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# Does the relative depth of flow influence fish passage in pool-type fishways?

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**ABSTRACT.** The introduction of habitat structures in river channels has become one of the most common ways to minimize the habitat losses derived from dam and weir construction. As a result, fishways related literature has seen a recent upsurge of interest in this kind of structures for improving fish passage. Despite their increasing utilization in nature-like fishways, little information exists on their performance for assisting fish passage in conventional pool-type facilities. The main goal of this study is to assess the performance of two different flow regimes, based on the relative depth (d/h) of flow, where d is the water depth and h is the height of artificial boulders, for assisting fish passage in an experimental full-scale pool-type fishway. Two series of experiments consisting of twenty replicates each and representing distinct flow regimes created by the placement of artificial boulder in the flume bottom – $d/h > 4$ (regime 1) and $1.3 < d/h < 4$ (regime 2) – were carried out by analyzing the number and timing of successful upstream movements of adult Iberian barbel (*Luciobarbus bocagei*) through the facility. Water velocity at different horizontal layers was measured by a 3D ADV Vectrino and used and used to calculate turbulence. Though no significant difference in passage success was observed between both regimes, fish transit time was lower in regime 2, characterized by the presence of surface waves and a recirculation region near the boulders. The results of these experiments showed that lower relative depths can be more beneficial to fish passage because they reduce the transit time for successful negotiation, thus providing a useful indication on how to improve fish passage through pool-type fishways.

**KEYWORDS:** *Pool-type fishway, relative depth of flow, artificial boulders, ADV Vectrino, cyprinids.*

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## 1. Introduction

The restoration of longitudinal connectivity of a watercourse altered by man-made obstacles is a key issue for the protection and safeguard of freshwater ecosystems and the construction of fish passes stand as a relevant ad hoc measure. The importance of these facilities was recently reinforced with the launch of water policy tools, such as the European Water Framework Directive (EWFD), which requires effective passage and undisturbed migration of fish as a key component to restore and manage watersheds (European Comission, 2000). Nonetheless, and in spite of increasing research on this subject, studies of fishway performance focused on species with low economic value and recreational value continue to be neglected (Roscoe & Hinch, 2010). This is rather unfortunate, since these species are an important biological component of fish assemblages and free instream movement is indispensable for their survival (Lucas *et al.*, 2000).

Pool-type fishways are presently the most common type of fishways built at small hydropower plants (Larinier, 2008). Their main purpose is to ensure adequate dissipation of the energy of the water while offer resting areas for fish. However, in southern-European countries, particularly in Iberia, most of the existing pool-type fishways failed to restore connectivity for fish, because their design and construction was based on model facilities from northern-European countries dominated by fast-flowing salmonids and therefore did not take into consideration the predominant group of fishes, mainly potamodromous cyprinids of limited swimming ability. It is therefore imperative to improve fishways efficiency for these species in order to develop adequate technical and scientific guidelines to correctly design future facilities.

The placement of perturbation blocks has been frequently used in nature-like fishways as a mean to improve connectivity for fish (*e.g.* Heimerl *et al.*, 2008). Upon studying the flow around a cylindrical obstacle of height h in a rectangular channel, Shamloo *et al.* (2001) found that the relative depth of the flow, d/h, was a key parameter in determining the flow regime around such an obstacle and in providing suitable hydraulic conditions for fish passage. Although common in nature-like fishways, so far no study has considered the placement of perturbation blocks in pool-type fishways in a tentative to aid upstream fish movements. This study aims to compare the effect of two different flow regimes, based on the relative depth (d/h) of flow, on the upstream movements of a potamodromous cyprinid species, the Iberian barbel *Luciobarbus bocagei*, migrating through a pool-type fishway.

## 2. Materials and methods

### 2.1. Experimental fishway

The experimental pool-type fishway consisted of a full-scale model, built on a steel frame and featuring acrylic glass panels on both side-walls. It is composed of 6 pools (each 1.9m long x 1.0 m wide x 1.2 m high) divided by compact polypropylene cross-walls, each one incorporating a submerged orifice positioned in an offset arrangement. The fishways slope was set at 8.5% creating a constant head drop between pools of 16.2 cm.

### 2.2. Experiments

Two different configurations (Table 1) with 20 replicates each, were tested by changing the relative depth of flow, *i.e.* the ratio between the water depth in the fishway (d) and the height of boulders placed on the flume bottom (h), resulting in the creation of two flow regimes: regime 1 ($d/h > 4$) and regime 2 ($1.3 < d/h < 4$). The boulders, square-shaped (15 cm x 15 cm) with variable height (10 and 15 cm), were positioned in five even spaced lines in symmetrical arrangements (Figure 1), and oriented according to the prevailing flow pattern, as previous studies demonstrated that it minimizes the creation of zones of strong vertical turbulence (Heimerl *et al.*, 2008). For each configuration, twenty upstream-migrating adult Iberian barbel were studied individually. The fish were previously captured in the river Sorraia, central Portugal by means of low-voltage electrofishing and brought to the laboratory facilities, where they remained in 800 L acclimation tanks, under environmental controlled conditions, for at least 48 h before they were tested. Each replicate lasted 1.5 hours ending as soon as the fish successfully negotiated the fishway. Recorded parameters included the success (or failure) in negotiating the fishway and the time taken to successfully negotiate the pool.

To characterize the hydraulic conditions in both configurations, three-dimensional (x, y and z) velocity measurements in two horizontal planes parallel to the flume bottom – boulders mid-height and 21 cm above the bottom – were conducted. A Vectrino 3D ADV (Nortek AS) oriented vertically down was used at a sampling frequency of 25 Hz for a period of 90s, to determine water velocity (WV) vectors and turbulence, namely the vertical component of Reynolds shear stress ($RSS_{xz}$) (Odeh *et al.*, 2002).

**Table 1.** Description of the two tested configurations. $d_m$ – water depth; $h_{blds}$ – height of boulders; $A_o$ – orifice area; $h_{m1}$ – water depth of plane 1 monitored by ADV; $h_{m2}$ – water depth of plane 2 monitored by ADV.

| Flow regime | $d_m$ (cm) | $H_{blds}$ (cm) | $A_o$ ($m^2$) | $h_{m1}$ (cm) | $h_{m2}$ (cm) | Fish size(cm) (mean ± SD) |
|---|---|---|---|---|---|---|
| 1 | 84 | 10 | 0.053 | 5.0 | 21 | 26.1 ± 6.9 |
| 2 | 53 | 15 | 0.053 | 7.5 | 21 | 25.9 ± 6.7 |

## 3. Results

### 3.1. Hydraulics

The mean velocity patterns recorded are shown on Figure 1 for the horizontal plane at boulders mid-height (21 cm above the bottom). In regime 1 at boulders mid-height (A), two different types of regions could be distinguished: i) a jet region, coming out from the inlet orifice in a longitudinal direction with a maximum velocity of 1.2 m $s^{-1}$, until it hits the boulder immediately downstream when decreases the magnitude and changes direction towards the outlet orifice; and ii) small recirculation regions occurring up and down from the main jet region. At the plane above the boulders (B), two regions could also be easily distinguished: i) a homogenous jet region coming out from the inlet orifice extending along the adjacent side-wall and ii) a large low-velocity recirculation region (range: 0.1-0.4 m $s^{-1}$), extending from the previous jet region to the opposite side-wall.

Velocity patterns recorded for regime 2 at the horizontal plane located at boulders mid-height (C) showed a high-velocity (c. 1 m $s^{-1}$) longitudinal jet region, extending from the inlet orifice to the block placed immediately downstream. Once the jet hit the downstream higher boulder (15 cm), no clear deviation of the velocity vectors was noted, despite they was strongly reduced across the pool, creating several small recirculation regions across the entire pool. At the plane of 6 cm above the boulders (or 21 cm above the bottom) (D), a jet region extending longitudinally towards the opposite cross-wall and showing a maximum velocity of 0.8 m.$s^{-1}$ was noted. However, contrarily to regime 1, instead of a large recirculation region, several smaller recirculation regions were observed (range: 0.1-0.3 m $s^{-1}$) from the main jet to the opposite side-wall.

The contours of the $RSS_{xz}$ at the plane of boulders mid-height are shown in Figure 2 for both flow regimes. In regime 1 (A), the absolute values of this parameter were found to be higher (10-40 N $m^{-2}$) along the streamline between the inlet orifice and the boulder located 0.6 m immediately downstream, decreasing from this point to the opposite side-wall. Regime 2 (B) showed a plane with more pronounced levels of turbulence around the boulders and distributed across a wider area (c. 40%) along the plane.

### 3.2. Fish

The proportion of fish that successfully negotiated the fishway was higher in regime 2 (50%) than in regime 1 (45%), though this difference was not significant ($\chi 2 = 0.101$, $p > 0.05$). However significant differences were found in the time taken to successfully ascend it. Accordingly, individual barbel took less time to ascend the fishway when flow was on regime 2 (mean ± SD (min.): 2.6 ± 1.6), relatively to regime 1 (mean ± SD (min.): 7.1. ± 5.8) (Mann-Whitney U-test, Z=1.89, $p < 0.05$).

## 4. Discussion

This study analyzed the effects of different flow regimes, based on the relation between the water depth (d) and the height of artificial square blocks (h), on the upstream movements of a potamodromous fish, the Iberian barbel, within an experimental pool-type fishway. Though the use of artficial blocks is a common feature in nature-like fishways (*e.g.* Katopodis *et al.*, 2001), so far no study has addressed the effects of different flow regimes created by placing such structures in the bottom of pool-type fishways.

The proportion of fish that successfully ascended the fishway was similar (45-50%) for both flow regimes, which could, a priori, be considered a low efficiency. However, contrarily to diadromous species where fishway efficiency should be > 90%, no minimum standards have been defined for potamodromous species (Larinier, 2008), for which the passage of a "reasonable" number of individuals in relation to the existing population, is sufficient to ensure the longitudinal connectivity of river systems and avoid fragmentation of the populations (Porcher & Travade, 2002).

We therefore believe that fishway efficiency obtained for both flow regimes represent a "reasonable" proportion of successful fish. Despite the similarity on the proportion of successful fish between both flow regimes, fish were able to negotiate the facility

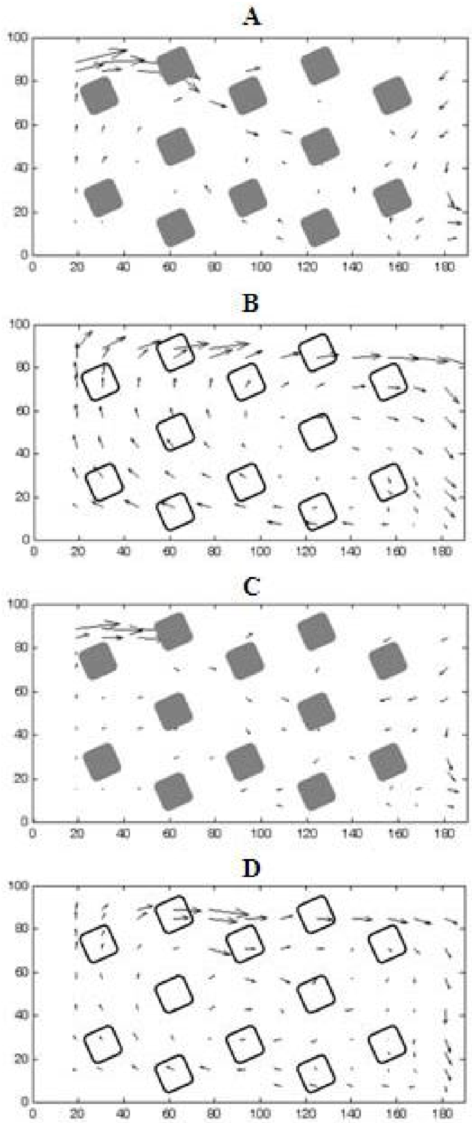


**Figure 1.** Plane velocity field in the pool: (A) regime 1 at boulders mid-height; (B), regime 1 at 21 cm from the flume bottom; (C) regime 2 at boulders mid-height; (D) regime 2 at 21 cm from the flume bottom. The squares represent the boulders with their position and alignment.

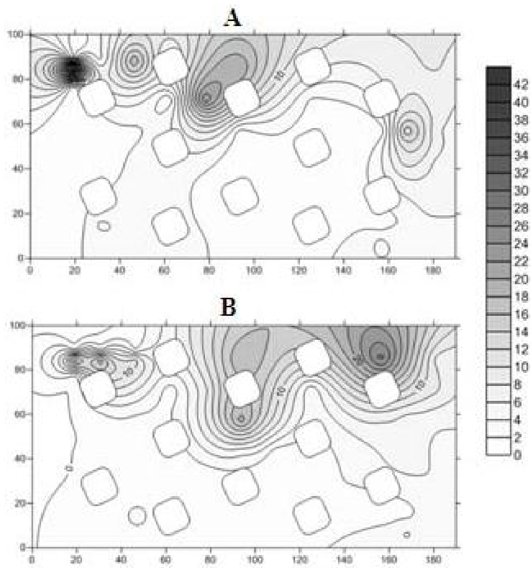


Figure 2. Contours of the vertical component of Reynolds shear stress ($RSS_{xz}$) on the plane at boulders mid-height for regime 1 (A) and regime 2 (B). Values are in $N.m^{-2}$. The squares represent the boulders with their position and alignment.

in significantly less time during regime 2 relatively to regime 1. In the former, the use of higher blocks in association with lower water depth seemed to have created a higher dissipation of water velocity vectors resulting in the formation of several small recirculation regions, instead of a large recirculation, as was observed in regime 1, that could trap the fish, by drastically increasing the transit time in the pool (Tarrade *et al.*, 2008).

The higher transit times reported on regime 1, could also be explained by the effect of turbulence. This parameter is considered to play an essential role in successful fish passage through a fishway (Rajaratnam *et al.*, 1998) and several recent studies have highlighted their importance for the upstream movements of barbel (Santos *et al.*, 2011; Silva *et al.*, 2011). In the present study, the more pronounced turbulence levels on regime 2, generated by the higher dissipation of water velocity when hitting the higher blocks, have resulted in the formation of several recirculation vortices of reduced dimensions (20-30m). Some of these vortices are smaller than the length of the fishes and could have been used to aid the progression along the pool. Similar results have been reported by Lupandin *et al.* (2005) who showed that the sizes of these vortexes are of great importance for the balance of fish in turbulent flows, *i.e.* if a vortex is smaller than a fish, its balance should not be affected due to an even distribution of the moments of force along its body. In contrast, if a vortex is much larger that a fish, the hydrodynamic rotating forces introduce a torque which tends to overturn the fish and decrease stability. Though not quantified, the expected higher proportion of larger vortices on regime 1 could have affected balance and hence, the swimming performance of individual barbel.

The results of this study showed that, in spite of similar proportions of successful fish, flow regimes with lower relative depths can be more beneficial to fish passage in pool-type fishways because they reduce the transit time for successful negotiation. Future studies should consider the use of more realistic block geometries and include clusters of rocks, both supplemented with relevant field observations with target species.

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