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Optimizing Flow Conditions and Fish Passage Success in Vertical Slot Fishways: Lessons from Fish Behavior Observations

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Abstract: This study investigates the behavior of chubs (*Squalius cephalus*) of mid-body length (9.7–15.6 cm) with respect to turbulent flow conditions in a pool representing an experimental vertical slot fishway. Velocity and turbulence were characterized using PIV data. The influence of turbulent flow on fish behavior was assessed through the number of successful fish passage attempts, the associated passage times, and the spatial distribution of fish in the pool. Turbulence conditions were modified by the addition of one or three vertical rigid cylinders inside the pool. The results show that these adaptations may facilitate the passage of chubs. Results provide valuable insights and information to understand the relationship between fish behavior and hydraulic conditions, especially in the context of improving the design of fishways.

Keywords: fish trajectories; hydraulic parameters; turbulent kinetic energy reduction; fishway efficiency

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1. Introduction

Habitat fragmentation is known to be one of the main impacting factors on biodiversity. This is especially true in networked river ecosystems, where a lot of obstacles have been constructed over time and sometimes induce habitat modifications and/or connection losses between functional habitats. One of the solutions to restore some kind of ecological continuity, at least for fish species, is to provide devices that allow or facilitate upstream and downstream fish movements at the level of impacting obstacles. Among the various types of fishways, vertical slot fishways (VSFs) are commonly used to improve fish passage. Historically, lots of VSFs were designed and sized by considering the passage of "good swimmer" fish species, particularly Salmonid species. A current consideration is that, once they have found the entrance of the fishway, other species (e.g., those with small body sizes) may encounter difficulties in progressing along the fishway due to inappropriate flow conditions in the successive pools. One aim of this study was to better understand the relationships between flow characteristics in VSFs and fish behavior, with the objective to investigate a "low-cost" way to modify flow characteristics in pools in order to improve the passage efficiency of small species in existing VSFs.

Fish can withstand turbulent flows if their stabilization aptitudes are sufficient with respect to the hydrodynamic environment, but they tend to avoid flows that interfere with their swimming trajectories [1–3]. Unfortunately, accurate links between hydraulic conditions in VSFs and fish swimming capabilities cannot be correctly anticipated from the hydraulic criteria commonly used to design such fishways (i.e., the maximum head difference between successive pools, Δh, and the maximum volumetric dissipated power, Pv). As a consequence, a better understanding of the relationships between fish behavior and positioning and accurate hydraulic conditions in the pools of VSFs is necessary to optimize these design criteria, as mentioned by [2].

In the past few decades, important turbulent descriptors with respect to fish swimming behavior have been identified: turbulent kinetic energy, Reynolds shear stress, turbulence intensity, strain, eddy length scale, flow orientation, and vorticity [4–10]. Moreover, numerous studies detailed the turbulent structures in several designs of VSFs and provided major knowledge for subsequent improvements to facilitate fish passage [8,9,11–20]. For example, Wang et al. [19] have explored the influence of slope, the shape ratio of pools and discharge on VSFs flow characteristics. They have defined two typical flow patterns, depending on the slope and the relative width of the pools. In the first flow pattern (FP1), generally observed in pools with large widths and low slope conditions, the principal flow enters the pools as a curved jet, which opens out before converging again towards the next (downstream) slot. This type of jet creates a large recirculation zone occupying roughly half of the pool surface and presents an unsteady beating movement near the large baffle. In the second flow pattern (FP2), generally observed in pools of small widths with high slope conditions, the entering jet has a high curve form and impacts the opposite side wall. Two large contra-rotating swirls are generated in the upstream corner of the pool in the convex part of the jet and a smaller one occurs near the large baffle. In FP2 conditions, the topology, spatial distributions of the velocity, turbulence kinetic energy, vorticity and non-stationary dynamics seem to be less appropriate for fish passage because VSF were previously designed using inadequate criteria [18,21,22].

The primary objective of the present study is to investigate the effects of turbulent flow conditions on the behavior of mid-body length chubs in a VSF pool. Fish behavior and their trajectories have been detailed and related to the four characteristics of turbulent flow suggested in the IPOS framework [23]: turbulence intensity (I), flow periodicity (P), flow orientation (O), and scale (S) of the significant eddies. For this purpose, the turbulence intensity, defined by turbulent kinetic energy, dynamics of the flow, instantaneous and 3D topologies, and the size of vortices were considered. Consequently, flow features were modified within a VSF pool through the addition of rigid, vertical cylinders, to better investigate the relationships between hydrodynamic conditions and fish behavior, particularly in terms of passage efficiency.

2. Materials and Methods

2.1. VSF Model and Cylinders

In the present paper, only a brief description of the VSF model and the metrology are given; further details can be found in [20]. The VSF model used in the present study (Figure 1) consisted of five similar pools (length L = 0.75 m, height H = 0.55 m, width B = 0.50 m). The width of the slots was b = 0.075 m, corresponding to a ratio of B/b = 6.67. The slope was set to 10% and the discharge to 23 $L \cdot s^{-1}$, resulting in a maximum velocity on a slot of 1.21 $m \cdot s^{-1}$. These settings induced a mean water depth in the pool of about 0.3 m, and a mean height drop between pools of about 0.075 m. The measurements of velocity were determined using particle image velocimetry (PIV) in a plane located at Z/b = 2 above the center of the bottom of the pool (which corresponds to a plane located at the mid-depth of the pool). All measurements were taken in the third pool of the model, to ensure uniform flow as the gravity is balanced by upstream dissipation. In total, 3000 instantaneous velocity fields were acquired throughout the pool, with a spatial resolution of 8 mm^2 at an acquisition frequency rate of 10 Hz. To modify flow (especially turbulence) conditions, one cylinder (diameter equal to b or diameter equal to b/2) or three cylinders (diameter equal to b/2) were placed vertically in each pool, near the upstream slot (Figure 2). The choice to introduce cylinders is based on the principle of dividing the entering jet into two parts (1 cylinder) and then dividing the secondary jet again into two parts (3 cylinders, in a triangle configuration). Cylinder positioning was optimized by calculation [24].

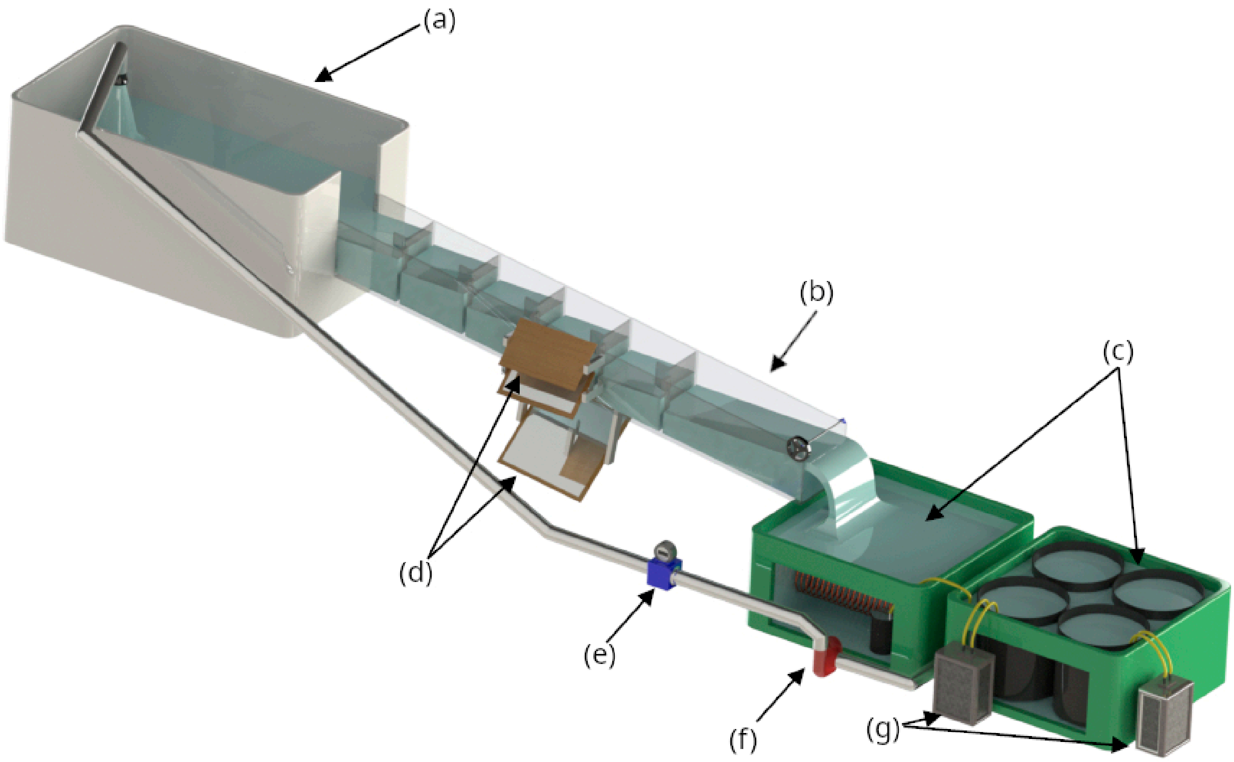

Figure 1. Experimental device: the 5 pools of the vertical-slot fish pass model, (a) upper tank, (b) lower tank, (c) fish-tank with 4 compartments, (d) mirrors for fish observation and image acquisition, (e) flowmeter, (f) pump, (g) filter pump.

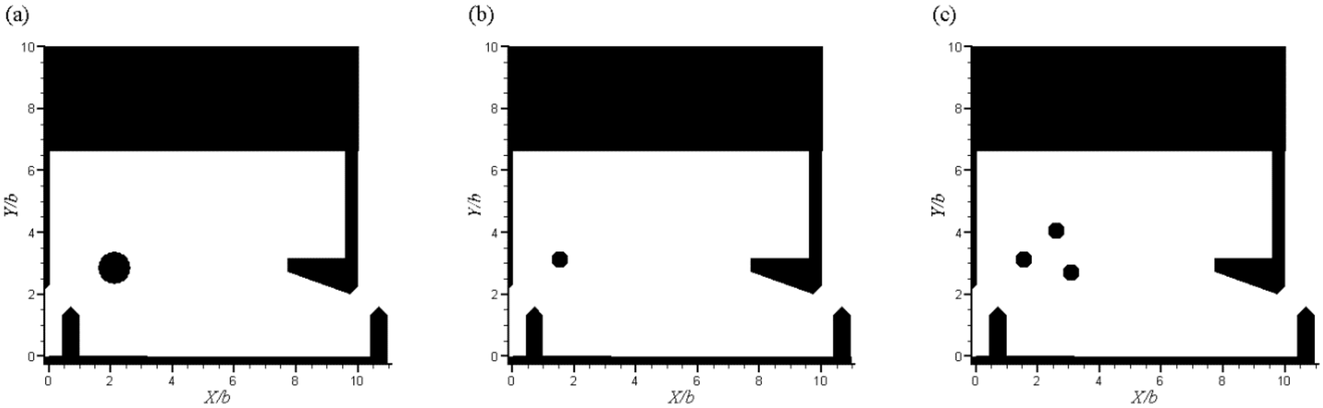

Figure 2. Experimental settings of the pool with additional cylinder(s). (**a**) one cylinder (diameter equal to b), (**b**) one cylinder (diameter equal to b/2), (**c**) three cylinders (diameters equal to b/2) (top views; flow direction: from left to right).

2.2. Fish Manipulation and Observation

Fish sampling was conducted in the "Petite Blourde" stream, a tributary of the Vienne River, in central France, using an electrofishing technique (HERON® model, DREAM Électronique Company, Pessac, France). Ninety chubs [min total length (TL) = 9.7 cm; max TL = 15.6 cm; average TL ± SD = 13.1 ± 1.9 cm] were collected and subsequently introduced, in the laboratory, into a fish tank that provided resting conditions with water characteristics similar to those during the experiments. Fish were kept in the fish tank (Figure 1) for one day before the beginning of the experiments, without food. After starting the pumps and waiting for flow stabilization in the pools, a group of 20–25 individuals, randomly selected from the fish tank, were transferred to the downstream pool (pool #5), separated from pool #4 by a mesh screen. The fish were held in pool #5 for 15 min before each trial, to allow them to adapt to flow conditions. The screen was then removed and the experiment began for a duration of 90 min (i.e., each 90 min period corresponds to one "trial"). A total of 18 trials were performed. At the end of each trial, the specimens used were transferred to a specific compartment in the fish tank, in order not to mix them with others and to use each individual only once per day at a maximum. Differences in water temperature among all trials were limited to <0.3 °C (mean water temperature during the experimental period = 16 °C). The water temperature during the experiments was very close to the optimum used by this species during its movements and in its breeding behavior [25]. The test room was illuminated with projectors at a constant brightness between 08.00 a.m. and 18.00 p.m. The flume walls were papered black, except the bottom of pool #3, to not disturb fish during observations and place them under light conditions as close as possible to real ones (walls of real fishways are opaque). We used young-of-the-year fish to carry out the tests. The chub (*Squalius cephalus* L.) is a very generalist species, colonising many rivers. It is highly adaptable to water temperature conditions and habitat characteristics. Its migratory behaviour is less marked than other species such as brown trout (*Salmo trutta* L.), but individuals regularly move between habitats.

A mirror positioned at a 45° angle under pool #3 enabled the observation of fish movements inside the pool (Figure 1), allowing a lateral view (to get the vertical fish position) and an underside view (to get the horizontal fish position) simultaneously. During each trial, these positions of fish and their behavior were continually recorded by a video camera (HDR-HC9E model, Sony Corporation, Tokyo, Japan). Frosted plexiglass plates were positioned above the pools to obtain video images without reflected light. The video recording device was surrounded by a tarp to avoid any stray light on the monitored pool. Each 90 min sequence was analyzed to (i) track fish movements between pools #2, 3 and 4, (ii) measure transit times through pool #3, (iii) track fish movements among and between previously defined hydraulic zones within pool #3 (see below) and (iv) measure the "resting-holding" time of individuals in each hydraulic zone. The 18 experimental trials performed represented 27 h of video.

There are few precise data available about the swimming capacity of chubs. In a study about the swimming capabilities of juvenile cyprinid species, Garner [26] gave a relation between the critical swimming speed (U_{crit}, in $cm \cdot s^{-1}$) of chubs, their body length (TL, in mm) and water temperature (T, in °C):

$$U_{crit} = 0.45 + 0.23 \cdot T + 0.55 \cdot TL \quad (1)$$

According to Equation (1), the U_{crit} of chub individuals used in our study ranged between 57 and 90 $cm \cdot s^{-1}$. We did not have information about the maximum swimming speed (U_{max}) of chubs, potentially used to overcome high flow velocities, but U_{max} is higher than U_{crit} in fish (e.g., up to 57% higher for rainbow trout, *Oncorhynchus mykiss* [27]). Therefore, considering the maximum velocity of V_{th} = 1.21 $m \cdot s^{-1}$ on the slot, chubs were placed in constraining flow conditions in our experimental VSF model.

3. Results

3.1. Flow Description

As previously mentioned (and see [19]), in the configuration studied without a cylinder, the jet had a notable curved form and hit the opposite side wall (Figure 3a). Two contra-rotating swirls were generated in the upstream part of the pool (one at each side of the jet) and another one occurred in the downstream part of the pool, near the large baffle (at its side opposite to the downstream slot).

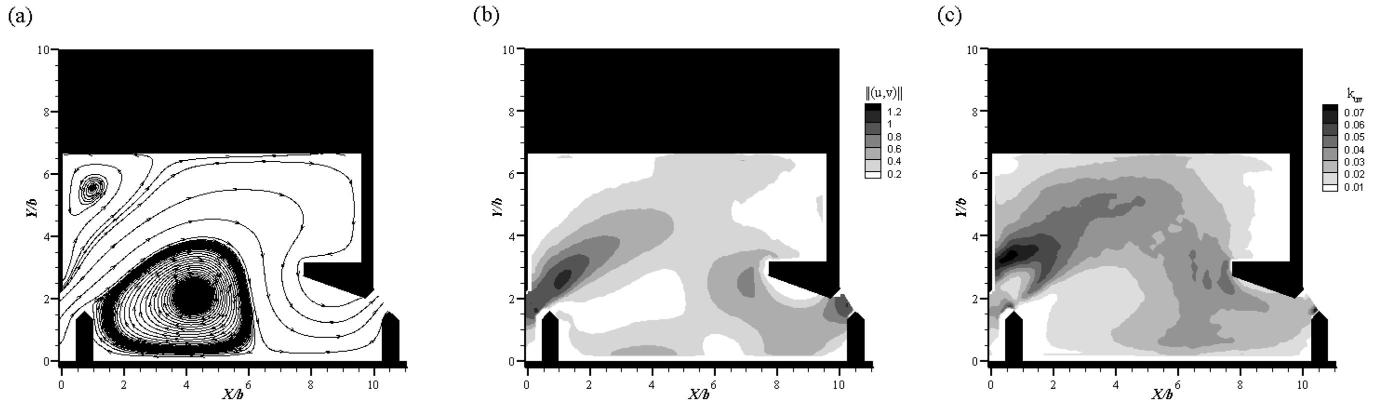

Figure 3. Mean flow features in pool #3 of the vertical-slot fishway model. (**a**) Streamlines, (**b**) velocity amplitude ($m \cdot s^{-1}$), (**c**) in-plane turbulent kinetic energy($m^2 \cdot s^{-2}$) (flow direction: from left to right).

The three zones containing the swirls can be assimilated as potential resting zones for fish. A layer with the mapping of these different zones and the boundaries of the pool has been added during the treatment of video-sequences, in order to facilitate image analyses (Figure 4).

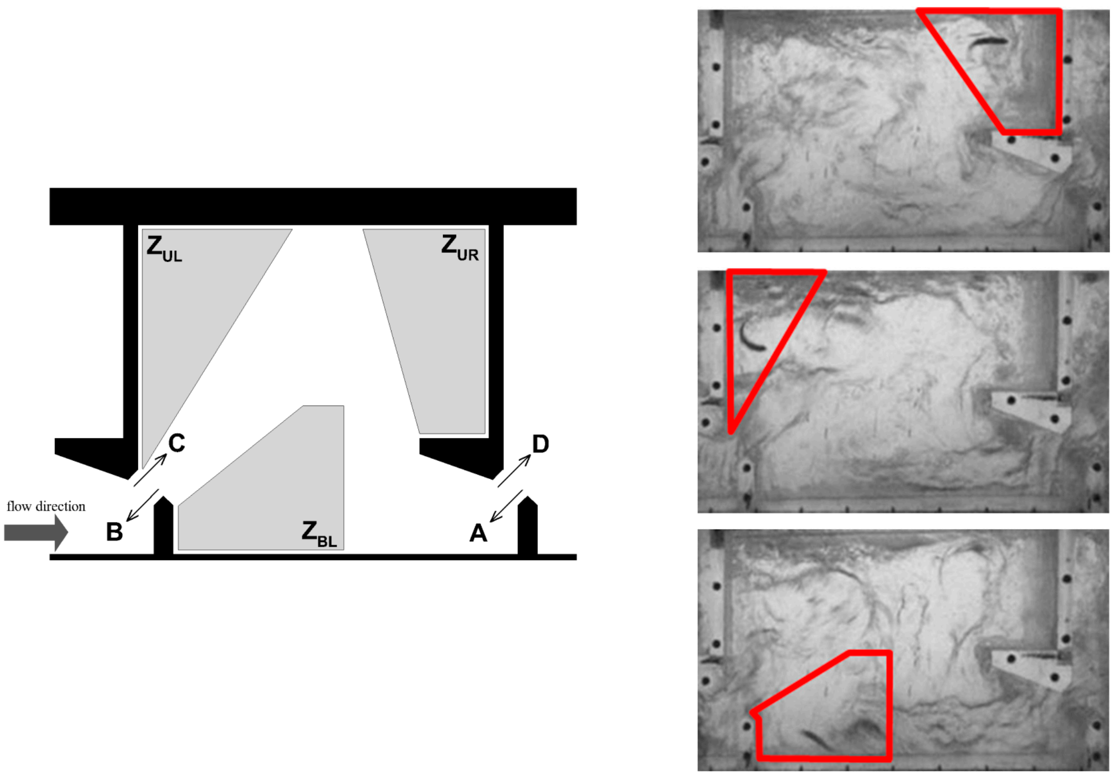

Figure 4. Bottom view of the third pool, recorded by a video camera, with an overlay of the 3 red zones containing the swirls (flow direction: from left to right). One fish is visible in each zone.

In the pool, high velocities were particularly present (i) at the upstream slot level, due to the head drop and flow constriction, and (ii) close to the large downstream baffle (Figure 3b). The large baffle locally generated high-velocity fluctuations that could stop or delay fish passage. At the upstream slot, the maximum velocity amplitude was equal to 93% of the theoretical maximum velocity in the slot, V_{th}, and the space-averaged mean flow velocity in the pool represented 28.2% of V_{th}. The average turbulence intensity, defined by the ratio between average turbulent kinetic energy (Figure 3c) and velocity (Figure 3b), may be of importance to understand fish behavior. The turbulence pattern in the pool was mainly due to the presence of the large baffle, which generated jet oscillations ("beating movements of the jet" defined in [20]), a complex kinematic process described in detail in [20,21]. The beating has a significant influence on the fluid motion in the pool, with a destabilization by the jet of the small region of recirculation located downstream from the small baffle (i.e., zone 2, Figure 4). Some velocity bursts, generated at the level of the upstream slot, also influenced the flow topology. Those bursts produced perturbations on the fluid motions and increased the average velocity magnitude in the pool [22]. The spatial distribution of the average turbulent kinetic energy (Figure 3c) was used to estimate the mean turbulent kinetic energy in the pool, which was equal to $0.017.V_{th}^2$. A total of 62% of the pool surface was characterized by a turbulence kinetic energy value lower than $0.017.V_{th}^2$.

3.2. Fish Trajectories in the Pool and Relationships with Turbulent Flow and IPOS Parameters

The displacement of fish within a pool is composed of upstream movements, downstream movements and stops or breaks in preferential zones. Video analyses showed three main scenarios of motion between pools:

- scenario A: crossing success, fish enter pool #3 from pool #4 and manage to enter pool #2,
- scenario B: crossing failures, fish enter pool #3 from pool #4 but are washed away in pool #4 later,
- scenario C: wash downstream, fish enter pool #3 after being washed downstream from pool #2.

No individual trackings were performed. As consequence, the same fish can be included in more than one scenario, for example, wash downstream and crossing success. In total, 111 situations were recorded during the 18 trials. Non-parametric statistical analysis (Kruskal–Wallis and Mann–Whitney tests) were used to compare (i) fish transit time through the pool, (ii) fish trajectories between the three different zones and (iii) the fish passage efficiency. We also used a homogeneity X^2 test with Yates' continuity correction to compare the distribution of fish associated with different patterns of using the zones inside the pool.

Scenario A, B and C represented 63.1%, 19.8% and 17.1% of the situations, respectively. Finally, the overall fish passage efficiency was calculated as the ratio between the number of success scenarios and failures and wash back scenarios accounted for 26.2%. The average time a successful fish spent in pool #3 was 6.4 s.

A more detailed investigation of fish trajectories inside the monitored pool was also performed (Figure 5). Upstream and downstream movements were observed. These movements can be continuous or discontinuous with stops in the pool. A detailed study of the trajectories reveals a very marked movement pattern. The most frequent trajectories are identified by thicker arrows. A total of 98.9% of the fish entered the pool directly into the ZBL. From the ZBL zone, 81.9% of the fish directly crossed the upstream slot and entered the upper pool without having entered any other zone of the pool. Fish movement patterns differ according to whether or not individuals have stopped in one of the zones of the basin. The movements of the fish that stopped for a moment in the pool were more diversified: they crossed the basin making a maximum of 16 movements between zones, whereas the fish that did not stop made a maximum of 5 movements across the pool. A total of 396 fish trajectories were recorded during the 18 trials. An average of 1.28 movements per fish viewed in the observed pool was acquired. Globally, fish located in zone ZBL orientated their head towards the upstream slot, whereas they orientated their tail towards this slot when they were located in zones Z_{UL} and Z_{UR}. Most of the fish entering the pool from the downstream slot sought to leave the jet by swimming toward zone Z_{BL} (98.9% of fish movements). Then, a little more than the half of the individuals located inside zone Z_{BL} left the pool via the upstream slot. A total of 23.9% of the remaining individuals swam to zone Z_{UL}, from which 27.3% of them successfully migrated upstream. Zone Z_{UR} was characterized by a significant rate of downstream migration (20.8% of fish). In summary, zones Z_{BL} and Z_{UL} were preferentially employed by fish before successfully migrating upstream.

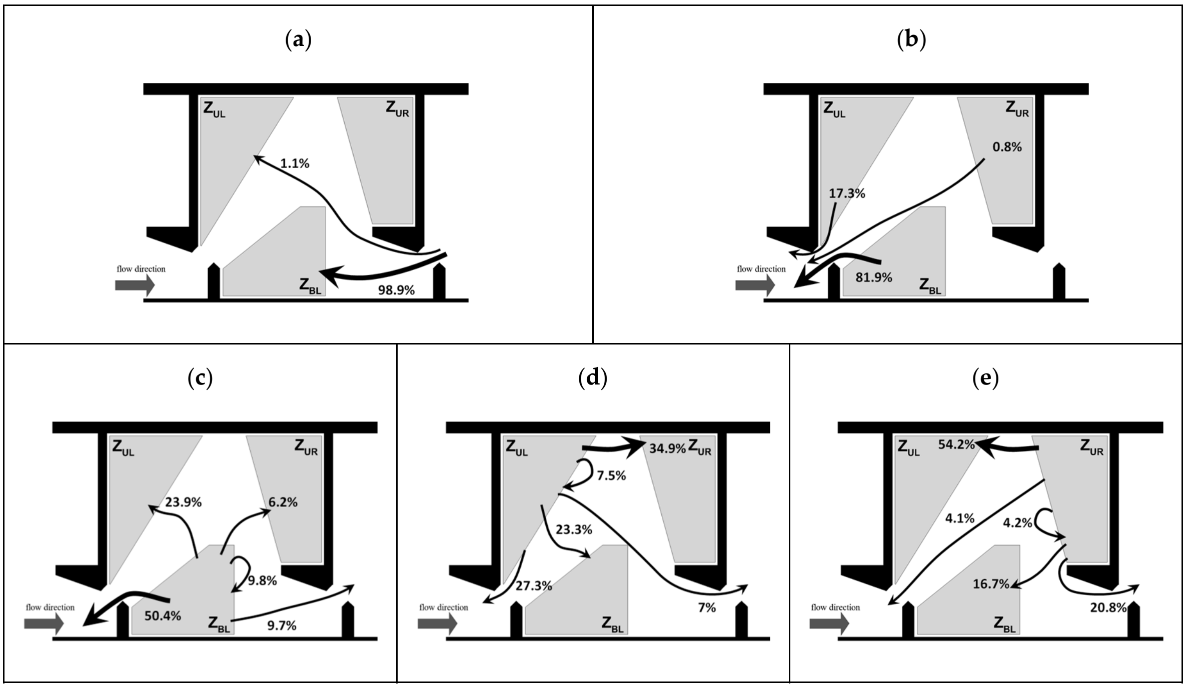

Figure 5. Chub trajectories to and from three potential resting zones (Z_{BL}, Z_{UL} and Z_{UR}, see Figure 4) in pool #3 of the VSF model (downstream = right-hand): (**a**) destination of individuals entering the pool; (**b**) origin of the individuals leaving the pool; (**c**) destination of the individuals leaving zone Z_{BL}; (**d**) destination of the individuals leaving zone Z_{UL}; (**e**) destination of the individuals leaving zone Z_{UR}.

Studying the relationships between fish behavior (e.g., trajectories and their use of resting zones) and the turbulence conditions in the pool could help to determine if the Intensity-Periodicity-Orientation-Scale (IPOS) approach [23] should be considered for improving fish passage through VSFs.

First, in terms of Intensity, the aim was to identify areas in the pool where intensities could be quite low and stable enough to be predictable and sustainable for fish. Four areas were considered (Figure 6), with respect to two threshold values for space-averaged velocity norm and turbulence kinetic energy, which could be considered as criteria to define the hydrodynamic environment of fish, see [21]. The choice of thresholds is only based on these hydraulic criteria. The aim is to identify locations in a pool where the flow could be considered as a "barrier" for fish. These values were set at $0.282 \cdot V_{th}$ (velocity) and $0.017.V_{th}^2$ (turbulence kinetic energy), respectively. In F11 areas (Figure 6), velocity and turbulence kinetic energy values were both over their respective threshold values. Inside these areas, the flow might be unpredictable for fish. In F00 areas, velocity and kinetic energy values were both under their respective threshold values. These areas might be considered as suitable for resting fish and/or for initiating an upstream movement and, as seen before, correspond to the preferential areas used by fish during the experimental trials. In F10 areas (compared to F01), the velocity value (relative to the turbulence kinetic energy value) was the only value higher than its threshold value.

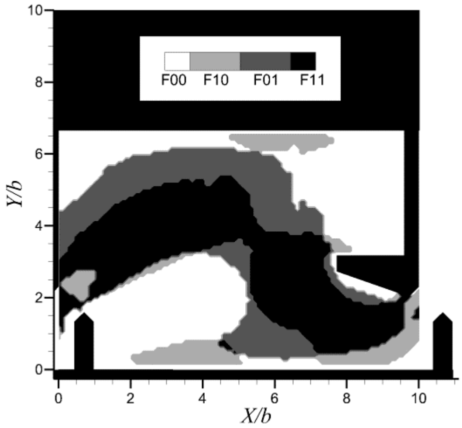

Figure 6. Representation of four levels of flow intensity, on average, in the studied pool (see text; flow direction: from left to right).

Second, in terms of Periodicity, non-stationary dynamics of the flow produced an oscillation of the F00 surface area (Figure 7). For example, velocity burst dynamics sometimes decreased or increased the total F00 area, in comparison to the average situation (e.g., Figures 7a and 7b, respectively). The small size vortices visualized were characterized by high rotation rates and were localized in the shearing region of the jet. Based on observations of fish videos, the assumption that velocity burst dynamics is the source of fish destabilization can be proposed: velocity bursts altered, during a short time, the stability of fish while they were initially resting in an F00 zone; subsequently, fish moved to another preferential zone or migrated upstream or downstream. Moreover, when velocity bursts decreased velocity magnitudes inside the slot, upstream migration could be facilitated (as fish should spend less energy moving) during short time sequences.

Third, in terms of Orientation, the topology and velocity field of the flow inside the VSF were mainly two-dimensional [2,19,20,26] and composed of vertical axis vortices. Based on our observations, the orientation of the large eddies with high vorticity values did not alter chub swimming behavior. Fish have not lost their postural alignment because of these eddies dominating the turbulent flow field. The orientation component of the IPOS framework (see [23]) seems therefore not to be a main parameter to consider to enhance fish passage success in VSFs when velocity fields are mainly 2D-oriented (i.e., upstream/downstream and laterally).

An example of the location of the small vortices is presented in Figure 7d,e. The small size vortices visualized are defined by significant rotation rates and are localized in the shearing region of the jet. The small size coherent structures seem to affect the swimming behavior of fish, as mentioned in the "Scales" parameter of IPOS framework. The small size vortices were used by fish and may allow fish to minimize swimming energy costs by taking advantage of the energy associated with eddies for propulsion. We studied the distribution of the Reynolds shear stresses (Figure 8a) that are estimated using a statistical analysis of turbulence based on time fluctuations. High-value areas are mainly located near the upstream slot, due to the mixing layer of the jet. To understand the physical barrier these conditions can oppose to fish displacement, the swirling structures must be precisely described in space and not only in time. We focused our analysis on the vorticity based on the mean flow (Figure 8b), which allowed us to quantify areas in the pool where shearing, stretching and rotation phenomena are significant, as in [20]. This detailed study of the vorticity allowed us to define the spatial distribution of coherent structures, which are not defined by the Reynolds shear stress data analysis. Significant rates of rotation, shearing and stretching phenomenon, marked by substantial vorticity intensity, are parameters to minimize in order to increase the biological efficiency of a VSF.

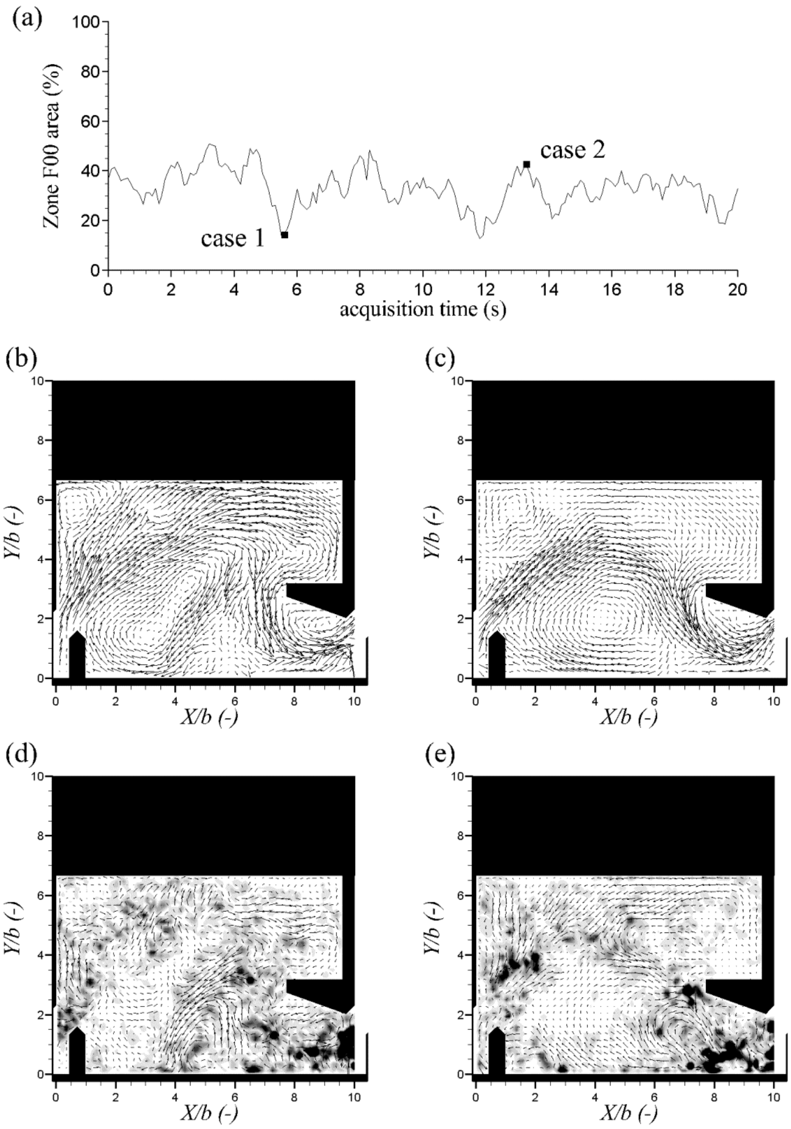

Figure 7. (**a**) Time evolution of the F00 area. (**b**) instantaneous velocity field, case 1. (**c**) instantaneous velocity field, case 2. (**d**) instantaneous location of the small size coherent structures, case 1. (**e**) instantaneous location of the small size coherent structures, case 2 (flow direction: from left to right).

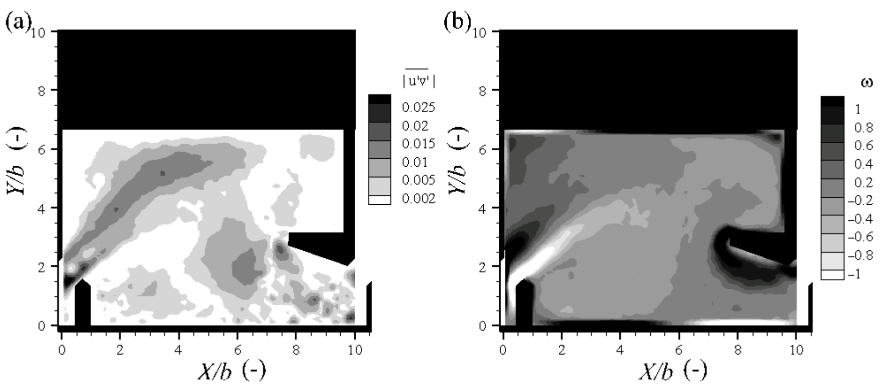

Figure 8. Mean flow features in the studied pool: (**a**) Reynolds shear stresses; (**b**) out-of-plane vorticity component (flow direction: from left to right).

3.3. Fish Passage Improvement in Existing VSFs

The previous results provided some explanations and hypotheses about the relationships between flow characteristics in VSF pools, fish behavior inside them and, subsequently, fish passage success. The following step was to try to improve these hydraulic characteristics in a simple (i.e., neither destructive nor expensive, with respect to existing VSFs) way to facilitate fish passage, especially for "small body species". Based on previous studies [21,22], we changed the turbulence conditions in the pools, by installing vertical cylinders inside (see Figure 2). Three different configurations were tested: (i) pools equipped with one cylinder of diameter D = b, (ii) pools equipped with one cylinder of diameter D = b/2 and (iii) pools equipped with three cylinders of diameter D = b/2 arranged in a triangle (Figure 9).

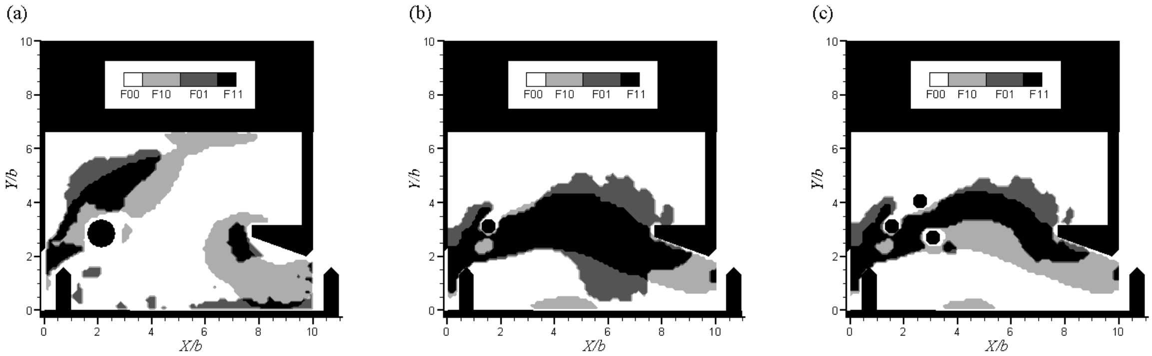

Figure 9. Representation of four levels of flow intensity (from F00 to F11, see text; flow direction: from left to right) for 3 VSF configurations: (**a**) with 1 cylinder of diameter D = b, (**b**) with 1 cylinder of D = b/2, (**c**) with 3 cylinders of D = b/2 arranged in a triangle.

The previous results helped us to understand the positive relationship between an increase in the proportion of low velocity and turbulence kinetic energy conditions in the pools, and the biological efficiency of VSFs. The effects of one or three cylinder(s) on the spatial distribution of these flow characteristics should therefore modify fish passage success in VSFs. In general, migrating fish are attracted to turbulent flows, but they have to maintain their stability in such hydrodynamic environments, especially when they try to pass over an obstacle. Consequently, they tend to avoid flows that have unpredictable velocity and turbulence components [3]. In this context, a quantification of "global estimators", in relation to the local hydrodynamic parameters, could help (i) to predict fish trajectories inside VSFs and (ii) to quantify the hydrodynamic effects of a cylinder, which could not be anticipated by the commonly used criteria, PV and Δh, during the dimensioning process of fishways. For that purpose, we have defined the hydrodynamic environment in the pool by using the averages, over space, of the following target flow quantities: velocity, turbulent kinetic energy and vorticity.

The adding of cylinder(s) in the VSF model globally reduced the proportion of areas where velocity, turbulent kinetic energy, rotation, shear and stress intensities are high, and reduced both average flow velocity and turbulent kinetic energy inside the pool (Figure 9, to be compared to Figure 6; Table 1). The presence of a cylinder with a diameter D = b significantly increased the average vorticity. The values of flow features that should affect fish passage success are poorly reduced by the use of one cylinder with a diameter D = b/2 (Figure 9b, to be compared to Figure 6). The use of three cylinders influenced the flow inside the VSF, in comparison with the experimental setting without a cylinder, by decreasing velocity, turbulence kinetic energy and vorticity average values by 28.8%, 40.0% and 17.3%, respectively (Table 1). The presence of three cylinders modified the flow inside the VSF by changing the jet shape from a curved pattern (Figure 6) to a more linear one, straightened towards the downstream slot (Figure 9c).

Table 1. Averages values over space of three flow characteristics in a VSF pool, for four experimental configurations (with and without cylinders, see Figure 2). D = cylinder(s) diameter, b = slot width.

Configuration	Velocity Norm	Turbulent Kinetic Energy	Absolute Value of Vorticity
No cylinder	$0.282 \cdot V_{th}$	$0.017 \cdot {V_{th}}^2$	$0.307 \cdot V_{th}/b$
1 cylinder D = b	$0.183 \cdot V_{th}$	$0.011 \cdot {V_{th}}^2$	$0.354 \cdot V_{th}/b$
1 cylinder D = b/2	$0.216 \cdot V_{th}$	$0.015 \cdot {V_{th}}^2$	$0.303 \cdot V_{th}/b$
3 cylinders	$0.263 \cdot V_{th}$	$0.013 \cdot {V_{th}}^2$	$0.254 \cdot V_{th}/b$

As hypothesized, lowering the average values of velocity, turbulent kinetic energy and vorticity in the pool by adding cylinders increased the proportion of fish passage success, from 26% without any cylinder to 47.4% with three cylinders (Table 2). The increase in biological efficiency (i.e., passage success) was also significant after adding one cylinder with a diameter D = b/2, shifting from 26.2% to 42.3%. There are statistically significant differences in the use of the three zones identified for each configuration studied (χ^2, $p < 0.05$). Nevertheless, note that the median transit time increased from 6.4 s in the configuration without any cylinder to 9.8 s in the experimental configuration with three cylinders (Kruskall–Wallis, $p = 0.12$).

Table 2. Fish passage efficiency and proportion of F00 areas in the pool (see text and Figures 6 and 9), with respect to different experimental configurations (with and without cylinders, see Figure 2). D = cylinder(s) diameter, b = slot width.

Configuration	Fish Passage Efficiency	Proportion of F00 Zone
No cylinder	26.2%	34.6%
1 cylinder D = b	28.5%	58.6%
1 cylinder D = b/2	42.3%	54.6%
3 cylinders	47.4%	60.9%

These results underline the importance of considering "global flow estimators" (e.g., levels of flow intensity) during the VSF design process to improve their biological efficiency in terms of passage success and transit time.

4. Conclusions

The relationship between flow characteristics and fish behavior inside a VSF pool was investigated. The preferential zones used by fish in the pool before attempting to pass upstream are characterized by relatively low turbulence intensities, quantified in this study as the ratio between average turbulent kinetic energy and velocity values.

Flow patterns in the pool could be changed and some hydrodynamic characteristics unfavorable to chub passage were reduced by adding cylinders in the VSF. Such devices modified the spatial intensity distribution of turbulent quantities (velocity, turbulent kinetic energy and vorticity) and stabilized the unsteady flow dynamics into a low disturbance flow state, making it less constraining for fish migration success (at least for chub, in our experimental conditions). The hydraulic conditions created by the addition of three cylinders resulted in a significantly higher rate of chub passage (47.4%) when compared to the VSF configuration without any cylinders (26.2%).

These results confirm the importance of optimizing flow characteristics in VSF pools in order to maximize fish passage success, for example, by modifying the length-to-width ratios of vertical slot passes [19], or by introducing energy dissipating devices like vertical cylinders [21].

The joint investigation of fish behavior (i.e., trajectories, time they spend in particular areas) and of the spatial distribution of some hydrodynamic characteristics in a fishway provides valuable insights to help engineers and biologists to improve design criteria for fishways. These results now have to be confirmed by in situ studies and for other fish species. Retrofitting of existing VSFs, which were initially designed for good swimmers, could be applied by adding cylindrical structures inside the pool for small fish species.

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