J. Hydrol. Hydromech., 74, 2026, 1, 11–19
https://doi.org/10.2478/johh-2026-0002

Journal of Hydrology and Hydromechanics

Hydraulic Optimization of Symmetric Wart-Type Baffle Spacing for Fish Passage in Open-Channel Flows

Hossein Sohrabzadeh Anzani*, Sameh Ahmed Kantoush, Sohei Kobayashi

Water Resources Research Center, Disaster Prevention Research Institute, Kyoto University, Uji 6110011, Japan.
* Corresponding author. E-mail: ho.sohrabzadeh@gmail.com

Abstract: This study investigates the role of symmetric wart-type baffles in facilitating fish passage under supercritical flow conditions in an open-channel flume. Experiments were conducted in a 7 m long, 0.5 m wide flume with a 2% bed slope at the Ujigawa Hydraulic Laboratory, Kyoto University. The impact of two baffle spacings (20 cm and 30 cm) on hydraulic characteristics was assessed and compared to a smooth channel. Velocity profiles, flow depth, and turbulence intensity were measured across ten longitudinal points to evaluate flow heterogeneity and energy dissipation. Results indicate that baffles significantly reduce flow velocity and create low-velocity resting zones critical for fish migration. The 20 cm spacing configuration proved most effective, offering a balance of reduced velocities (0.5–0.9 m/s) and sufficient hydraulic diversity to support energy-efficient fish passage. In contrast, the 30 cm spacing resulted in higher velocities and reduced low-velocity zones, potentially challenging weaker swimmers. Turbulence intensity was lowest with 30 cm spacing (TI_{mean}= 0.053), indicating smoother flow but fewer refuges compared to 20 cm spacing (TI_{mean}= 0.069). The smooth channel exhibited uniform, high velocities, unfavorable for most fish species. These findings highlight the importance of optimized baffle spacing in fishway design to enhance river connectivity and support aquatic biodiversity.

Keywords: Fish passage; Baffles; Barriers; Remediation; Ecohydraulics; Turbulence intensity.

1 INTRODUCTION

Over the course of their lives, fish often undertake long-distance movements between different habitats. These journeys may serve several purposes, such as seeking food and supporting growth (feeding migration), escaping unfavorable environmental conditions (refuge migration), or reaching suitable sites for reproduction (reproductive migration) (Lucas and Baras, 2001). The upstream movement of fish is often obstructed by man-made structures such as dams (Meshkati et al., 2025; Anzani et al., 2025a–c), culverts (Kapitzke, 2010; Franklin and Baker, 2025), weirs (Ghodsian, 2023a,b; Anzani and Ghodsian, 2023; Sohrabzadeh and Ghodsian, 2022, 2024; Sohrabzadeh et al., 2024a,b, 2025a–c; Mahdian Khalili et al., 2025), and road crossings, which can significantly hinder fish migration. These barriers have been shown to harm fish (Alcott et al., 2021; Lucas et al., 2009; Tamario et al., 2019), insects and other small animals (Blakely et al., 2006), mollusks (Liu et al., 2020), and their habitats (Birnie-Gauvin, Aarestrup, et al., 2017) by blocking access to important areas and resources. This can reduce populations, disturb reproduction, and limit gene flow (Wilkes et al., 2019). Such barriers block or disrupt migration pathways, which can significantly impact fish populations and even threaten the survival of certain species (Radinger and Wolter, 2014).

For a fish to successfully traverse a culvert or tunnel, it must sustain swimming speeds greater than the flow velocity long enough to cover the entire length of the structure. If the water velocity within the culvert surpasses the swimming capacity of the fish, their ability to move upstream will be restricted or completely blocked (Crawford et al., 2025; Laborde et al., 2016). To address these challenges, fishways have been developed to restore longitudinal connectivity and facilitate fish migration in both upstream and downstream directions. Fishways are hydraulic constructions designed to counteract the adverse impacts of human-made obstructions in waterways, enabling fish to migrate both upstream and downstream and thereby reinstating longitudinal connectivity.

There are different types of fishway such as Rock ramp (Swar et al., 2023; Stuart et al., 2024), Pool and Weir fish ladder (Alvarez-Vázquez et al., 2008; Krebs et al., 2021), Pool and Orifice fish ladder (Liu et al., 2022), Vertical slot fish ladder (Garcia and Rodríguez, 2020; Hameed and Hilo, 2021), Baffle fishway(Rajaratnam et al. 1991), and Fish elevator (Fuentes-Perez et al., 2017).

One strategy to improve fish passage through high-velocity environments, such as culverts or diversion tunnels, is the installation of baffles (Khodier and Tullis, 2018). Wart-type baffles, characterized by their low-profile, rounded, and symmetrical shapes attached to the channel bed or walls, are designed to increase hydraulic roughness and create localized low-velocity zones. Baffles increase flow depth, reduce flow velocity, and create resting zones that allow fish to conserve energy during migration. Olsen and Tullis (2013) evaluated the swimming performance of wild brown trout in smooth culverts equipped with baffles, finding that baffle installation significantly enhances fish passage success. Similarly, Khodier and Tullis (2014) observed two distinct resting zones for fish swimming upstream in baffle-equipped culverts. In the context of diversion tunnels, which are commonly used during dam construction or operation to reroute river flow, baffles can serve a similar purpose by modifying the hydraulic conditions to make the tunnel passable for fish. The advantage of baffle fishways over other fish passage methods lies in their effectiveness at slowing water flow and creating resting areas for fish (Feurich, 2012). Moreover, Marsden (2017) demonstrated that baffle systems can provide hydraulic benefits; however, blockage remains a critical concern for designers when implementing such structures. According to Franklin et al. (2018), spoiler baffles are recommended for culverts with diameters greater than 1.2 m. If the diameter will be less than this amount, baffles will also decrease culver capacity, increase roughness and may increase the risk of blockage by debris.

Researches of Rajaratnam et al. (1991) and Ead et al. (2002) confirm the baffle size is important factor. So, Barnes et al., (2008) examined different dimension of baffles. Results showed for slopes up to 2%, use rectangular baffles in alternating rows with 0.2 m between rows and 0.12 m between blocks. Barnes et al., (2008), examined suggests that using smaller baffles with the same configuration and spacing, may be more effective at reducing water velocities in culvert with slopes of 3% (Stevenson et al., 2008).

Several studies have investigated the hydraulic characteristics of baffle-equipped structures, including culverts and diversion tunnels. Rajaratnam et al. (1991) and Rajaratnam and Katopodis (1990) measured flow velocity at the centerline of culverts using a Pitot-static tube, demonstrating the impact of baffles on flow dynamics. Field experiments by Pearson et al. (2013) showed that juvenile coho salmon prefer low-velocity zones near the walls of baffle-free corrugated culverts. The research by Pearson et al. (2006) shwed that culverts with baffles significantly improve juvenile fish passage compared to those without. Similarly, preliminary studies on diversion tunnels suggest that baffles can reduce flow velocity and create heterogeneous flow fields, enhancing their suitability as fish passage routes (Meshkati et al., 2025). Morrison et al. (2009) examined the interaction between juvenile fish passage and flow turbulence but found no significant correlation. Laboratory studies using particle image velocimetry (PIV) have further elucidated fish-flow interactions in baffled structures. Liao et al. (2003) investigated the effect of vortices on rainbow trout swimming in a short channel section, showing that fish can exploit vortical flows to conserve energy. Tritico and Cotel (2010) studied the influence of vortex size and flow structures on swimming speed and stability, demonstrating effects on habitat selection, migration, and swimming performance. Smith et al. (2005) used acoustic Doppler techniques to show that juvenile trout prefer high-velocity, low-turbulence regions over low-velocity, high-turbulence areas. Additionally, Feurich et al. (2011) used three-dimensional simulations to demonstrate that spoiler baffles reduce flow velocity in culverts compared to baffle-free conditions. These findings are particularly relevant for diversion tunnels, where high flow velocities can be mitigated through baffle installation to create favorable conditions for fish passage.

When flow velocity exceeds the swimming capacity of fish, successful passage becomes impossible. A widely adopted solution is the installation of baffles within culverts and diversion tunnels, which dissipate excess flow energy and create localized resting zones. According to Franklin et al. (2018), baffles, constructed as plates, blocks, or sills arranged in various patterns, enhance hydraulic roughness, reduce flow velocity, dissipate energy, and generate heterogeneous flow fields. These structures not only slow the water but also establish calm zones that provide refuge for fish during upstream passage.

Previous studies on fishway design have primarily focused on subcritical flows or asymmetric baffles (Rajaratnam et al., 1991; Feurich et al., 2011; Franklin et al., 2018). These investigations demonstrated that baffles can reduce flow velocity and create low-velocity zones for fish resting; however, most of them addressed baffles in large culverts or low-gradient flows. In contrast, the influence of symmetric wart-type baffle spacing under supercritical flow conditions, which are common in diversion tunnels or steep channels, has received little attention. Moreover, limited information exists on how different baffle spacings affect turbulence intensity (*TI*) and velocity distribution under such conditions. In this study, the experimental model examines the role of baffles in facilitating fish passage through a diversion tunnel under supercritical flow conditions. In the absence of baffles, the flow within the tunnel remains fully supercritical, posing a significant barrier to fish migration. By introducing baffles, the influence of baffle spacing on hydraulic characteristics is systematically evaluated, with particular emphasis on velocity distribution, flow intensity, and the formation of resting zones within the tunnel. The results provide clear insight into the effectiveness of baffles as a hydraulic measure for improving the performance of diversion tunnels as fish passage routes, thereby contributing to the restoration of longitudinal connectivity in regulated river systems.

2 MATERIAL AND METHODS

2.1 Experimental Setup and Methodology

The experiments were conducted using a recirculating open-channel flume system at the Ujigawa Hydraulic Laboratory, Kyoto University (Fig. 1). The flume was constructed from transparent Plexiglas and featured a length of 7 m, a rectangular cross-section 0.5 m wide, and a fixed bed slope of 2%. Flow regulation was maintained through a constant-head supply tank coupled with a closed-loop pump system. Precise discharge control (Q= 15 L/s) was achieved using a Mitsubishi FREQROL-A700 variable frequency drive (VFD), with fine adjustments performed via a calibrated gate valve.

2.1.1 Baffle Configurations and Measurement Protocol

The experimental program investigated the effect of symmetric wart-type baffles on flow characteristics under supercritical conditions. Velocity profiles were measured along the centerline within a 1 m test section located 5 m downstream of the flume inlet. Measurements were taken at 10 transverse stations (A–J), each spaced 10 cm apart. At each station, vertical velocity data were collected from 10 mm above the bed to the water surface at 5 mm increments. Figure 2 shows a schematic view of the baffle configuration. Each baffle was cubic, with dimensions of 3.5 × 3.5 × 3.5 cm.

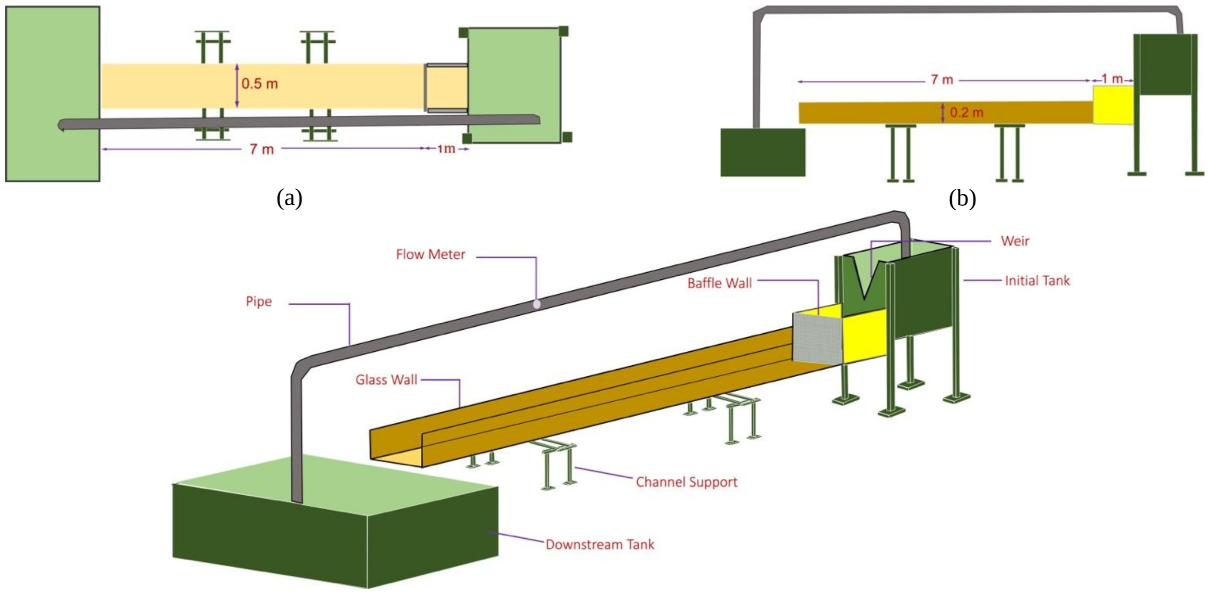
Two baffle spacing configurations were tested: 20 cm (S = 20 cm) and 30 cm (S = 30 cm). Three-dimensional velocity components at each measurement point were recorded using a Kenek VP3000 electromagnetic current meter, capturing 60 samples at 100 Hz per point. All points were measured twice to ensure reproducibility. Flow depth at the midpoint of the test section was monitored using a digital point gauge (±0.1 mm accuracy), with video recordings serving as secondary verification. The system was allowed to stabilize for 10 minutes prior to data collection to ensure steady-flow conditions.

A total of 210 measurement points were obtained: 30 for the smooth bed (baseline), 90 for the 20 cm baffle spacing, and 90 for the 30 cm baffle spacing (Figure 3).

2.1.2 Implications for Fish Passage

The installation of symmetric wart-type baffles significantly alters the hydraulic environment in the flume. Baffles increase hydraulic roughness, dissipate flow energy, and create heterogeneous velocity distributions along the channel. These modifications generate localized calm zones, which are essential resting areas for fish attempting upstream passage under high-velocity, supercritical conditions.

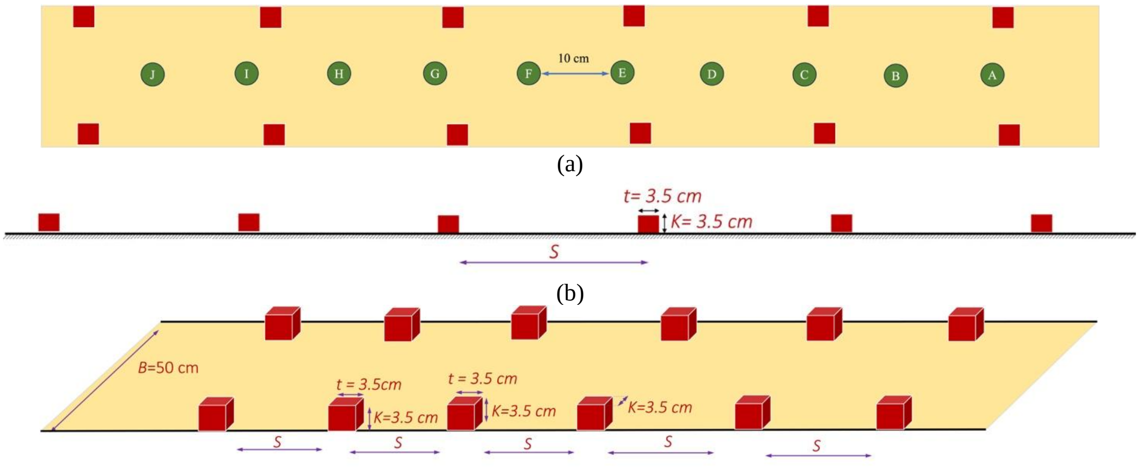
The spacing of baffles directly affects flow patterns: tighter spacing (*S* = 20 cm) produces more frequent zones of reduced velocity, potentially enhancing fish passage by offering shorter intervals between resting areas. Wider spacing (*S* = 30 cm) may result in longer high-velocity stretches, which could challenge weaker swimmers. Velocity profiles and depth measurements provide critical insights for designing fishways that optimize both energy dissipation and the availability of resting zones, ensuring safe and efficient passage for target species.



(a) (b)

(c)

Fig. 1. Schematic diagrams of the experimental flume: (a) plan view, (b) side view (c) and side elevation.



(a)

(b)

(c)

Fig. 2. Schematic representation of the baffle configuration showing (a) plan view, (b) side view, and (c) side elevation.

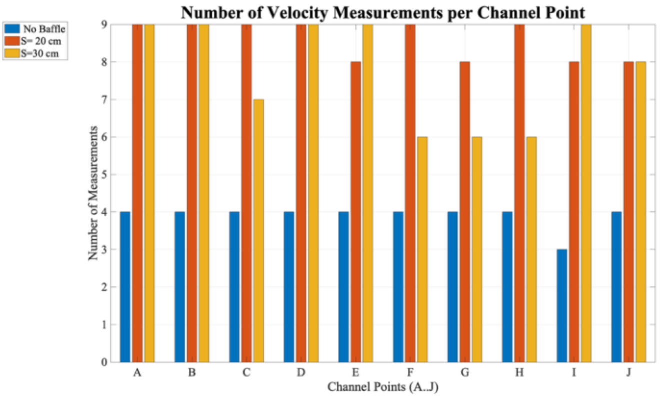


Fig. 3. Number of experiments.

3 RESULTS

3.1 Velocity Distribution

Figure 3 illustrates the radar charts of depth-averaged velocity. In this study, the depth-averaged velocity represents the time-averaged velocity integrated over highlights spatial variability under different roughness scenarios. This visualization enables a rapid comparison of the overall flow structure across the channel and highlights spatial variability under different roughness scenarios.

In the smooth channel, the radar chart reveals a nearly circular and balanced distribution of velocities, with only minor fluctuations between channel points. This indicates a relatively uniform velocity field, which lacks strong heterogeneity across the cross-section. While such conditions might support efficient bulk transport of water, they offer limited hydraulic diversity and relatively fewer refuge zones for fish.

With the introduction of baffles at 20 cm spacing (*S* = 20 cm), the radar plot becomes markedly irregular. Some points (e.g., H, I, J) show noticeably higher velocities, while others remain significantly lower. This irregularity highlights the emergence of spatial heterogeneity within the channel, where areas of reduced flow coexist with faster currents. From an ecological perspective, this heterogeneity is highly beneficial. Slower zones can serve as resting areas for fish, while faster jets provide pathways for active swimming and orientation. Furthermore, under the wider baffle spacing condition (*S* = 30 cm), the radar chart shows a moderate level of irregularity, while the average velocities are generally higher compared to the denser baffle arrangement (*S* = 20 cm). This suggests that while roughness increases overall turbulence and mixing, excessive roughness may lead to elevated average velocities at many channel points, potentially increasing the swimming challenge for weaker species. Nevertheless, the persistence of velocity variability ensures that certain low-velocity regions remain available, which may temporarily reduce the energetic cost of upstream movement.

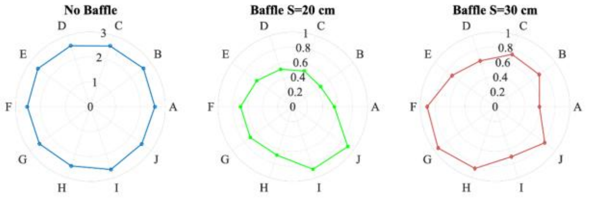


Fig. 4. Radar chart of velocity.

3.2 Velocity Contours and Implications for Fish Passage

To understand the hydraulic conditions and potential fish passage performance within the experimental flume, velocity distributions were visualized using velocity contour plots for all three scenarios (Fig. 4). Contour plots provide a continuous representation of flow magnitude over the depth and along the channel length, allowing clear identification of high- and low-velocity regions that could affect fish movement. This approach ensures that the flow near the bed, where resting zones for fish are likely to form, is represented accurately. Using filled contours with clearly labeled contour lines, regions of accelerated flow and relative calm are easily distinguishable.

In the smooth bed scenario (no baffles), the velocity contours show a more uniform distribution along the depth, with gradual acceleration towards the channel centerline. In contrast, the baffle cases (*S* = 20 cm and *S* = 30 cm) demonstrate significant modification of the flow field. Baffles induce localized turbulence and energy dissipation, creating alternating zones of lower and higher velocities. These low-velocity zones adjacent to the baffles represent potential resting areas for fish, while the high-velocity zones indicate regions that could challenge fish passage if the velocity exceeds the swimming capacity. Moreover, the spacing of the baffles clearly influences the flow pattern. The closer spacing (*S* = 20 cm) results in more frequent low-velocity pockets, whereas wider spacing (*S* = 30 cm) produces larger, but fewer, calm areas.

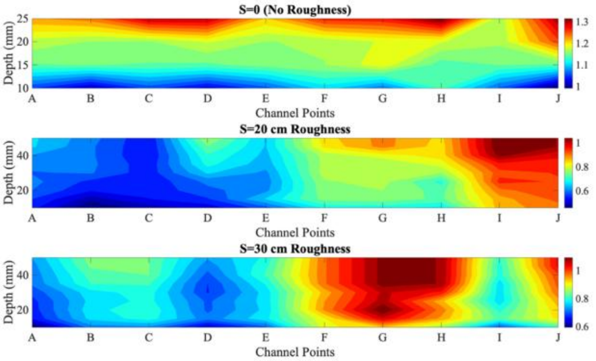


Fig. 5. Velocity Contour plot for different conditions.

3.3 Heatmap analysis

Figure 5 presents the heatmaps of velocity distribution at various depths and channel points.

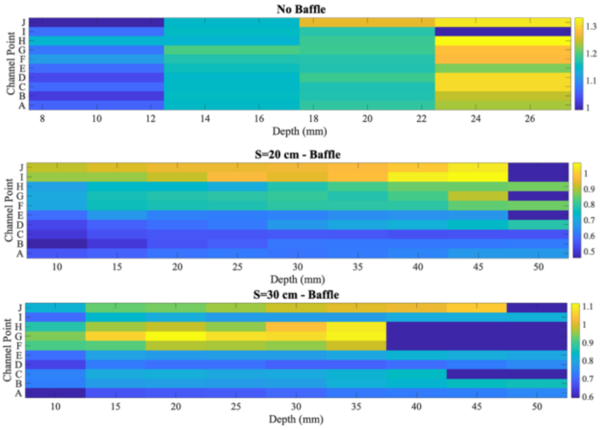


Fig. 6. Heatmaps of velocity distribution across channel points (A–J) and depths under three conditions.

In the smooth channel, the heatmap shows relatively uniform velocity distributions across most channel points and depths. The color gradient is nearly homogeneous, with only minor variations between the upper and lower measurement depths. This uniformity indicates that the flow field lacks spatial heterogeneity, leading to limited hydraulic complexity within the channel. Although such conditions may favor efficient water conveyance, they provide minimal velocity refuges that are essential for fish passage. When roughness elements with a height of 20 cm are introduced, the velocity distribution becomes markedly irregular. Certain points exhibit zones of relatively high velocity, while others remain in lower ranges. The heterogeneity revealed by the heatmap highlights the formation of coexisting fast and slow flow regions. From a hydraulic and ecological perspective, this variability is advantageous, as reduced velocity zones may function as temporary resting areas for fish, while faster jets provide orientation cues and pathways for active swimming. At the highest roughness condition (*S* = 30 cm), the heatmap indicates a moderate irregularity, yet the average velocity values are generally higher than those at *S* = 20 cm. This suggests that increased roughness heightens turbulence and mixing intensity, thereby raising the overall energy in the flow field. While elevated velocities may challenge weaker swimming species, the persistence of variability across channel points ensures that low-velocity zones remain available, thus supporting potential fish passage through intermittent resting opportunities.

3.4 Turbulence Intensity (*TI*)

Turbulence Intensity is a hydraulic index that measures the magnitude of velocity fluctuations relative to the mean flow velocity. This parameter is particularly important for assessing fish passage conditions, since highly turbulent flows may hinder fish movement or increase their energy expenditure.

Mathematically, the approximate *TI* defined as:

$$TI = \frac{\sigma_U}{\bar{U}} \tag{1}$$

where σ_U is the standard deviation of velocities at different depths of the section, and $\overline{U}$ is the depth-averaged velocity. *TI* is a dimensionless parameter and is often expressed as a percentage.

The standard deviation of velocity, denoted by σ_U, characterizes the intensity of velocity fluctuations at a specific measurement point. It is mathematically formulated as:

$$\sigma_U = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(u_i - \bar{u})^2} \tag{2}$$

where u_i corresponds to the instantaneous velocity recorded at the location, $\bar{u}$ denotes the local mean velocity, and *n* represents the total number of observations. This expression computes the root mean square of deviations from the mean, thereby quantifying the variability in the velocity field. Larger values of σ_U reflect enhanced unsteadiness in the flow, indicative of stronger turbulent activity at the measurement site.

For each of the flow conditions, the *TI* was computed at every longitudinal measurement point along the channel (A to J). Furthermore, the overall mean *TI* across the entire channel length was calculated to provide a general indicator of flow stability under each configuration. The detailed results of these measurements are summarized in the table 1.

Table 1. Turbulence Intensity (*TI*) at longitudinal channel points (A–J) under three flow conditions: smooth channel, channel with baffle *S* = 20 cm, and channel with baffle *S* = 30 cm.

Point	*TI* (without roughness)	*TI* (*S*=20 cm)	*TI* (*S*=30 cm)
A	0.063	0.061	0.066
B	0.081	0.099	0.050
C	0.085	0.031	0.041
D	0.096	0.131	0.041
E	0.055	0.039	0.040
F	0.057	0.058	0.034
G	0.071	0.072	0.059
H	0.074	0.085	0.077
I	0.049	0.073	0.047
J	0.121	0.040	0.073
Mean	0.075	0.069	0.053

According to table 1, for the smooth channel, the turbulence intensity (*TI*) at most locations ranged between 0.05 and 0.12, with an overall channel mean of 0.075. The highest *TI* value was observed at point J, indicating increased flow turbulence near the downstream end of the channel. This relatively uniform turbulence suggests limited low-velocity refuges for fish, meaning that although passage is possible, resting opportunities are minimal.

In the case of the channel with baffles spaced at 20 cm (S=20 cm), the *TI* reached its maximum at points D and B (0.131 and 0.099), while remaining relatively low at other sections. These localized high *TI* zones indicate strong turbulence near the baffles, creating alternating areas of high and low velocities. From a fish passage perspective, this is advantageous because the low-velocity pockets act as resting zones, while the higher-velocity areas provide orientation and movement cues, allowing fish to traverse the channel without excessive energy expenditure.

For the channel with roughness elements spaced at 30 cm (S=30 cm), the *TI* values were generally lower than in the other two cases, with an overall channel mean of 0.053. The reduction in turbulence intensity implies fewer extreme velocity fluctuations, creating smoother flow conditions. While this supports passage for weaker swimming species by reducing energy demands, the lower variability may limit the number of accessible resting zones for fish, potentially challenging smaller or less agile individuals in continuous high-velocity stretches.

3.5 Turbulence Intensity Profile

In hydraulic studies, particularly for fish passage design, *TI* serves as a measure of hydrodynamic quality and flow stability, influencing fish swimming performance and energy expenditure. Fish navigating artificial or natural channels are sensitive to both flow velocity and turbulence conditions. Excessive turbulence can increase energy expenditure, reduce swimming performance, and hinder passage, while moderate turbulence can generate vortical structures and resting zones, facilitating gradual fish movement. Therefore, analyzing *TI* variations across the channel under different bed roughness conditions is critical for optimizing fish passage designs.

Fig. 6. indicates the distribution of *TI* along the flume channel at different points. The results show that in the smooth-bed condition, *TI* remains relatively low across the channel, with limited spatial variation (*TI* = 0.075). For the baffle space 20 cm (*S*=20 cm), *TI* increases noticeably, reaching peak values at mid and downstream locations. This indicates localized turbulence zones where flow oscillations are more intense, while calmer conditions exist elsewhere. For the 30 cm roughness condition (*S*=30 cm), *TI* values are generally lower, with a mean of 0.053, suggesting smoother flow overall. However, *TI* increases at specific downstream points, indicating localized turbulence due to wider baffle spacing. This contrast highlights that while the overall flow is less turbulent for *S*=30 cm, specific regions experience elevated velocity fluctuations. These localized turbulence zones can still provide beneficial hydrodynamic features, such as low-velocity pockets, but less frequently than with *S*=20 cm.

The increased *TI* with roughness elements reflects altered flow structures, creating both challenges and opportunities for fish passage. Elevated turbulence may pose difficulties for weaker swimmers, but within an optimal *TI* range, it can generate resting areas through vortical structures. Thus, baffle spacing should be designed to maintain *TI* within a range suitable for target fish species, balancing turbulence and low-velocity zone availability.

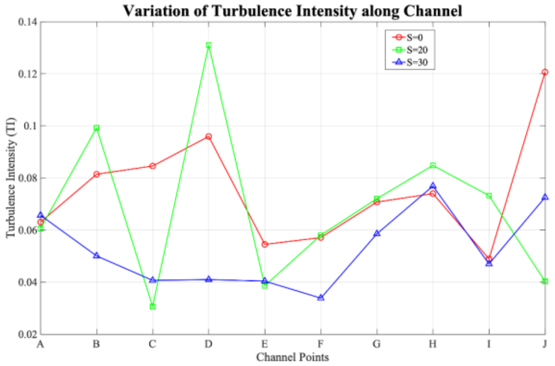


Fig. 7. Distribution of *TI* along the flume channel for three different bed configurations.

3.6 Velocity vs Turbulence

Fig. 7. presents a combined plot that serves as a powerful visual tool for analyzing the relationship between flow velocity and turbulence intensity. It clearly demonstrates that variations in bed roughness and baffle height significantly influence flow behavior. These findings can inform the design of fish passage routes and the optimization of channel environmental conditions. Fig. 7. shows a combined plot was generated to examine the relationship between flow velocity and Turbulence Intensity (*TI*) in the channel. The aim of this visualization was to highlight the effects of variations in channel bed conditions and the presence of different baffle configurations on flow behavior and fish passage conditions. By simultaneously displaying depth-averaged velocity and *TI*, the plot allows assessment of how channel geometry and bed roughness influence flow stability and the distribution of turbulent energy.

For each longitudinal section, the depth-averaged velocity was first calculated to provide an overview of the dominant flow at that section. *TI* was then defined as the ratio of the standard deviation of depth-wise velocities to the depth-averaged velocity. In the scatter plot, each point represents a longitudinal section, while different colors correspond to the different channel configurations. It is observed that increasing baffle height and altering bed geometry leads to higher *TI* values and a modified velocity distribution compared to the smooth channel. This pattern indicates that increased roughness enhances flow turbulence and reduces velocity uniformity along the channel, which can influence fish passage and aquatic flow behavior.

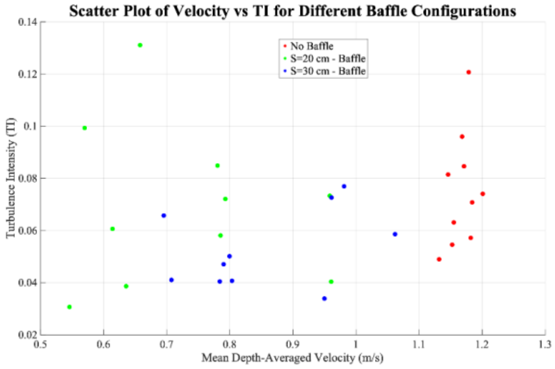


Fig. 8. Relationship between mean depth-averaged velocity and turbulence intensity (*TI*) for three roughness configurations.

4 DISCUSSION

The findings from this experimental study underscore the pivotal role of baffle spacing in modulating hydraulic characteristics under supercritical flow conditions, thereby influencing the efficacy of fish passage structures. The introduction of symmetric wart-type baffles at 20 cm and 30 cm spacings markedly disrupted the uniform velocity profiles observed in the smooth channel, where velocities exceeded 1 m/s across most points, rendering it largely impassable for many fish species. In contrast, the 20 cm spacing significantly reduced mean velocity (0.5–0.9 m/s) and increased flow heterogeneity, as shown by the velocity patterns. This heterogeneity manifests as alternating high- and low-velocity zones, which are essential for creating hydraulic refuges that allow fish to rest and recover during upstream migration. The closer spacing effectively dissipates kinetic energy through increased friction and eddy formation, aligning with theoretical principles of energy dissipation in roughened channels. Such modifications not only lower the overall flow momentum but also enhance spatial variability, promoting conditions conducive to ecohydraulic balance.

Turbulence intensity emerged as a critical metric for evaluating flow stability and its ecological ramifications. The mean *TI* values, 0.075 for the smooth channel, 0.069 for 20 cm spacing, and 0.053 for 30 cm spacing reveal a counterintuitive trend where wider spacing yields smoother flows but at the expense of reduced hydraulic diversity. Localized peaks in *TI* for the 20 cm configuration, particularly at points B and D (0.099 and 0.131, respectively), indicate the formation of turbulent eddies downstream of baffles, which, while potentially energy-demanding for fish in short bursts, contribute to the creation of sheltered low-velocity pockets. This is consistent with prior research demonstrating that moderate turbulence can facilitate energy exploitation by fish through vortex shedding. Conversely, the lower *TI* in the 30 cm setup suggests a more laminar-like regime over longer stretches, which may minimize disorientation but offers fewer intermittent refuges, potentially disadvantaging weaker swimmers such as juvenile salmonids. This necessitates a closer examination of how reduced turbulence influences the availability of resting zones critical for fish passage, as discussed below.

The lower turbulence intensity (mean *TI* = 0.053) observed with 30 cm baffle spacing, compared to 20 cm spacing (mean *TI* = 0.069), suggests a smoother, more laminar-like flow regime that might intuitively appear advantageous for fish passage due to reduced instability. However, this smoother flow comes at the cost of reduced hydraulic heterogeneity, as evidenced by fewer low-velocity zones in the 30 cm configuration. Fish, particularly weaker swimmers such as juvenile salmonids, rely on spatially diverse flow fields with frequent low-velocity refuges to rest and conserve energy during upstream migration. The 20 cm baffle spacing, despite generating higher localized *TI* at certain points, creates more frequent and pronounced low-velocity pockets due to increased eddy formation and energy dissipation. These microhabitats are critical for facilitating energy-efficient passage, as they allow fish to exploit vortical structures and rest intermittently. In contrast, the smoother flow in the 30 cm configuration, while less energetically taxing in terms of turbulence, provides fewer resting opportunities, which can challenge species with limited swimming capacities. This highlights that an optimal *TI* range, neither too high to cause disorientation nor too low to limit hydraulic diversity, is essential for effective fish passage. Thus, the 20 cm spacing better balances turbulence and refuge availability, aligning with the ecohydraulic needs of diverse fish species.

From an ecohydraulic perspective, the 20 cm baffle spacing optimizes conditions for fish passage by striking a balance between velocity attenuation and turbulence management, thereby supporting biodiversity in fragmented river systems. The frequent low-velocity zones identified in heatmaps and contours align with the swimming capacities of target species. This configuration enhances longitudinal connectivity in structures like diversion tunnels and culverts, addressing barriers highlighted in global assessments.

This study advances the understanding of ecohydraulic design by quantifying the spacing-dependent effects of wart-type baffles in supercritical flows within an open-channel flume, an area less explored than subcritical regimes. Unlike Rajaratnam et al. (1991) and Feurich et al. (2011), who investigated velocity reductions using 3 to 4 baffles in large-scale culverts, this research focuses on symmetric wart-type baffles placed along the sides of a 0.5 m wide laboratory flume with a 2% slope, employing precise spacings of 20 cm and 30 cm. Precise *TI* measurements reveal that the 20 cm spacing outperforms wider intervals in generating hydraulic heterogeneity and low-velocity microhabitats critical for fish passage.

5 CONCLUSIONS

The experimental study highlights the significant impact of baffle spacing on hydraulic conditions for fish passage in supercritical open-channel flows. The key findings are summarized in the following points:

i. Symmetric wart-type baffles at 20 cm and 30 cm spacings substantially altered flow dynamics compared to a smooth channel. The 20 cm spacing reduced mean velocities to 0.5–0.9 m/s, creating heterogeneous flow fields with low-velocity zones critical for fish resting. The 30 cm spacing resulted in higher velocities and fewer refuges, whereas the smooth channel exhibited uniformly high velocities (>1 m/s), making it unsuitable for most fish species.

ii. *TI* was lowest with 30 cm spacing (mean *TI* = 0.053), indicating smoother flow but reduced hydraulic diversity. The 20 cm spacing (mean *TI* = 0.069) generated localized turbulence, enhancing flow variability and providing more resting zones. The smooth channel (mean *TI* = 0.075) showed moderate turbulence with limited spatial variation, offering fewer ecological benefits for fish passage.

iii. The 20 cm baffle spacing proved most effective, balancing reduced flow velocities with sufficient hydraulic heterogeneity. This configuration supports energy-efficient migration by providing frequent low-velocity refuges, accommodating diverse fish species. The 30 cm spacing, while still beneficial, posed greater challenges for weaker swimmers due to higher velocities and fewer calm zones.

iv. Baffle-induced flow heterogeneity creates microhabitats that enhance river connectivity and support biodiversity. Low-velocity pockets near the bed, particularly with 20 cm spacing, serve as critical resting areas, reducing the energetic cost of upstream migration and improving passage success for fish with varying swimming abilities.

v. The findings advocate for moderate baffle spacing (*S*=20 cm) in fishway design to optimize hydraulic conditions for fish passage. These insights are vital for developing effective fish passage structures in high-energy flow environments, contributing to the restoration of fragmented river systems and the conservation of aquatic ecosystems.

For future studies, experiments with varying flow rates and channel slopes are recommended to investigate their influence on baffle performance. In addition, behavioral tests with live fish should be conducted to directly assess passage efficiency. Exploring combined baffle configurations could further support the optimization of ecohydraulic designs.

Acknowledgement: This work was supported by the Japan Society for the Promotion of Science (JSPS) through KAKENHI, including Grant Number JP25H00757 (3S Project, Principal Investigator: Prof. KANTOUSH Sameh). Support was also provided by the Japan Science and Technology Agency (JST) under the NEXUS Program, Grant Number JPMJNX24A2.

REFERENCES

Alcott, D., Goerig, E., Rillahan, C., He, P., Castro-Santos, T., 2021. Tide gates form physical and ecological obstacles to river herring (Alosa spp.) spawning migrations. Canadian Journal of Fisheries and Aquatic Sciences, 78, 869–880. https://doi.org/10.1139/cjfas-2020-0347

Alvarez-Vázquez, L.J., Martinez, A., Vázquez-Méndez, M.E., Vilar, M.A., 2008. An optimal shape problem related to the realistic design of river fishways. Ecological Engineering, 32(4), 293–300. https://doi.org/10.1016/j.ecoleng.2007.10.008

Anzani, H.S., Kantoush, S.A., Kobayashi, S., 2025a. Impact of bed roughness configurations on flow dynamics and hydraulic resistance in open-channel flows. Scientific Reports, 15, Article number: 33650. Available at: https://doi.org/10.1038/s41598-025-33650-y

Anzani, H.S., Kantoush, S.A., Kobayashi, S., 2025b. Influence of one-side wart-type roughness on flow dynamics in open channels: Experimental and statistical analysis. Applications in Engineering Science, 15, p.100283. https://doi.org/10.1016/j.apples.2025.100283.

Anzani, H., Khalili, A.M., Kantoush, S.A., Hamidi, M., 2025c. Hydraulic performance of an isolated strip roughness with varying heights on flow dynamics in open channels. Hydrology Research, 56(8), 655–671. https://doi.org/10.2166/nh.2025.167

Anzani, H., Ghodsian, M., 2023. Energy dissipation of rectangular and trapezoidal piano key weir. Irrigation and Drainage Structures Engineering Research, 24(90), pp.17-32. https://doi.org/ doi.org/10.22092/IDSER.2023.361138.1531

Barnes, C., Bethea, D.M., Brodeur, R.D., Spitz, J., Ridoux, V., Pusineri, C., Chase, B.C., Hunsicker, M.E., Juanes, F., Kellermann, A., Lancaster, J., 2008. Predator and prey body sizes in marine food webs: Ecological Archives E089-051. Ecology, 89(3), 881–881. https://doi.org/10.1890/07-1551.1.

Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Borger, L., Segura, G., Castelletti, A., van de Bund, W., Aarestrup, K., Barry, J., Belka, K., Berkhuysen, A., Birnie-Gauvin, K., Bussettini, M., Carolli, M., Consuegra, S., Dopico, E., Feierfeil, T., Fernandez, S., … Zalewski, M., 2020. More than one million barriers fragment Europe’s rivers. Nature, 588, 436–441. https://doi.org/10.1038/s41586-020-3005-2

Blakely, T.J., Harding, J.S., McIntosh, A.R., Winterbourn, M.J., 2006. Barriers to the recovery of aquatic insect communities in urban streams. Freshwater Biology, 51, 1634–1645. https://doi.org/10.1111/j.1365-2427.2006.01601.x

Birnie-Gauvin, K., Aarestrup, K., Riis, T.M., Jepsen, N., Koed, A., 2017. Shining a light on the loss of rheophilic fish habitat in lowland rivers as a forgotten consequence of barriers, and its implications for management. Aquatic Conservation: Marine and Freshwater Ecosystems, 27(6), 1345–1349. https://doi.org/10.1002/aqc.2795

Crawford, R., Franklin, P.A., Gee, E., Hicks, B.J., Nolte, D., Dupont, D., 2025. Accounting for interspecies and intraspecies variation in swimming performance for fish passage solutions. Journal of Applied Ecology, 62, 231–241. https://doi.org/10.1111/1365-2664.14828

Ead, S.A., Rajaratnam, N., Katopodis, C., 2002. Generalized study of hydraulics of culvert fishways. Journal of Hydraulic Engineering, 128(11), 1018–1022. https://doi.org/10.1061/(ASCE)0733-9429(2002)128:11(1018)

Franklin, P.A., Baker, C.F., 2025. Culvert baffle design to improve fish passage for small-bodied fishes: A rapid evidence synthesis. Conservation Science and Practice, e70082. https://doi.org/10.1111/csp2.70082.

Franklin, P., Gee, E., Baker, C.F., Bowie, S., 2018. New Zealand fish passage guidelines: for structures up to 4 metres. NIWA Taihoro Nukurangi, New Zealand.

Franklin, P.A., Sykes, J., Robbins, J., Booker, D.J., Bowie, S., Gee, E., Baker, C.F., 2022. A national fish passage barrier inventory to support fish passage policy implementation and estimate river connectivity in New Zealand. Ecological Informatics, 71, 101831. https://doi.org/10.1016/j.ecoinf.2022.101831.

Feurich, R., Boubée, J., Olsen, N.R.B., 2012. Improvement of fish passage in culverts using CFD. Ecological Engineering, 47, 1–8. https://doi.org/10.1016/j.ecoleng.2012.06.013

Feurich, R., Boubée, J., Olsen, N.R.B., 2011. Spoiler baffles in circular culverts. Journal of Environmental Engineering, 137(9), 854–857. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000395

Fuentes-Pérez, J.F., García-Vega, A., Sanz-Ronda, F.J., de Azagra Paredes, A.M., 2017. Villemonte’s approach: a general method for modeling uniform and non-uniform performance in stepped fishways. Knowledge and Management of Aquatic Ecosystems, 418, 23. https://doi.org/10.1051/kmae/2017013

Garcia, L.P., Rodríguez, I.R., 2020. Study of a vertical slot fish ladder. https://upcommons.upc.edu/server/api/core/bitstreams/0e9ef4fb-f270-447c-b358-f76ff3596a5a/content

Ghodsian, M., 2023a. Comparison of discharge capacity of Piano Key Weir with Ogee and Sharp Crest Weirs. Modares Civil Engineering Journal, 23(5), 129–138.

Ghodsian, M., 2023b. Experimental study on flow over rectangular Piano Key Weirs with sloped side crests. Modares Civil Engineering Journal, 23(2), 167–175.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M.E., Meng, J., Mulligan, M., … Zarfl, C., 2019. Mapping the world's free-flowing rivers. Nature, 569, 215–221. https://doi.org/10.1038/s41586-019-1111-9

Hameed, I.H., Hilo, A.N., 2021. Design of vertical slot fish ladder. In: IOP Conference Series: Earth and Environmental Science, 779(1), 012080. IOP Publishing. Available at: https://doi.org/10.1088/1755-1315/779/1/012080

Jones, J., Borger, L., Tummers, J., Jones, P., Lucas, M., Kerr, J., Kemp, P., Bizzi, S., Consuegra, S., Marcello, L., Vowles, A., Belletti, B., Verspoor, E., Van de Bund, W., Gough, P., Garcia de Leaniz, C., 2019. A comprehensive assessment of stream fragmentation in Great Britain. Science of the Total Environment, 673, 756–762. https://doi.org/10.1016/j.scitotenv.2019.04.125

Kapitzke, I.R., 2010. Culvert fishway planning and design guidelines. Stage 1-project based guidelines: Part E–fish passage design site scale.

Khodier, M.A., Tullis, B.P., 2018. Experimental and computational comparison of baffled-culvert hydrodynamics for fish passage. Journal of Applied Water Engineering and Research, 6(3), 191–199. https://doi.org/10.1080/23249676.2017.1287018

Khodier, M.A., Tullis, B.P., 2014. Fish passage behavior for severe hydraulic conditions in baffled culverts. Journal of Hydraulic Engineering, 140(3), 322–327. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000831

Krebs, E., Gravenhof, D.A., Caasi, J.M., Hanten, R.P., Huysman, N., Voorhees, J.M., Barnes, M.E., 2021. Fish ladder weir modifications to minimize escapement. Engineering, 13(4), 173–183. https://doi.org/10.4236/eng.2021.134013

Laborde, A., González, A., Sanhueza, C., Arriagada, P., Wilkes, M., Habit, E., Link, O., 2016. Hydropower development, riverine connectivity, and non-sport fish species: Criteria for hydraulic design of fishways. River Research and Applications, 32, 1949–1957. https://doi.org/10.1002/rra.3040

Liao, J.C., Beal, D.N., Lauder, G.V., Triantafyllou, M.S., 2003. Fish exploiting vortices decrease muscle activity. Science, 302(5650), 1566–1569. https://doi.org/10.1126/science.1088295

Liu, X., Wu, R., Chen, X., Zhou, Y., Yang, L., Ouyang, S., Wu, X., 2020. Effects of dams and their environmental impacts on the genetic diversity and connectivity of freshwater mussel populations in Poyang Lake Basin, China. Freshwater Biology, 65, 264–277. https://doi.org/10.1111/fwb.13419

Liu, M., Xu, M., Liu, Z., Sun, D., Guala, M., 2022. Ecohydraulic characteristics of a differential weir-orifice structure and its application to the transition reach of a fishway. Water, 14(11), 1711. https://doi.org/10.3390/w14111711

Lucas, M.C., Bubb, D.H., Jang, M.-H., Ha, K., Masters, J.E.G., 2009. Availability of and access to critical habitats in regulated rivers: Effects of low-head barriers on threatened lampreys. Freshwater Biology, 54, 621–634. https://doi.org/10.1111/j.1365-2427.2008.02136.x

Lucas, M.C., Baras, E., 2001. Migration of freshwater fishes. Oxford, UK: Blackwell Science. https://doi.org/10.1002/9780470999653

Mahdian Khalili, A., Sohrabzadeh, H., Hamidi, M., Kantoush, S.A., 2025. Experimental study on influence of height of full-width plate weirs on flow behavior, discharge, and energy dissipation. Hydrology, 12(7), 176. https://doi.org/10.3390/hydrology12070176

Marsden, T., Berghuis, A., Stuart, I., 2017. Fitzroy Barrage Cone Fishway Upgrade and Monitoring Report. Report to the Fitzroy Basin Association.

Meshkati, E., Kantoush, S.A., Sumi, T., Nguyen, B.Q., Anzani, H.S., 2025. Experiments to classify in-ground stilling basins and determine the factors affecting the optimization of flood mitigation dams. Results in Engineering, 25, 104368. https://doi.org/10.1016/j.rineng.2025.104368

Morrison, R.R., Hotchkiss, R.H., Stone, M., Thurman, D., Horner-Devine, A.R., 2009. Turbulence characteristics of flow in a spiral corrugated culvert fitted with baffles and implications for fish passage. Ecological Engineering, 35(3), 381–392. https://doi.org/10.1016/j.ecoleng.2008.10.012

Olsen, A.H., Tullis, B.P., 2013. Laboratory study of fish passage and discharge capacity in slip-lined, baffled culverts. Journal of Hydraulic Engineering, 139(4), 424–432. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000697

Pearson, T., Walker, S., Brown, S., 2013. Sourcebook for land use, land-use change and forestry projects. World Bank, Washington, DC.

Pearson, W.H., Southard, S.L., May, C.W., Skalski, J.R., Townsend, R.L., Horner-Devine, A.R., Thurman, D.R., Hotchkiss, R.H., Morrison, R.R., Richmond, M.C., Deng, D., 2006. Research on the upstream passage of juvenile salmon through culverts: retrofit baffles (No. WA-RD 644.1). Battelle Memorial Institute, Pacific Northwest Division.

Radinger, J., Wolter, C., 2014. Patterns and predictors of fish dispersal in rivers. Fish and Fisheries, 15, 456–473. https://doi.org/10.1111/faf.2014.15.issue-3

Rajaratnam, N., Katopodis, C., Lodewyk, S., 1991. Hydraulics of culvert fishways IV: spoiler baffle culvert fishways. Canadian Journal of Civil Engineering, 18, 76–82. https://doi.org/10.1139/l91-010

Rajaratnam, N., Katopodis, C., 1990. Hydraulics of culvert fishways III: weir baffle culvert fishways. Canadian Journal of Civil Engineering, 17(4), 558–568. https://doi.org/10.1139/l90-064

Smith, D.L., Brannon, E.L., Odeh, M., 2005. Response of juvenile rainbow trout to turbulence produced by prismatoidal shapes. Transactions of the American Fisheries Society, 134(3), 741–753. https://doi.org/10.1577/T04-069.1

Sohrabzadeh, H., Ghodsian, M., 2024. Experimental study of flow over piano key weirs with different plan shapes. ISH Journal of Hydraulic Engineering, 30(2), 185–195. https://doi.org/10.1080/09715010.2024.2302808

Sohrabzadeh, H., Kantoush, S.A., Mahdian Khalili, A., Hamidi, M., 2024a. Energy dissipation assessment in flow downstream of rectangular sharp-crested weirs. Water, 16(23). https://doi.org/10.3390/w16233371

Sohrabzadeh, H., Kantoush, S.A., Mahdian Khalili, A., Hamidi, M., 2024b. Experimental investigation of slit weir discharge. ISH Journal of Hydraulic Engineering, 30(5), 645–654. https://doi.org/10.1080/09715010.2024.2401845

Sohrabzadeh, H. and Ghodsian, M., 2022. Experimental study of the effect of sidewall slope over the triangular PK weir. Journal of IranianHydraulics, 17(4), 17–30. https://doi.org/10.30482/jhyd.2022.326177.1581

Sohrabzadeh, H., Ghodsian, M., Kantoush, S.A., 2025a. Energy loss prediction and analysis for rectangular, triangular, and trapezoidal piano key weirs. Journal of Aqua. https://doi.org/10.2166/aqua.2025.034

Sohrabzadeh, H., Ghodsian, M., Kantoush, S.A., 2025b. Flow profiles and hydraulic behavior of rectangular piano key weirs: Effect of sloping crest and orientation across different scales. Results in Engineering, 107066. https://doi.org/10.1016/j.rineng.2025.107066

Sohrabzadeh, H., Kantoush, S.A., Mahdian Khalili, A., Hamidi, M., 2025c. Experimental investigation of energy loss in low-discharge weirs with rectangular opening. Modeling Earth Systems and Environment, 30(2). https://doi.org/10.1007/s40808-025-02620-8

Stevenson, C., Kopeinig, T., Feurich, R., Boubée, J., 2008. Culvert barrel design to facilitate the upstream passage of small fish. Auckland Regional Council Technical Publication, 366.

Stuart, I.G., Marsden, T.J., Jones, M.J., Moore, M.T., Baumgartner, L.J., 2024. Rock fishways: Natural designs for an engineered world. Ecological Engineering, 206, 107317. https://doi.org/10.1016/j.ecoleng.2024.107317

Swarr, T.R., Fitzpatrick, R.M., Myrick, C.A., 2023. Design, construction, and preliminary hydraulic evaluation of a model rock ramp fishway. North American Journal of Fisheries Management, 43(4), 935–946. https://doi.org/10.1002/nafm.10902

Tamario, C., Calles, O., Watz, J., Nilsson, P.A., Degerman, E., 2019. Coastal river connectivity and the distribution of ascending juvenile European eel (Anguilla anguilla L.): Implications for conservation strategies regarding fish-passage solutions. Aquatic Conservation: Marine and Freshwater Ecosystems, 29, 612–622. https://doi.org/10.1002/aqc.3064

.

Received 3 October 2025
Accepted 12 January 2026