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Short communication

Stopping invaders: Moving towards a selective vertical slot fishway to prevent the passage of non-native cyprinids

Filipe Romão [a,*], Ana Quaresma [a], Joana Simão [b], Susana Amaral [c], Renan Leite [a,c], Francisco J. Bravo-Córdoba [d], Francisco J. Sanz-Ronda [e], António N. Pinheiro [a], José M. Santos [c]

[a] CERIS – Civil Engineering for Research and Innovation for Sustainability, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal
[b] LNEC – National Laboratory for Civil Engineering, Hydraulics and Environment Department, Water Resources and Hydraulic Structures Department, Av. Do Brasil 101, 1700-066, Lisbon, Portugal
[c] CEF – Forest Research Centre, Associate Laboratory TERRA, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017, Lisbon, Portugal
[d] GEA – Ecohidráulica, Centro Tecnológico Agrario y Agroalimentario Itagra.ct, 34004, Palencia, Spain
[e] GEA – Ecohidráulica, Area of Hydraulics and Hydrology, Department of Agroforestry Engineering, University of Valladolid, 34004, Palencia, Spain

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ABSTRACT

Invasive fish species are a major driver of freshwater ecosystem degradation across the globe. This urgent problem is particularly tough to manage in dammed rivers, where the reestablishment of longitudinal connectivity for native fish is achieved through the placement of fish passage devices, which can open a new corridor for the dispersal of these taxa to previously inaccessible habitats. In an attempt to solve this dilemma and prevent their dispersal, an experimental study was conducted in a full-scale Vertical Slot Fishway (VSF) to assess the passage performance of the common carp (*Cyprinus carpio*), an invasive non-native cyprinid species widespread in the Iberian Peninsula. With this objective, two configurations were designed and tested, where the main hydraulic parameters that govern fishway operation (discharge, flow velocity, turbulence and slope) were adjusted to exceed design guidelines set for cyprinid species. Common carp passage trials were conducted in configuration VSFh1 and VSFh2 (N = 8 in each configuration), varying in water depth – 0.55 m and 0.80 m, respectively, and both were set up with a high slope (15,2 %), head drop (Δh = 0.28 m) and volumetric dissipation power higher than literature recommendations ($Pv > 150$ Wm^{-3}). Fish movements were assessed in terms of motivation, transit time and ascent analysis using a time-to-event approach. The hydrodynamic scenarios experienced by fish during the trials were investigated with a computational fluid dynamic (CFD) model. Common carp passage results were compared with the performance of a native cyprinid species, namely the Iberian barbel (*Luciobarbus bocagei*), and pointed to selective fishway configurations, which hindered invasive fish passage movements, but favored the native species. In both configurations, common carp revealed a lower motivation with a significantly lower probability of performing passage attempts compared to the Iberian barbel. Regarding the ascent movements, none of the common carp tested managed to pass VSFh1 while in VSFh2 only one individual managed to ascend (of 3 that attempted – 33 %). Comparatively, the Iberian barbel managed to ascend both configurations, with VSFh1 showing a higher number (17) of these movements (of 17 that attempted to pass – 100 %). Overall, these promising results point to a selective passage under the tested configurations, specifically configuration VSFh1 that can assist managers in reestablishing river connectivity while deterring the spread of non-native invasive fish. Nonetheless, further studies and field validation are required to reinforce the present findings.

* Corresponding author.
E-mail addresses: filipe.romao@tecnico.ulisboa.pt (F. Romão), analopesquaresma@tecnico.ulisboa.pt (A. Quaresma), jsimao@lnec.pt (J. Simão), samaral@isa.ulisboa.pt (S. Amaral), renanleite@edu.ulisboa.pt (R. Leite), fjbravo@itagra.com (F.J. Bravo-Córdoba), jsanz@uva.es (F.J. Sanz-Ronda), antonio.pinheiro@tecnico.ulisboa.pt (A.N. Pinheiro), jmsantos@isa.ulisboa.pt (J.M. Santos).

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1. Introduction

Worldwide, non-native invasive fish species are considered a major threat to aquatic ecosystems functioning (Larson et al., 2011; Su et al., 2021; Britton, 2023). Invasive non-native species disturb mechanisms that maintain balance in the ecosystem such as predation, competition and water quality (Gallardo et al., 2016). Hybridization and the spread of diseases represent a primary health and environmental problem driven by these invaders (Reid et al., 2019). These factors contribute to the loss of biodiversity and result in billions of dollars in financial costs throughout the globe annually (Haubrock et al., 2022) due to large-scale physical removal (Bajer et al., 2024), trapping and sorting (Stuart et al., 2006; Rahel and McLaughlin, 2018), barrier installation (Rahel, 2013) and freshwater ecosystem restoration actions (Weber and Brown, 2009).

Generally, the main solution used to prevent the dispersal of non-native invasive fish species in freshwater ecosystems is the installation of barriers, although they can also hinder native fish movements (Houdt et al., 2005; Rahel, 2013). As a prime example, the sea lamprey (*Petromyzon marinus*) stands out, due to the colossal effort engaged to prevent its propagation to the Great Lakes of North America, where physical, chemical, and electrical barriers have been installed (Johnson et al., 2014; Jones et al., 2021). Additionally, the common carp (*Cyprinus carpio*), the silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*) are also regarded as signature species when it comes to invasive fish, and large-scale efforts are being conducted to prevent their dissemination throughout the world (Chick and Pegg, 2001; McLaughlin et al., 2013).

River longitudinal connectivity is a key element in ensuring ecosystem functioning, and fishways are generally the main mitigation solution implemented to allow native fish movements in fragmented rivers (*e.g.* Lucas and Baras, 2001; Bravo-Córdoba et al., 2023). On the other hand, these structures could also contribute to spreading invasive fish (Franklin et al., 2021; Ovidio et al., 2023) and trade-offs must be carefully accounted for when planning their installation (McLaughlin et al., 2013). Currently, there is an emerging tension between the urge to reestablish connectivity, through the implementation or retrofitting of fishways in weirs and dams, but also the need to block the passage of invaders, which may have access to non-colonized environments and negatively interact with native species and habitats (Rahel and McLaughlin, 2018; Kerr et al., 2021). In an ideal scenario, engineering solutions should aim to evolve towards selective fishways, where passage by native species prevails over non-native ones. To achieve this, the main hydraulic parameters that govern fishway functioning (discharge, flow velocity, turbulence and slope) should be assessed, tested and adapted to provide safe passage for site-specific target native species while stopping potential invaders, taking into consideration the differences in the swimming behavior, migration, morphology and ecology of fish (Rahel, 2013).

In this experimental approach, we hypothesized that a Vertical Slot Fishway (VSF), currently considered one of the most suitable types of technical fishways (Fuentes-Pérez et al., 2014) could prevent the upstream passage of the common carp, if hydraulic parameters, such as flow velocities and turbulence, were set beyond cyprinid threshold values proposed in literature guidelines (FAO/DVWK, 2002; Larinier, 2008; Baudoin et al., 2014). For this, common carp passage performance tests were conducted in an experimental fishway setup with a high slope (15.2 %) and head drop of $\Delta h = 0.28$ m, which generated flow velocities and turbulence higher than literature guidelines provided for cyprinids – volumetric power dissipation - $Pv > 150$ W m^{-3} (Larinier, 2002, 2008). Subsequently, the passage performance of the common carp was compared with the performance of the Iberian barbel (*Luciobarbus bocagei*), a widespread cyprinid native species in the Iberian Peninsula, which was previously tested under the same experimental conditions (Romão et al., 2024).

2. Material and methods

The passage performance tests were carried out in a full-scale fishway prototype (rectangular flume of 10.0 m long; 1.0 m wide; and 1.2 m high) at the National Laboratory for Civil Engineering, Portugal (Fig. 1). Further details about the experimental facility are presented in Romão et al. (2024).

The VSF tested was based on design 11 proposed by Rajaratnam et al. (1992), a cost-effective design for distinct cyprinids with different ecological traits (Romão et al., 2017) and two water depths were experimented (h1 = 0.55 m; h2 = 0.80 m), representing two fishway configurations (VSFh1 and VSFh2). Table 1 summarizes the hydraulic parameters of the configurations under analysis. The volumetric dissipated power, in a pool, was computed with the following equation: $Pv = \frac{\rho g Q \Delta h}{L B h_m}$ in Wm^{-3}; where ρ is the water-specific mass = 1000 kg m^{-3}; g is the gravitational acceleration = 9.81 m s^{-2}.

Common carp (mean total length - TL ± SD: 38.9 ± 3.4 cm; mean total body mass ± SD: 724.4 ± 168.8 g) were caught in the wild in June, during the migration season (Kottelat and Freyhof, 2007), in a small reservoir from the Tagus basin (Portugal), using an electric fishing gear (Hans Grassl, IG-200). Within the migration season, in both lentic and lotic ecosystems, this species congregates in large numbers in areas with shallow waters and dense vegetation to spawn (Watkinson et al., 2021; Bajer et al., 2024). After the capture procedure, fish were transferred to the laboratory 700 L holding tanks, equipped with mechanical and biological filters (High-Performance Canister Filter FX5, Fluval, Québec, QC, Canada) and with a turnover rate of 2300 L h^{-1} in a closed circuit, where they were held for acclimation purposes before marking and experimentation. Water quality in the holding tanks [temperature (mean ± SD: 22.2 ± 0.2 °C), pH (mean ± SD: 7.47 ± 0.13) and conductivity (mean ± SD: 252.5 ± 43.3 μS cm^{-1})] and the fishway [temperature (mean ± SD: 22.2 ± 1.2 °C), pH (mean ± SD: 7.97 ± 0.02) and conductivity (mean ± SD: 212.5 ± 4.6 μS cm^{-1})] was checked daily with a multi-parametric probe (HANNA Instruments, HI 9812-5). During the experiments, water temperature was within the optimal spawning temperature (18–23 °C) where the reproductive activity is at its peak (Fernández-Delgado, 1990).

For the marking procedure, fish were anaesthetized with eugenol (50 mg L^{-1} diluted in ethanol in proportion 1:10; exposure time between 1 and 2 min) and marked in the posterior quarter of their peritoneal cavity with PIT-tags (glass transponder 12 mm × 2.12 mm, and 0.1 g, Half Duplex - HDX ISO 11784/11785 -, Oregon RFID®). Individual fish movements were tracked using a PIT-tag system consisting of two antennas, placed at the first and last slot of the fishway, connected to a dedicated reader (Oregon RFID®, Portland, OR, USA). The trials began with an acclimatization period (30 min) in which the fish were placed in a 0.60 m^2 confined area, delimited by two mesh panels at the entrance of the fishway, to be previously acclimated to the flow conditions. In each configuration tested, four 90 min trials were conducted with common carp, each composed of a group of two adult-tagged individuals (N = 8 per configuration). This period was selected according to previous studies (Branco et al., 2013; Romão et al., 2017) to enable comparisons with other fishway designs. Each fish was used only once to avoid training effects (Ficke et al., 2011). Subsequently, trial results were compared with the passage performance of the Iberian barbel in five similar 90 min trials, each composed of 5 tagged individuals (N = 25 per configuration tested; mean TL ± SD: 17.4 ± 2.3 cm; mean total body mass ± SD: 56.5 ± 24.6 g) from a previous recent study (Romão et al., 2024) also conducted during the reproductive season when this species is most motivated to swim upstream. Water quality in the holding tanks [temperature (mean ± SD: 21.5 ± 0.1 °C), pH (mean ± SD: 7.40 ± 0.10) and conductivity (mean ± SD: 242.8 ± 1.4 μS cm^{-1})] and the fishway [temperature (mean ± SD: 22.4 ± 1.1 °C), pH (mean ± SD: 7.60 ± 0.30) and conductivity (mean ± SD: 253.8 ± 6.6 μS cm^{-1})] was also checked daily with a multi-parametric probe (HANNA Instruments, HI 9812-5).

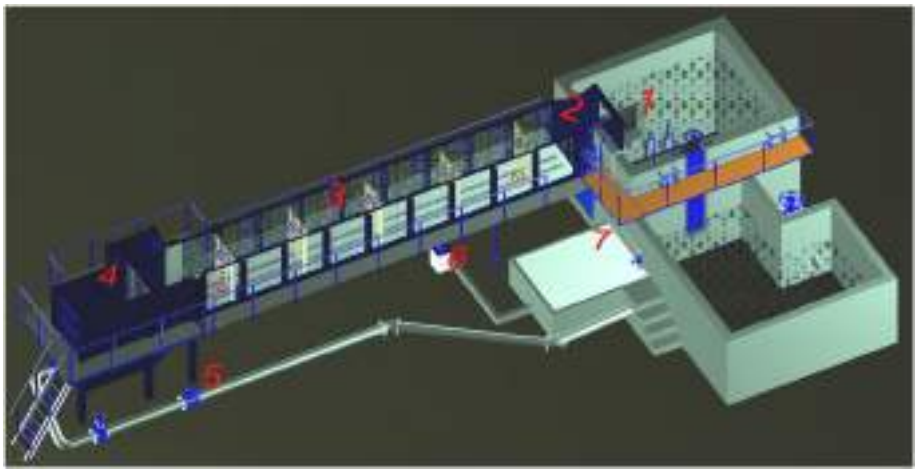

Fig. 1. Full-scale experimental VSF. 1 - downstream tank; 2 - acclimation chamber; 3 - open-channel; 4 - upstream tank; 5 - flow meter; 6 - hydraulic jack (slope range: 0–15.2 %); 7 - pump; Pit tag antennas (A1 - downstream and A2 – upstream); S1 to S5 (slot 1 to slot 5, dividing the VSF into 6 pools).

Table 1
The main hydraulic variables of the tested setups (VSFh1 and VSFh2) regarding experiments conducted with Iberian barbel (native species, Romão et al., 2024) and common carp (non-native invasive, present study) on the experimental VSF.

Hydraulic variables	VSFh1	VSFh2
I (%)	15.2	
L (m)	1.85	
B (m)	1.00	
b (m)	0.10	
Δh (m)	0.28	
Q (Ls^{-1})	81	110
h_m (m)	0.55	0.80
Cd	0.50	0.50
P_v (Wm^{-3})	222	208
Uavg (ms^{-1})	0.41	0.46
Umax (ms^{-1})	2.52	2.48

I - channel slope, L - pool length, B - pool width, b - slot width, Δh - head drop between pools, Q - flow discharge, h_m - pool mean water depth, Cd - discharge coefficient, P_v - volumetric power dissipation, *Uavg – average flow velocity and Umax - maximum flow velocity.*

It is important to note that length at sexual maturity is different between the species, with common carp typically maturing at a larger size (>30 cm TL, Brown et al., 2005) than Iberian barbel (10–20 cm TL, Santos et al., 2011); hence the common carp tested were larger than Iberian barbel.

To analyze fish passage movements, a survival analysis (Castro-Santos and Perry, 2012) using Cox Proportional Hazard regression was applied. For this, the metrics motivation, passage success (or ascend success) and transit time were analyzed. Regarding motivation, the time between the beginning of the trial and the first attempt (detection in antenna A1) was assumed. For the ascent success (complete passage of the fishway), each fish that crossed both antennas (A1 and A2) was considered. These movements were also analyzed in terms of transit time (passage time needed to swim between A1 and A2) and to compare with other studies, this was relativized by the water height difference between antennas (transit time per meter of ascended height). Cox Proportional Hazard regression statistical analyses were conducted in Statgraphics Centurion (Statgraphics Technologies, Inc., The Plains, Virginia, USA) statistical software (Version 18.1) and SAS® (PHReg procedure) (version 9.4). Differences were considered statistically significant at $p < 0.05$). The non-proportionality assumption was tested through Martingale and Schoenfeld residuals. For an overview of the method used, including censored observations, see Romão et al. (2024).

To determine the hydrodynamic environment of the tested VSF configurations, a numerical model was developed with FLOW-3D®, a commercial 3D Computational Fluid Dynamics (CFD) model. The use of CFD enabled us to represent and compare the whole flow field, obtaining hydrodynamic parameters of the entire pool volume. This was not viable with experimental measurements due to the high turbulence and aeration of both configurations, and the low water depths of VSFh1, which made the velocity measurements unfeasible, the costs and time needed to perform velocity measurements for the whole pool volume would also be unviable. The validation of the numerical model results achieved was performed through *in-situ* flow discharge and water depth measurements. Comparisons between the values measured in the experimental facility and the numerical model show relative differences lower than 5 % and 4 %, for the discharge and water depth measurements, respectively. These differences are in line with the ones found for the same configuration with a different slope and for other previously tested configurations (Quaresma et al., 2018; Quaresma and Pinheiro, 2021). In these studies, the numerical model was thoroughly verified and validated for several hydrodynamic parameters, like time-averaged velocity magnitude (U), turbulent kinetic energy (TKE) and Reynolds shear stress parallel to the bottom component (RSS) by comparing its results with ADV (Acoustic Doppler Velocimetry) and PIV (Particle Image Velocimetry) measurements, showing that the model accurately reproduced the flow fields under analysis. Further details about the method used are described in Quaresma et al. (2018) and Romão et al. (2024).

Each operation related to the sampling and handling of fish rigorously followed European standards (Directive 2010/63/EU) and Portuguese legislation (Decree-Law 113/7 of August 2013, article 35, no. 5), which transposes the European Directive on animal experimentation (Directive 2010/63/EU). Testing and maintenance of fish in the Laboratory holding facilities were authorized by the Directorate of Animal Health and Protection Services, following the recommendations of the "protection of the use of animals for experimental and scientific purposes".

3. Results

In terms of hydrodynamic scenarios, both configurations presented high values of volumetric dissipated power in the pools, with VSFh1 generating a $Pv = 222$ W m^{-3} while VSFh2 a $Pv = 208$ W m^{-3}. VSFh1 also presents shallower water depths when compared to VSFh2. CFD results show a higher maximum Reynolds shear stress in VSFh1 (RSS = 1151 Pa) compared to VSFh2 (RSS = 1038 Pa), although Turbulent Kinetic Energy (TKE) maximum magnitudes were similar between both configurations tested (TKE = 0.73 m^2 s^{-2} – VSFh1, and TKE = 0.76 m^2 s^{-2} – VSFh2), as well as the percentage of pool volume with TKE higher than 0.05 m^2s^{-2} (46 % - VSFh1, and 49 % in VSFh2). Average flow

velocities in the pools (*Uavg* = 0.41 m s^{-1} – VSFh1, and 0.46 m s^{-1} – VSFh2), as well as maximum magnitudes found in the slot area (*Umax* = 2.52 m s^{-1} – VSFh1, and 2.48 m s^{-1} – VSFh2) were similar between configurations. Fig. 2 presents the mean velocity magnitude and TKE in both configurations at two planes: i) one parallel to the flume bottom, located at mid-water depth, and ii) another parallel to fishway side walls, located in the middle of the slot. Higher mean velocity magnitudes and TKE exist in the slot and surrounding area, in both configurations. However, the shallower water depth in VSFh1 intensifies the effect of the plunging jet on the slot and pool hydrodynamics (Fig. 2). This configuration shows a larger region with higher mean velocity magnitudes and TKE in the slot and downstream area (Fig. 2a and c), when compared to VSFh2 (Fig. 2b and d). In VSFh1, the head drop between pools is 70 % of the downstream water depth, whereas in VSFh2, it is only 43 %, which explains this difference.

There were differences in the passage performance between the Iberian barbel and common carp tested herein. In terms of motivation, common carp displayed a longer time to perform the first attempt (*i.e.* the time between the beginning of the trial and the first attempt) compared to the Iberian barbel, in both configurations tested. The fastest common carp attempted passage in 43.8 min (VSFh1) and 21.8 min (VSFh2), while the Iberian barbel did so in 1.8 min (VSFh1) and 0.4 min (VSFh2). Median times (± standard error) were 87.3 ± 11.1 min (VSFh1) and 43.3 ± 19.8 min (VSFh2) for common carp, and 23.2 ± 3.2 min (VSFh1) and 10.5 ± 4.9 min (VSFh2) for Iberian barbel. These movement patterns are represented by Kaplan-Meier curves (Fig. 3), illustrating the proportion of fish over time from trial initiation to the first attempt (Romão et al., 2024). Regarding this metric, Cox proportional hazard regression showed significant differences when comparing both scenarios and for both species (in all cases $p < 0.05$; Hazard Rates between 3.2 and 4.5), which reflects that the common carp had a much lower probability of passage attempts compared to Iberian barbel ([HR-1] ×100 = 69–78 %).

In VSFh1 configuration, none of the common carp tested was successful in ascending (of 4 that attempted to pass). In VSFh2 configuration, only one managed to ascend the fishway (of 3 that attempted – 33.3 %), with a total transit time per meter of ascended height of 10 min m^{-1}. Comparatively, the Iberian barbel displayed a median transit time of 11 min m^{-1} in VSFh1, with a total of 17 complete passages (of 17 that attempted – 100 %), while in configuration VSFh2 the median transit time was 17 min m^{-1}, in 8 complete ascents (of 9 that attempted to pass – 88.9 %).

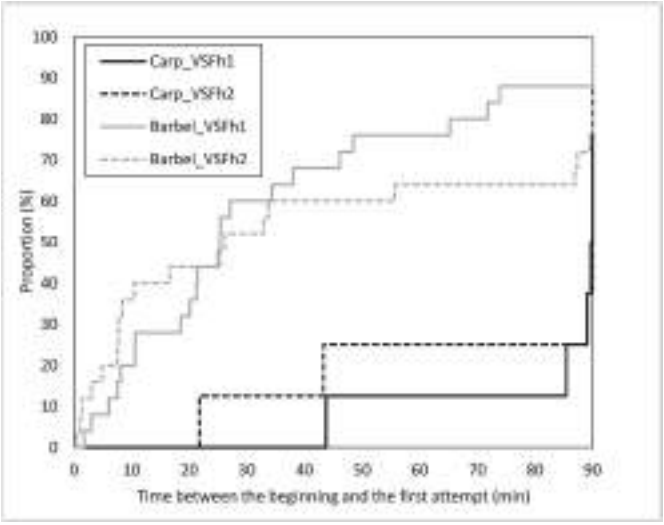

Fig. 3. Kaplan-Meyer curves for the proportion of fish detected in the first antenna (A1) considering the beginning of the trial in VSFh1 (Q = 81 L. s^{-1}) and VSFh2 (Q = 110 L. s^{-1}).

4. Discussion

Common carp is a native species from Eurasia and is one of the world's most widely distributed freshwater fish (Zambrano et al., 2006). Their migratory behavior is well described, where extensive mass movements have been documented searching for spawning grounds with macrophytes areas with shallow water (Butler and Wahl, 2010; Watkinson et al., 2021; Piczak et al., 2023). They are a very tolerant species, able to withstand adverse conditions of oxygen depletion and

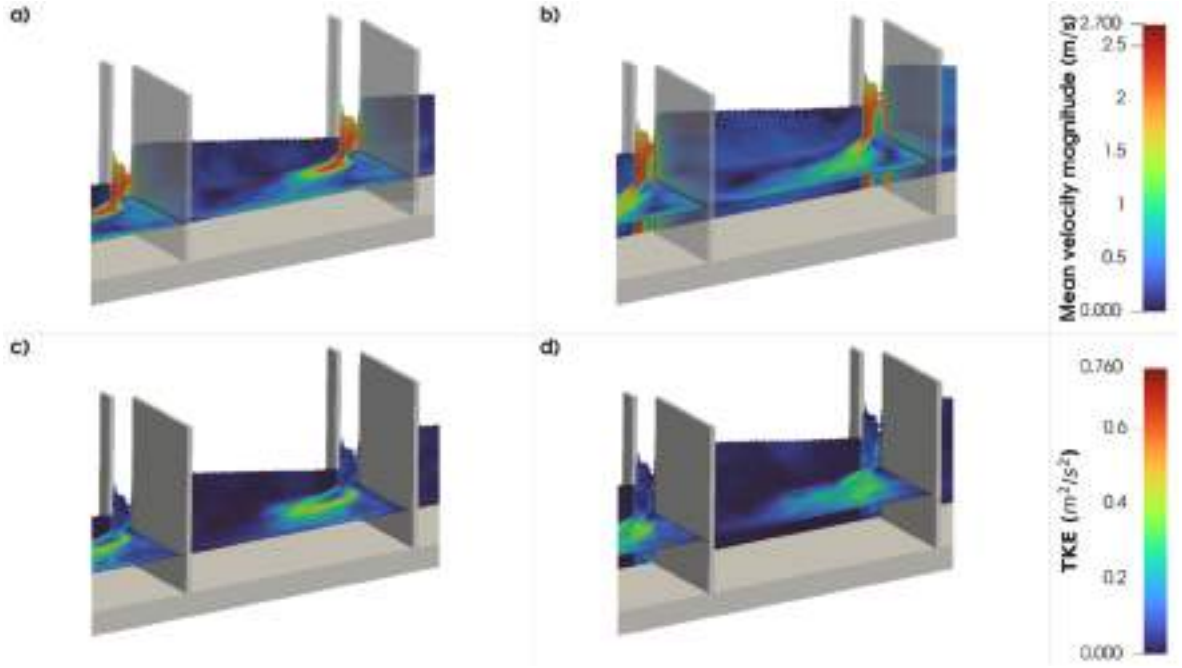

Fig. 2. Mean velocity magnitude at mid-water depth in the pools (z = 50 % h_m) and mid slot: (a) VSFh1; (b) VSFh2; and turbulent kinetic energy (TKE) at mid-water depth in the pools (z = 50 % h_m) and mid slot: (c) VSFh1; (d) VSFh2.

water quality degradation, which means that once established, they are extremely difficult to eradicate (Matsuzaki et al., 2009; Watkinson et al., 2021). A single female has the potential to lay around 100.000–200.000 eggs per kg of body mass and can reach over 30 kg (Swee and McCrimmon, 1966). Therefore, the primary objective in designing selective fishways should ideally be to prevent the passage of all individuals, as even a small portion of the population (<1 %) can have devastating effects on the ecosystem.

The results of this study revealed a low motivation of the common carp to pass both configurations. Significant interspecific differences were found concerning the time taken for the first passage attempt. The median time displayed by common carp was 87.3 min in VSFh1 and 43.3 min in VSFh2. In contrast, Iberian barbel attempted to pass much more rapidly, with median times of just 23.2 min in VSFh1 and 10.5 min in VSFh2, highlighting a clear disparity in their motivation to perform entrance movements. This behavioural trait exhibited by common carp appears to be the primary factor influencing their performance rather than a limitation in swimming capacity since both species present a similar critical swimming capacity when comparing individuals with similar lengths. As reported by Li et al. (2023) common carp critical swimming speed (Ucrit) threshold for a fish with 20 cm (total length) is around 0.78 m s^{-1} while the Iberian barbel is 0.75 m s^{-1} for the same size (Mateus et al., 2008). Therefore, the observed differences in entrance attempt times are more likely attributed to a species-specific trait, affecting carp's willingness to enter the configurations tested, rather than a physiological constraint. According to Domenici (2010), what drives a migratory fish to swim upstream depends on the stimulus received, which can enhance or inhibit the motivation to pursue these movements. Since it relies on a multitude of extrinsic (*e.g.* flow velocities and direction, turbulence, temperature) and intrinsic factors (e.g. age, energy content, life history), it is particularly challenging to assess and predict. Given that both species were tested during the migratory season, they were à priori motivated to swim upstream. Nonetheless, the challenging hydrodynamic conditions generated in the tested configurations, with high velocities and turbulence, most likely contributed to hindering the swimming motivation of the common carp to perform entrance attempts and progress through the VSF.

Flow turbulence contributes to the hydrodynamic heterogeneity of natural fish habitats and significantly influences fish behavior by affecting their locomotion (Farrell, 2011). In general, fish swimming costs increase with turbulence (Enders et al., 2005; Liao, 2007; Silva et al., 2012). For instance, in turbulent flows, fish commonly extend their pectoral fins to stabilize themselves against the current, which increases hydraulic resistance and thereby decreases swimming speed (Lupandin, 2005), as well as their motivation to progress through fishways (Rodríguez et al., 2006; Silva et al., 2012; Tan et al., 2019). Additionally, different ecological guilds are adapted to select streams with varying turbulence levels (Lupandin, 2005). The species examined in this study, both cyprinids, belong to distinct ecological guilds: common carp, primarily limnophilic (Barakov et al., 2024) preferring low turbulent environments, and Iberian barbel, rheophilic (Doadrio et al., 2011). Thus, turbulence may differentially influence fish motivation based on habitat preference, attracting or inhibiting movement accordingly. In a meta-analysis study designed to update the consensus on fishway efficacy, Hershey (2021) showed that models comparing efficiency between ecological guilds of fishes (pelagic or benthic and rheophilic or limnophilic) evidenced that attraction and passage efficiency were highest for rheophiles and lowest for limnophiles, a finding that is in accordance with the present study. Both configurations tested exceeded turbulent thresholds for cyprinids, $Pv > 150$ W m^{-3}, proposed by Larinier (2008). Nonetheless, the Iberian barbel managed to successfully negotiate both configurations with a much higher proportion than the common carp, suggesting that fish passage selectivity may be achieved by manipulating the main hydraulic parameters that govern fishway functioning. In accordance, the configuration VSFh1, the most turbulent configuration which generated a higher Pv (222 W m^{-3}), was revealed to be the most efficient for the Iberian barbel while completely deterring the passage of invasive common carp, where none of the individuals tested managed to pass.

Other possible reasons that inhibited the upstream movements of common carp were most likely related to the hydrodynamic conditions experienced. For instance, the shallower water depths of VSFh1 may have precluded the deeper-bodied common carp from passing this configuration, a hypothesis already raised by Franklin et al. (2021) to explain the failure of common carp to overcome an artificial baffled ramp. Additionally, given that the common carp is a larger and deeper-bodied fish than the Iberian barbel, it may have experienced a larger drag force. Wiegleb et al. (2022) also showed that the hydrodynamic burdens experienced by fish differ significantly between species due to the individual body shape characteristics of the species conditioning their passage success in a VSF equipped with a prototype hydraulic barrier. It is also worth noting that testing a larger sample size, or trials with larger groups, would be recommendable to reinforce the present findings (Goettel et al., 2015; Zhang et al., 2024). Even so, despite the low sample size, which could be considered as a study limitation, the number of individuals assessed is within the range of those used in fish passage experiments, while balancing a sufficiently large enough number of subjects to allow statistical difference to be determined and ethical concerns on using wild species (Branco et al., 2013; Gonino et al., 2019; Leite et al., 2022).

In general, common carp are considered a highly invasive species, which can attain overwhelming population densities and dominate the rivers to which they have been introduced (Hicks and Ling, 2015; Stuart and Conallin, 2018; Raboin et al., 2023). While large-scale efforts are being conducted worldwide to manage and control the spread of this species and other invaders, the results achieved in this study represent a potential solution that may assist aquatic conservation managers, practitioners and decision-makers in restoring longitudinal connectivity through selective fishways, which may hinder non-native invasive fish movements to non-colonized areas, while providing safe passage to native species and therefore protecting fish habitats (Ovidio et al., 2023). This will allow tackling two key threats to freshwater biodiversity, promoting river connectivity and avoiding non-native invasive fish expansion. Nevertheless, further testing and field validation are required to endorse and reinforce the results achieved. Follow-up studies should encompass a larger sample using similarly sized fish between species to avoid bias in swimming performance but also assess seasonal passage movements under different fishway configurations. Equally important is to ensure that these VSFs with challenging hydrodynamics, able to reduce invasive fish movements, will not compromise native species passage; therefore, a site-and-species specific approach should be undertaken when planning the installation of such devices. The suggested approach should carefully balance the benefits and drawbacks of promoting river connectivity with the suggested VSF configuration taking into consideration the migratory guilds present at a specific river system (*e.g.* catadromous, anadromous, potamodromous) to ensure that non-native invasive fish may be deterred but native fish passage is accomplished.

Other strategies have been assessed and revealed encouraging insights about selective migration, such as the use of baffled ramps to avoid common carp dispersion (Franklin et al., 2021) or the installation of a prototype hydraulic barrier in a VSF, which has proven to be effective to block the passage of the invasive round goby (*Neogobius melanostomus*) while allowing native fish passage (Wiegleb et al., 2022). Even so, studies focusing on the hydraulic features specifically designed to improve the selectivity of fish passage devices are still seldom, yet extremely necessary to preserve freshwater ecosystems and evolve this emerging path of research. Up until now, most of the studies have focused on the development of trap-and-sort mechanisms, which are very demanding in terms of human effort (Stuart et al., 2006), and screens or other types of physical barriers (Bulow et al., 1988; Rahel, 2013).

Overall, the present study aimed to contribute to solving the dilemma of connecting or fragmenting rivers to exclude potential invasive fish species. By using ecohydraulics principles of fishway design, it seems viable that these facilities may operate with conditions that favor native fish, while mostly precluding the invasive common carp, even if the operational regime of these devices may change throughout the year (Romão et al., 2018), for instance by changing the water height in the pools, slot configurations (Romão et al., 2017) or through the installation of discharge-control mechanisms that may allow regulating the flow entering the passage. Hereafter, further assessments of other non-native invasive species (*e.g. Micropterus salmoides*, *Sander lucioperca*, *Alburnus alburnus*) should be conducted, to evaluate how the passage performance would be affected by these VSF configurations, as well as other native migratory fish, to achieve a balanced design that would provide an efficient passage to reconnect fish habitats and preserve freshwater ecosystem health.

CRediT authorship contribution statement

Filipe Romão: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Ana Quaresma:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Joana Simão:** Data curation, Conceptualization. **Susana Amaral:** Conceptualization. **Renan Leite:** Investigation. **Francisco J. Bravo-Córdoba:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Francisco J. Sanz-Ronda:** Writing – review & editing, Resources, Conceptualization. **António N. Pinheiro:** Writing – review & editing, Resources, Conceptualization. **José M. Santos:** Writing – review & editing, Resources, Conceptualization.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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