with and without passage notches. The simulated water surface profiles confirmed two distinct flow regimes present within the structures: weir flow and transitional flow. When notches were added to the rock weir, the pool average water depth decreased by approximately 7% and the maximum velocity increased by about 20%. As water flows over the rock-weir, flow is directed towards the center of the downstream pool, then started to change direction from center line to channel banks when approaching the next weir, distributing flow across the weir. The magnitude and extent of the high velocity zone, and re-circulation zone in the pool varied between the trials with and without notches. The slow velocity zones which fish require for resting in a pool increased 1.5 times in a pool with notches compared to a pool without notches. On the other hand, the average volumetric energy dissipation rates in a pool with notches increased approximately 15% over that in a pool without notches. From the perspective of fish swimming performance, both rock-weirs with and without notches ensured flow fields low enough to be overcome by 250 mm long salmonids or cyprinids at flow rates of 1.92 m^3s^{-1} or less in a full scale prototype structure (1:4). The results of this research study have improved our understanding of flow fields associated with rock-weir NLFs and improved design procedures for designing rock-weir NLFs.

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