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DEVELOPMENT OF AN IMAGE ANALYSIS-BASED METHOD FOR TRACKING FISH BEHAVIOUR IN VERTICAL SLOT FISHWAYS

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ABSTRACT

Fish migration is hindered by anthropogenic barriers, contributing to declines in freshwater and diadromous species. Vertical slot fishways (VSFs) are widely used to restore connectivity, yet their effectiveness depends on how fish interact with complex hydraulic conditions. This study develops an image analysis–based method to track fish behaviour in laboratory VSFs, enabling high-resolution assessment of movement patterns, resting behaviour, and hydrodynamic interactions. Using brown trout (*salmo trutta*) and chub (*squalius cephalus*), we evaluate how flow conditions influence passage success, transit times, and spatial use within pools. By integrating behavioural tracking with hydrodynamic modelling, the study identifies key factors affecting passage efficiency and provides guidance for refining VSF design to better accommodate diverse species.

Keywords: image analysis, deep learning, ecohydraulics; fish trajectories, vertical slot fishway, fish passage, turbulent flow

1. Introduction

Fish migration is essential for completing life cycles, yet river fragmentation caused by anthropogenic barriers disrupts these movements, leading to declines in freshwater and fish populations. Vertical slot fishways (VSFs) are widely used to mitigate these impacts, but their effectiveness depends on aligning design with species-specific swimming abilities and hydrodynamic conditions. While traditional design criteria focus on critical swimming speeds, a deeper understanding of fish behaviour within VSFs (particularly interactions with turbulence, resting zones, and passage efficiency) remains limited. This study aims to develop an innovative image analysis-based method to track fish behaviour in VSFs, enabling high-resolution monitoring of movement patterns, resting behaviour, and hydrodynamic interactions. Using two species (brown trout (*salmo trutta*) and chub (*squalius cephalus*)) we investigate how flow conditions influence passage success, transit times, and spatial preferences within pools. By integrating image analysis with hydrodynamic modeling, we seek to identify key factors affecting fish passage and refine VSF design criteria to better accommodate diverse species. The primary objectives of this study are to design and validate an image analysis-based tracking system capable of accurately capturing fish trajectories, resting behaviour, and movement patterns within Vertical Slot Fishways. Behavioural analysis will focus on quantifying transit times, resting durations, and spatial occupancy in VSF pools to assess passage efficiency and identify preferential migration routes. Additionally, the study will correlate fish behaviour with local hydrodynamic conditions, including turbulence and velocity, to determine the hydrodynamic thresholds necessary for successful passage.

2. Methods

2.1. Experimental Setup: Vertical Slot Fishway Model

The vertical slot fishway (VSF) model used in this study has been described in detail previously (Tarrade et al., 2011). The model consisted of five identical pools, each with dimensions of length (L) = 0.75 m, height (H) = 0.55 m, and width (B) = 0.50 m (Figure 1) with a slope of 7.5% and a discharge of 23 $L.s^{-1}$. The slot width was set to b = 0.075 m. Each pool was constructed from plexiglass and lined with black paper to simulate natural environmental conditions. The third pool (P3) remained uncovered to facilitate observation, and a mirror was positioned at a 45° angle beneath it to enable overhead visualization and image acquisition.

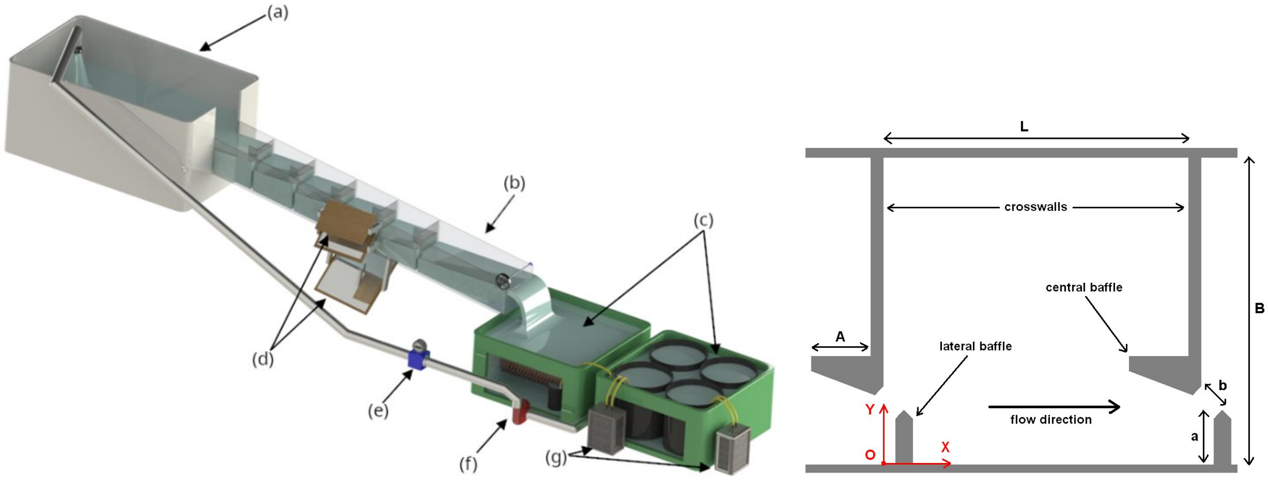

Fig. 1. Experimental device (not to scale)
Left: the five pools of the vertical-slot fish pass model, (a) upper tank, (b) lower tank, (c) fish-tank with four compartments, (d) mirrors for fish observation and image acquisition, (e) flowmeter, (f) pump, (g) filter pump. From Calluaud et al. (2024)
Right: VSF pool configuration

2.2. Hydrodynamic Conditions

Hydrodynamic conditions within the pools have been previously characterized (Tarrade et al., 2011; Calluaud et al., 2014). Flow visualizations and two-component, two-dimensional Particle Image Velocimetry (2C-2D PIV) were used to map the flow topology in pool P3. Under experimental conditions, the jet from the slot exhibited a curved trajectory generating two contra-rotating swirls in the upstream corner and the convex region of the jet. This flow pattern corresponds to the FP2 topology described by Wang et al. (2010) and Tarrade et al. (2011). The maximum velocity in the jet reached 1.1 $m \cdot s^{-1}$, and the volumetric dissipated power in the pool was 110 $W \cdot m^{-3}$.

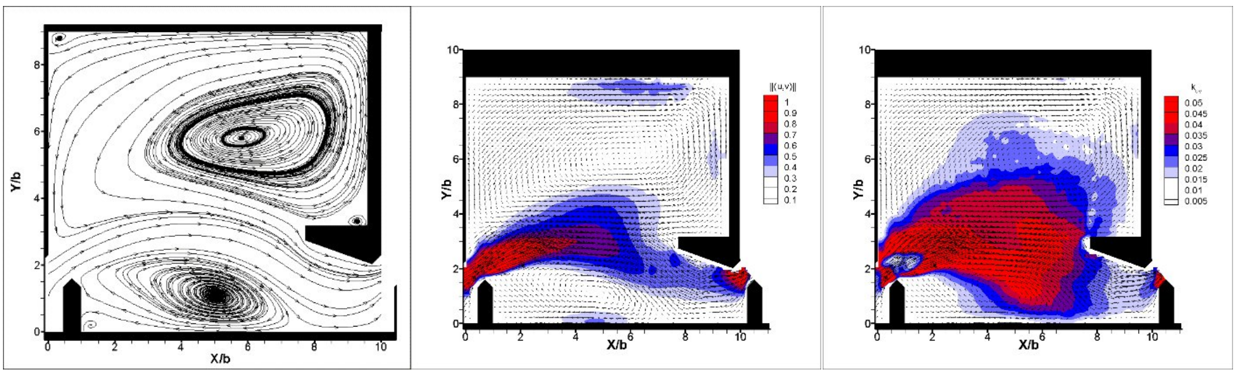

Fig. 2. Mean flow features at a relative flow depth of z/H =0.5. (a)flow topology, (b) Mean velocity amplitude. (c), (d) in-plane turbulent kinetic energy.

2.3. Fish Capture and Selection

Two species known for their swimming proficiency in French rivers were selected for this study: chub (*squalius cephalus L.*) and brown trout (*salmo trutta L.*). Chubs were collected from the Petite Blourde stream, a tributary of the Vienne River in central France, using electrofishing (DREAM Electronique HERON® model). Ninety chubs were divided into three batches of 30 individuals, with a mean total length (TL) of 12.1 ± 2.0 cm and a mean weight (W) of 17.2 ± 8.6 g. Brown trouts were sourced from the Cauterets hatchery in southern France, with 120 individuals divided into four batches of 30. Their mean TL was 10.2 ± 0.6 cm, and their mean weight was 10.1 ± 1.9 g.

2.4. Video Recording and Environmental Control

Fish behaviour and positioning were continuously recorded for 90 minutes using a video camera (SONY HDR-HC9E) at a frequency of 25 frames per second (fps). The 90-minute duration was selected based on preliminary tests, which indicated that no significant changes in observed behaviour occurred beyond this period. Frosted plexiglass plates were placed above the pools to minimize light reflection, and the recording device was enclosed to prevent external light interference. Water for the experiments was sourced from the domestic supply and circulated through the system for at least one week prior to testing to ensure dechlorination. A temperature regulation system, consisting of a copper coil supplied with chilled water, maintained the desired temperature in the lower tank. Daily temperature checks ensured consistency, and a filter pump in the stall tank, along with a recirculation pump between the lower and stall tanks, maintained oxygenation and temperature homogeneity. Four stall tanks provided resting conditions similar to those in the experimental setup. Water temperature was maintained at a mean (± SD) of 16 ± 0.3°C, and the room was illuminated with projectors at constant brightness from 8:00 a.m. to 6:00 p.m. Prior to each trial, the VSF model was filled with water, and the water level was allowed to stabilize. A group of 20–25 individuals (of a single species), randomly selected from a batch, were transferred to the lower pool, which was separated from the upstream pools by a screen. Fish were held in P5 for 15 minutes to acclimate to the flow conditions. The screen was then removed, and the trial starts for 90 minutes. A total of 18 trials were conducted: 11 for chubs and 7 for trouts. Each batch of fish was used at least twice (up to four times for chubs and twice for trouts), resulting in a total of 263 chubs and 144 trouts being tested. To minimize bias from fish learning or fatigue, a rest period of at least one day was enforced between trials.

3. Video analysis and Results

Our object detection pipeline relies on a YOLOv12-m deep learning model for segmentation (Tian and Doermann, 2025; CVAT). To further refine the segmentation masks produced by YOLO, Otsu (1979) thresholding is applied to the pixels contained within each predicted mask. A dataset of 10,000 images was generated from the source videos and manually annotated using CVAT. The dataset was split into training (70%), validation (20%), and test (10%) subsets. The YOLOv12-m model was trained for approximately 300 epochs. Segmentation performance was evaluated using two metrics: mAP50, corresponding to the mean Average Precision (mAP) at an Intersection over Union (IoU) threshold of 0.50, and mAP50–95, which represents the mAP averaged across IoU thresholds ranging from 0.50 to 0.95. The trained model achieved a mAP50 of 96% and a mAP50–95 of 55%. The mAP metric assesses both detection accuracy precision, recall and the agreement between predicted masks and ground-truth annotations. In particular, mAP50 reflects performance under a relatively permissive overlap criterion (IoU = 0.50), indicating the model's ability to detect and localize objects. Conversely, mAP50–95 evaluates performance under increasingly strict IoU thresholds (0.50–0.95), providing a more comprehensive measure of localization accuracy and mask quality. These results indicate that detection performance approaches human-level accuracy, although segmentation quality still requires improvement. To estimate fish pose, the central axis of each segmented fish is computed using a thinning algorithm (Zhang and Suen, 1984). The head and tail are then identified by selecting the endpoint located on the widest part of the shape as the head and the opposite endpoint as the tail. Individual fish are subsequently tracked using a basic tracking algorithm. Overall, the proposed approach provides robust estimates of fish position and pose and performs reliably even under challenging video conditions. However, segmentation accuracy could still be improved—particularly for fish tails—and multi-fish tracking stability remains limited.

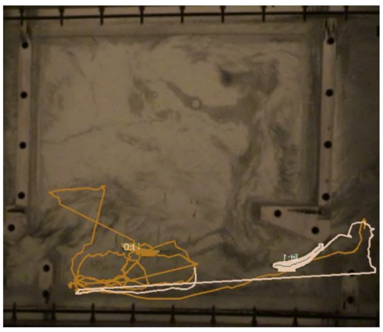

Fig. 3. Example of trajectory tracking

Based on the acquired positional coordinates of the experimental fish (figure 3), a statistical analysis out of a hundred videos was conducted to extract trajectories and heat maps of positions (figure 4-a) and estimate speed of fish (figure 4-b). Moreover, the fish central axis can be used to get its orientation (figure 4-c) and a rough estimation of the amplitude and the frequency of its caudal tail.

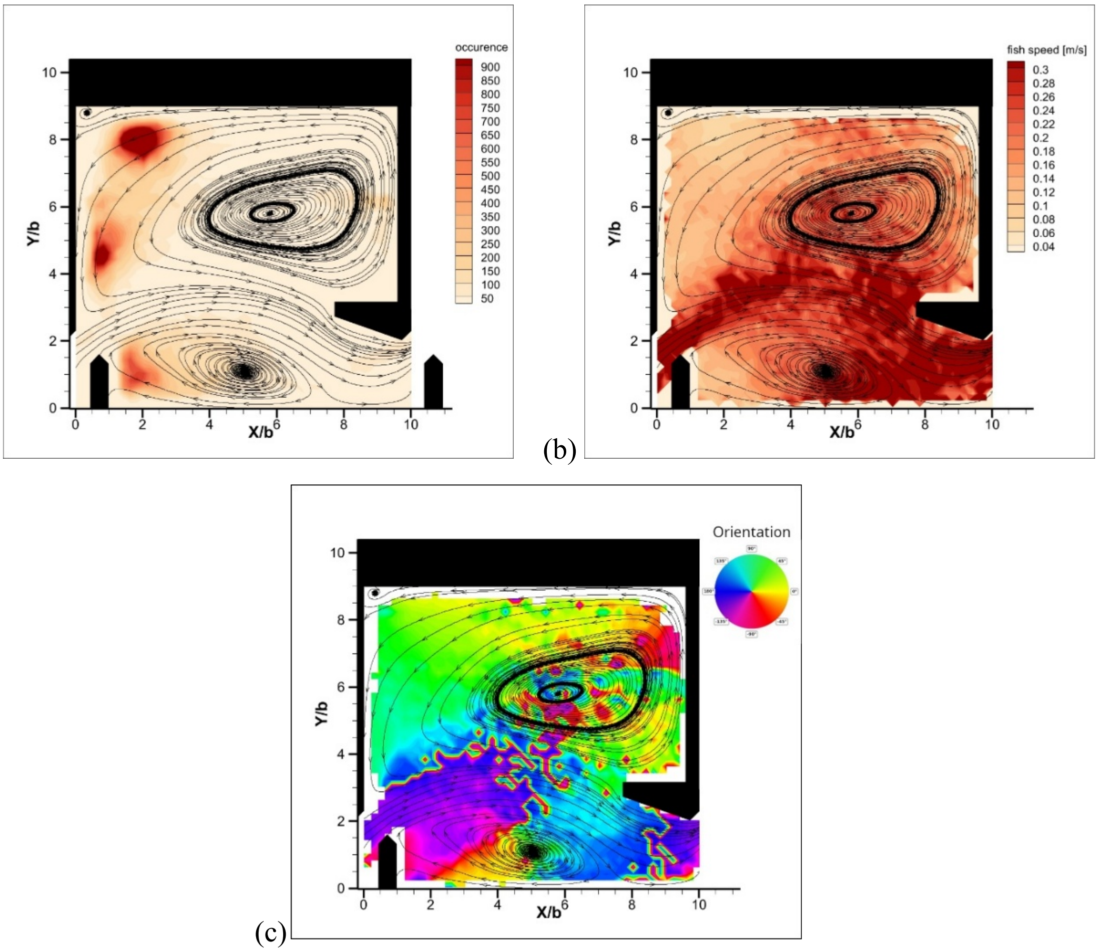

Fig. 4. (a) heatmap of occurrence of fish inside VSF, (b) heatmap of instantaneous fish speed inside VSF, (c) colormap of fish orientation

4. Conclusion

Development and validation of an image analysis–based method to track fish behaviour in VSFs are proposed. The investigation of the fish behaviour, the used trajectories and the associated turbulence levels provide valuable insights, which may help engineers and biologists to improve new criteria in relation with flow features, turbulence activity and spatial distribution of the flow in VSF. Based on this coupled knowledge of turbulence and fish behaviour inside existing VSF, adapting VSF with cylinders for weak swimmers, or to cater for small fish might be a significant effect on fish passage efficiency without decreasing head drops between pools and, as result, the attraction flow velocity at the downstream entrance.

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