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Effect of two flow regimes on the upstream movements of the Iberian barbel (*Luciobarbus bocagei*) in an experimental pool-type fishway

By J. M. Santos[1], P. J. Branco[1], A. T. Silva[1], C. Katopodis[2], A. N. Pinheiro[3], T. Viseu[4] and M. T. Ferreira[1]

[1]*Forest Research Centre (CEF), Instituto Superior de Agronomia, Technical University of Lisbon, Lisboa, Portugal;* [2]*Katopodis Ecohydraulics Ltd., Winnipeg, MB, Canada;* [3]*Centre for Hydrosystems Research (CEHIDRO), Instituto Superior Técnico, Technical University of Lisbon, Lisboa, Portugal;* [4]*Hydraulics and Environment Department, Laboratório Nacional de Engenharia Civil, Lisboa, Portugal*

Summary

Literature related to pool-type fishways has seen a recent upsurge of interest in the placement of instream structures for improving fish passage. However, there is still no information on how different flow regimes created by boulder placement have an influence on upstream fish movements. The main goal of this study was to assess the performance of two different flow regimes, characterized by the relative depth of flow (d/h), where d is the water depth and h is the height of artificial bottom substrata, in assisting fish passage in an experimental full-scale pool-type fishway. Two series of experiments consisting of 20 replicates each and representing distinct flow regimes created by boulder placement in the flume bottom – $d/h > 4$ (regime 1) and $1.3 < d/h < 4$ (regime 2) – were carried out to analyse the proportion and timing of successful upstream movements of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*). Although no significant differences ($P > 0.05$) in passage success were observed between regimes (55% and 60%, respectively), fish transit time was significantly lower ($P < 0.05$) in regime 2 (mean ± SD: 2.6 ± 1.6 min.) than in regime 1 (7.1 ± 5.8 min.). The results of these experiments show 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.

Introduction

Habitat fragmentation caused by dams and weirs has been cited as one of the major threats to aquatic biodiversity, including freshwater fishes (e.g. Dynesius and Nilsson, 1994; Aarts et al., 2003). Species particularly impacted are those that undergo considerable seasonal migrations within river systems (potamodromy) (Lucas and Baras, 2001; Poulet, 2007), since dams and weirs are a hindrance to reaching the spawning grounds. Restoration of the longitudinal connectivity of rivers remains a key issue for the recovery of freshwater ecosystems, and the construction of fishways is a relevant *ad hoc* measure.

Pool-type fishways are among the most common types built at small hydropower plants (Larinier, 2008). These fishway facilities consist of a series of consecutive pools, separated by cross-walls arranged in a stepped pattern, with each pool higher than the one immediately downstream (Katopodis et al., 2001). These cross-walls are equipped with submerged orifices at the bottom and/or surface notches, which are used by the fish to move from pool to pool. However, in southern European countries, particularly in Iberia, most of the existing pool-type fishways failed to restore the connectivity because their design was biased by salmonid-based guidelines while the predominant groups of fishes needing passage are potamodromous cyprinids, which exhibit different behaviours and have limited swimming ability (Pinheiro and Ferreira, 2001; Santos et al., 2011). It is therefore imperative to develop adequate technical and scientific guidelines for these species to improve existing fishways or to design more suitable facilities in the future.

The placement of boulder substrata on the bottom of pool-type fishways has been advocated to improve fish passage, in particular benthic species such as gudgeon (*Gobio lozanoi*), loach (*Cobitis paludica*) and eel (*Anguilla anguilla*), because it reduces flow velocities near the bottom (FAO/DVWK, 2002). The increased roughness provided by embedded boulders makes it possible for species with rather poor swimming capabilities to exploit the small velocity refuges formed by the individual boulder roughness to migrate upwards through the fishway. Despite the potential influence for aiding fish passage, no study has so far considered the effects on how the relative depth of flow, i.e. the ratio between the water depth of the fishway and the height of the boulders, affects upstream fish movements. Upon studying the flow around a hemispherical boulder of height h in a rectangular channel, Shamloo et al. (2001) found that the relative depth of the flow was a key parameter in determining the flow regime around an obstacle and in providing suitable hydraulic conditions for fish passage. Accordingly, they hypothesized that lower relative depths (i.e. higher boulders at lower water depths) could be more favourable for fish movements as, due to a more noticeable boulder effect, complex flow conditions that enhance fish movements, such as a greater proportion of negative horizontal velocity vectors and the presence of recirculation regions, are more likely to occur.

This study compares the effects of two different flow regimes, based on the relative depth of flow, on the upstream movements of a widespread potamodromous cyprinid species, the Iberian barbel *Luciobarbus bocagei* (hereafter barbel), migrating through an experimental pool-type fishway. Specifically, the questions posed were: (i) are there significant differences on the horizontal and vertical velocity patterns between the two flow regimes?, (ii) are there significant differences in the proportion of fish that successfully ascend the fishway between flow regimes?, and (iii) do successful fish take the same amount of time (i.e. transit time) to ascend the fishway in each flow regime?

Materials and methods

Experimental facility

The study took place in an experimental pool-type fishway installed at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon. It consisted of a full-scale model (10 m long, 1 m wide and 1.2 m high), built on a steel frame and featuring acrylic glass panels on both sidewalls. It was composed of six pools each 1.9 m long, except those most downstream and upstream, which were 1.8 and 0.6 m, respectively. The pools were divided by compact polypropylene cross-walls, each one incorporating a submerged orifice and a surface notch of adjustable area. The fishway slope was set at 8.5%, which falls within the range used for these types of facilities (Larinier, 2008). The fishway also encompassed an upstream and a downstream chamber. The former included a slot gate to control the discharge entering the flume, whereas the latter (4.0 × 3.0 × 4.0 m), separated from the flume by two mesh panels, allowed acclimation of fish prior to the start of experiments.

Hydraulics

Two different configurations (Table 1) 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 at the flume bottom (h), resulting in the creation of two flow regimes: regime 1 ($d/h > 4$) and regime 2 ($1.3 < d/h < 4$). These flow regimes have been previously defined to study the flow around simple habitat structures (i.e. boulder substrata) to be used in river restoration studies (Shamloo et al., 2001). Thus, regime 1 had higher relative depth than regime 2. Discharge (Q) was kept constant (circa 62.7 L/s) among regimes. Twelve square-shaped boulders (15 × 15 cm) with rounded corners and presenting two heights (10 and 15 cm) were positioned along five evenly-spaced lines in symmetrical arrangements. They were oriented with a diagonal along the flow passing through the inlet orifice, as previous studies demonstrated that it minimizes the creation of zones of strong turbulence due to vertical vortices (Heimerl et al., 2008) (Fig. 1).

The efficiency of a fishway is highly dependent on how existing hydraulic conditions, in particular changes in water velocity, suit the respective target species and their behaviour (Williams et al., 2012). Consequently, to characterize the hydraulic conditions in both configurations, three-dimensional (x, y and z) instantaneous velocity measurements were conducted in two horizontal planes parallel to the flume bottom – at mid-height of the boulders and at 15% of the water column above the boulders (i.e. 21 cm from the flume bottom). The reason for sampling at this height is because the ADV needs a minimum depth of 5 cm from the tip of the probe to obtain accurate readings (Nortek AS). As the maximum high of the boulders is 15 cm, measuring at 21 cm from the flume bottom guaranteed the collections of accurate velocity readings in the layer immediately contiguous to the boulders. The spacing of each measured point varied according to the measured plane. Accordingly, at the plane above the boulders, the entire pool layer was available for measurement and therefore spacing was tighter (5–8 cm in x- and y-directions), than at the plane of boulder mid-height (10–13 cm in x- and y-directions), which was constrained by the physical presence of boulders. In both cases, spacing between points was narrower near the inlet and outlet orifices as these are typically areas of more pronounced velocity fluctuations (Silva et al., 2011). Altogether, a grid with 49 (plane of mid-height of boulders) and 88 sampling points (plane at 21 cm above the bottom) was sampled by a Vectrino 3D ADV (Acoustic Doppler Velocimeter) (Nortek AS) oriented vertically downward at a frequency of 25 Hz for a period of 90 s to characterize flow velocity. The ADV sampling period of 90 s was established from previous tests in the same fishway (for more details see Silva et al., 2011). The orifice dimensions were the same (i.e. 0.23 × 0.23 m) for both configurations, while the surface notches remained closed, as a previous study revealed species avoidance for these openings (Silva et al., 2009). On the whole, 2250 instantaneous measurements were recorded for each sample point. Measurements were taken at the second downstream pool, which was considered to be representative of hydraulic conditions within the fishway due to identical flow patterns and head drops between the pools ($\Delta h = 0.162$ m).

Fish

For each configuration, twenty replicates, each one consisting of monitoring an upstream-migrating adult barbel individual, were performed between dusk and early night (1700–2200 h), to capture their nocturnal movement (Santos et al., 2002, 2005). Fish were previously captured in the Sorraia River, central Portugal, using low-voltage electrofishing during a natural reproductive migration, which generally takes place from April to June (Santos et al., 2005). All fish were mature as shown by in situ macroscopic observations of their gonads development stage, particularly their volume, vascular irrigation and visibility of oocytes, and by the presence of nuptial tubercles. The fish were then transported to the laboratory facilities, where they were held in 800 L tanks, under a controlled environment (further details in Santos et al., 2011) for 48–96 h before being tested (Romão et al., 2011). At the start of each experiment the mesh panels were removed to enable fish access to the fishway, whereby each fish was allowed to ascend of its own volition. Each replicate lasted 1.5 h (maximum) or ended

Table 1
Description of two tested configurations based on different flow regimes. d – water depth; h – boulder height; A_o – orifice area; h_{m1} – water depth at plane 1 (mid-height of boulders) monitored by ADV; h_{m2} – water depth at plane 2 (above boulders) monitored by ADV. Number of fish (N) and mean (±SD) size of individuals used in the experiments are also shown

						Fish	
Flow regime	d (cm)	h (cm)	A_o (cm^2)	h_{m1} (cm)	h_{m2} (cm)	N	Size [mean ± SD (cm)]
1	84	10	529	5.0	21	20	26.1 ± 6.9
2	53	15	529	7.5	21	20	25.9 ± 6.7

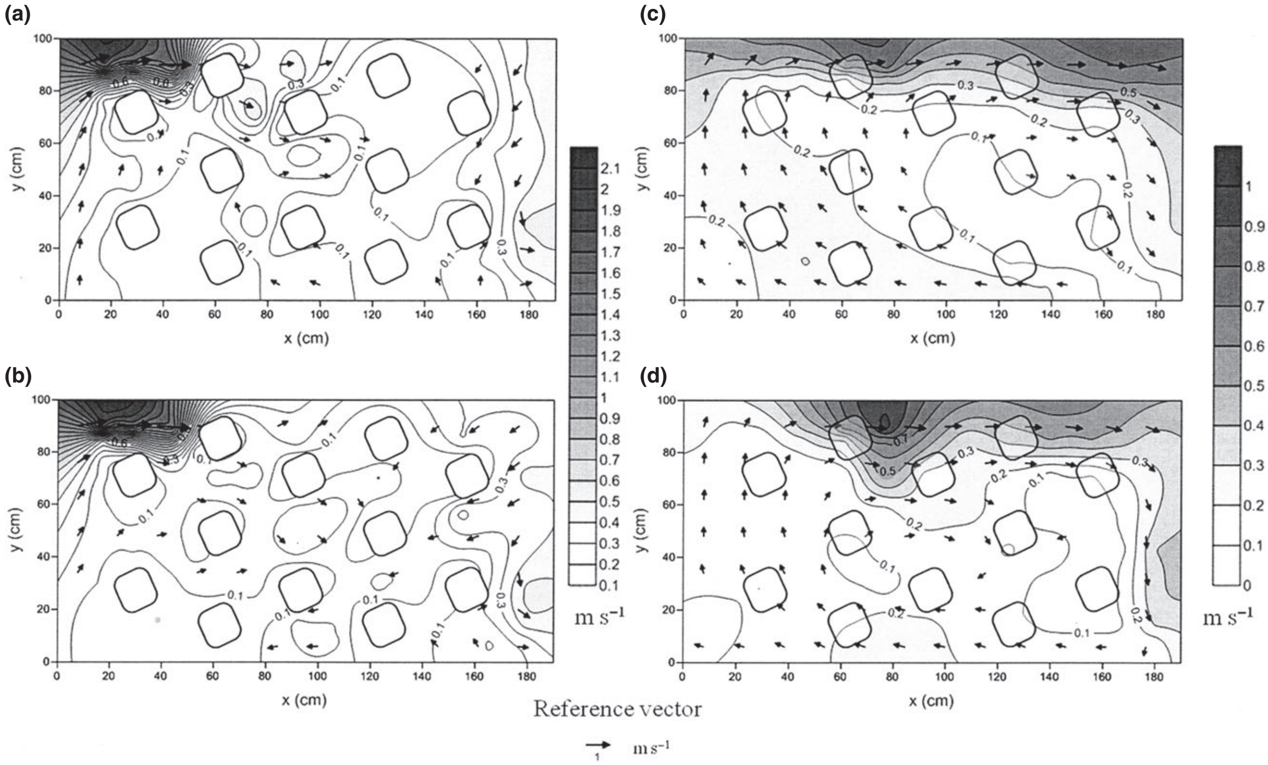

Fig. 1. Horizontal velocity field (magnitude and direction) in pools according to different flow regimes and measurement planes: (a) regime 1 at horizontal plane corresponding to mid-height of boulders; (b) regime 2 at horizontal plane corresponding to mid-height of boulders; (c) regime 1 at horizontal plane corresponding to 21 cm above flume bottom; (d) regime 2 at horizontal plane corresponding to 21 cm above flume bottom. Arrows = velocity direction and magnitude. Squares = boulders, showing positions and alignments. Flow enters the pool at the top left corner of the diagram and exits at the bottom right corner of the diagram

when each individual fish successfully negotiated the fishway. Fish movements were monitored continuously by visual observations as well as by video recordings taken with two video cameras (Sony DCR-HC23E; top and side views). Infrared lamps, scheduled to operate beginning at 2030 h, were employed whenever natural light was no longer sufficient to obtain accurate images. Recorded parameters were (i) the success (or failure) in negotiating the fishway, and (ii) the time fish took to successfully negotiate the fishway.

Data analysis

Instantaneous measures of velocity were first filtered using the Goring and Nikora (2002) phase-space threshold despiking method, modified by Wahl (2003). Velocity data were then analysed by quantifying at each plane the percentage of velocity records for which the direction differed from the bulk flow (streamwise v_x), i.e. the proportion of negative values. This metric gives an approximate indication of the extent to which the local direction of fluid motion deviated from the prominent direction of flow, therefore describing the spatial hydraulic heterogeneity (Kemp et al., 2011). Comparisons of the proportion of streamwise negative values between the two flow regimes were then performed by χ^2 tests. Next, the v_x and v_y instantaneous measures obtained at each point on the x and y direction, respectively, were used to calculate the horizontal velocities according to the equation:

$$v_{xy} = \sqrt{v_x^2 + v_y^2}$$

Maps with the horizontal velocity contour lines were then generated for the two planes studied and their resulting patterns were then compared by Wilcoxon match-paired tests to search for differences between the two flow regimes.

However, measurements and evaluation of the horizontal velocity distribution alone may not provide sufficient information about the structure of the secondary currents (Song and Chiew, 2001). Deviations of the velocity vectors from the horizontal direction, i.e. the presence of the vertical component in the current velocity, are likely to perturb the fish's behaviour (Wang et al., 2010) and should be taken into account. Therefore, to adequately describe the secondary nature of flow, measurements of the vertical component, v_z, were used to generate contour maps of this variable for both flow regimes, where negative values represent descending velocities and positive values represent ascending ones. The patterns obtained at each plane for the two flow regimes were then compared by Wilcoxon match-paired tests.

A χ^2 test was performed to compare the proportion of fish that successfully ascended the fishway for each of the two flow regimes. A nonparametric Mann–Whitney *U*-test was also employed to test the null hypothesis that the time taken to successfully ascend the fishway was similar in the two flow regimes tested.

Results

Hydraulics

The horizontal velocity patterns are shown in Fig. 1 for both flow regimes and for both planes: boulder mid-height and

15% of the water column above the boulders. No significant differences in velocity patterns were found between the two flow regimes (Wilcoxon match-paired test; N = 49, Z = 1.06; $P > 0.05$) at the plane corresponding to the boulders mid-height (Fig. 1a, b). At this plane, two types of regions could be distinguished for both flow regimes: (i) a jet region, which emerges from the inlet orifice in a longitudinal direction with a maximum velocity of circa 1.60–1.70 m s^{-1}, and continues until it hits the boulder immediately downstream; this causes a pronounced reduction in the magnitude and direction of the primary velocity vector, as evidenced by the creation of two secondary flow paths of reduced velocity (0.20–0.25 m s^{-1}) on each side of the boulder, and (ii) a small recirculation region of reduced velocity (0.10–0.20 m s^{-1}) that occurs below the main jet region and extends further downstream towards the opposite side-wall.

At the horizontal plane located above the boulders, significant differences in velocity patterns were found between the two flow regimes (Wilcoxon match-paired test; N = 88, Z = 2.37; $P < 0.05$). In regime 1 (Fig. 1c), two regions could easily be determined: (i) a homogenous jet region, emerging from the inlet orifice and extending along the adjacent side-wall towards the outlet, and (ii) a large low-velocity recirculation region (range: 0.10–0.30 m s^{-1}), extending from the homogenous jet region to the opposite side-wall. Velocity patterns recorded for regime 2 (Fig. 1d) also revealed a jet region extending longitudinally towards the opposite cross-wall and showing a maximum velocity of circa 1.0 m s^{-1}. However, in contrast to regime 1, and instead of a large recirculation region, several smaller recirculation regions were observed (velocity range: 0.1–0.3 m s^{-1}) from the main jet towards the opposite side-wall, namely on the downstream 2/3rds of the pool. Spatial hydraulic heterogeneity on this plane was also higher in regime 2, though marginally significant, relative to regime 1 (χ^2=3.89, $P < 0.10$).

The observed vertical velocity field was significantly different between the two flow regimes (Wilcoxon match-paired test; N = 49, Z = 2.16; $P < 0.05$). At the plane corresponding to the boulders mid-height, regime 1 (Fig. 2a) showed a greater predominance for positive and ascending velocities relative to regime 2 (Fig. 2b), particularly in the vicinity of both inlet and outlet cross-walls. At the plane located above the boulders, the pattern of vertical velocities was similar between the two flow regimes (Wilcoxon match-paired test; N = 88, Z = 0.87; $P > 0.05$), with lower and descending values occurring near both cross-walls, while ascending velocities were noted mainly within the area between boulders (Fig. 2c,d).

Fish

The proportion of fish that successfully ascended the fishway was greater in regime 2 (60%) than in regime 1 (55%), but this was not significant ($P > 0.05$, χ^2 test) (Table 2). However, differences were found in the time taken to negotiate the facility. As a matter of fact, fish in regime 2 (mean ± SD: 2.6 ± 1.6 min.) took significantly less time to ascend the fishway relative to regime 1 (7.1 ± 5.8 min.) (Mann–Whitney *U*-test, Z = 1.89, $P < 0.05$).

Discussion

This study analysed the effects of two different flow regimes based on the relative depth (d/h) of flow on the passage

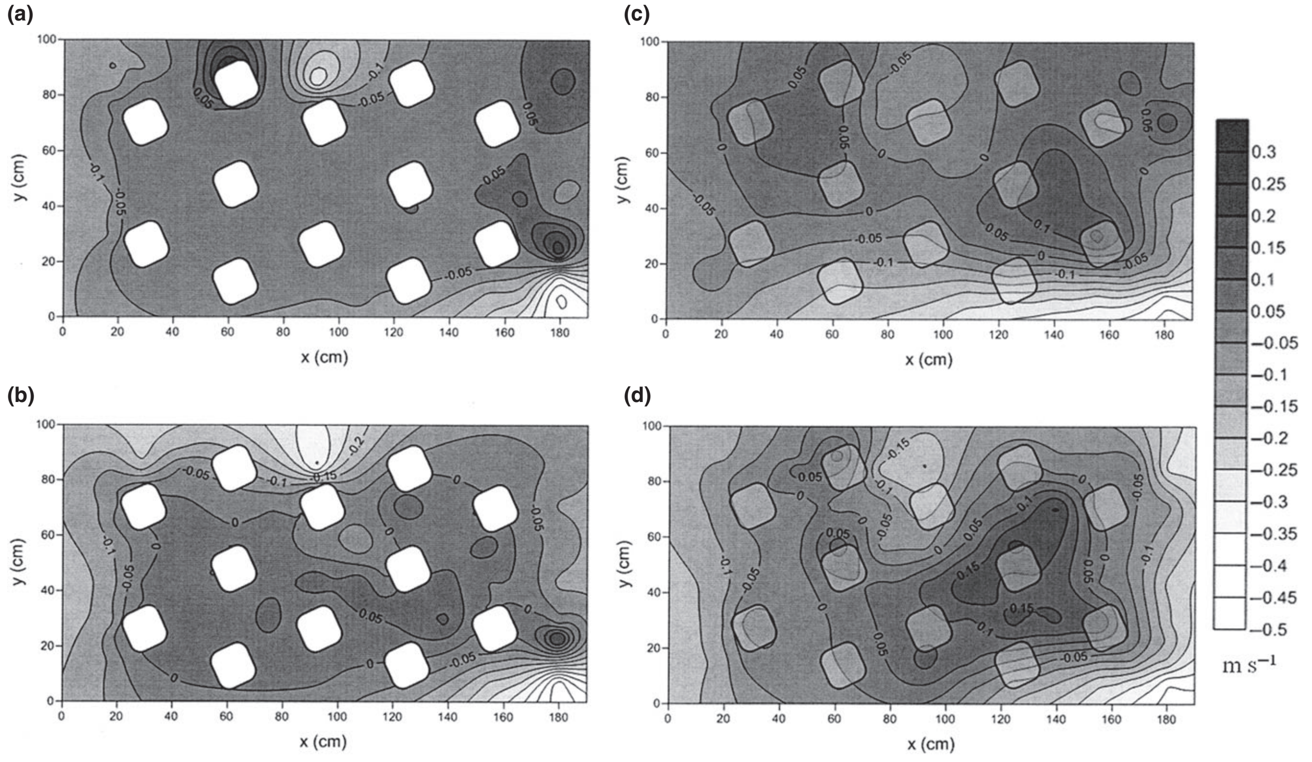

Fig. 2. Vertical velocity contours in pools according to different flow regimes and measurement planes: (a) regime 1 at horizontal plane corresponding to mid-height of boulders; (b) regime 2 at horizontal plane corresponding to mid-height of boulders; (c) regime 1 at horizontal plane corresponding to 21 cm above flume bottom; (d) regime 2 at horizontal plane corresponding to 21 cm above flume bottom. Squares = boulders, showing positions and alignment. Flow enters the pool at the top left corner of the diagram and exits at the bottom right corner of the diagram

Table 2
Passage efficiency (%) and time taken by fish [mean ± SD (min.)] to successfully negotiate the experimental pool-type fishway in different flow regimes. χ^2 (passage efficiency) and Mann–Whitney test results are also shown

	Flow regime		
Parameter	1	2	P
Passage efficiency (%)	55	60	ns
Time for successful negotiation (min)	7.1 ± 5.8	2.6 ± 1.6	< 0.05

success and timing of a widespread potamodromous cyprinid species migrating through an experimental full-scale pool-type fishway. The proportion of fish that successfully ascended the fishway was similar, 55–60%, for both flow regimes. In a recent review of 65 papers (1960–2011) addressing worldwide quantitative estimates of fish passage efficiency, Noonan et al. (2011) found that for conventional pool-type fishways, i.e. with no substrate embedded on the bottom, mean upstream passage efficiency for non-salmonid fishes was approximately 40%. Though the present study was not designed to compare fish passage performance between a smooth bottom (no embedded substrate) and a boulder rugosity bottom, the present findings suggest that boulder placement might facilitate fish movement by increasing fish passage efficiency, highlighting the usefulness of these structures as potential drivers for aiding fish passage in pool-type fishways.

Despite the similarity in the proportion of success in both flow regimes, fish were able to negotiate the facility in significantly less time in regime 2. Although no differences were found between regime 1 and 2 on the horizontal velocity patterns at the plane that corresponds to the mid-height of the boulders, there were significant differences between the two regimes when comparing velocities at the plane above the boulders. In the latter, the use of higher boulders in association with lower water depth generated greater water velocity reductions, which resulted in higher spatial hydraulic heterogeneity, creating several small recirculation regions. The presence of such small reverse-flow fields is known to aid upstream movements of many fishes in the wild. For example, Hinch and Rand (1998) found that upstream movements of sockeye salmon (*Oncorhynchus nerka*) were facilitated when fish were able to exploit these hydraulic phenomena. On the other hand, the presence of a large recirculation region occupying most of the pool area for regime 1 could have caused fish disorientation and hence a delay in fish movements. In such recirculation regions, typically much larger than the body length of the fish, it is known that the hydrodynamic rotation forces introduce a torque that tends to overturn the fish and decrease stability (see Lupandin, 2005 for a schematic view). Such regions may become traps for the fish, thereby dramatically increasing transit times in the pools (Tarrade et al., 2008). This was particularly evident in the vicinity of the orifices in regime 1, when some of these fish were seen to spread their pectoral fins in an attempt to stabilize their body position.

Vertical velocity patterns could also partially explain the shorter fish transit times observed in regime 2. The vertical velocity field was found to be significantly different between the two flow regimes, with regime 2 showing a predominance of negative (descendent) values relative to regime 1, which could have prevented fish from moving away from the preferential bottom route (Scheibe and Richmond, 2002). Positive vertical velocities are known to disturb the fish's behaviour by generating a secondary flow that may force the fish to shift from one depth to another. This shift is frequently associated with a change in the hydrostatic pressure, which may change fish behaviour (Pavlov et al., 2002) even in the presence of shallow water depths (<1 m) as in the present study. Pavlov et al. (2002) reported that the sensitivity threshold to the pressure change in water is within the 10 cm range of the water column. For example, minnows (*Phoxinus phoxinus*) show a hydrostatic reaction when changing the depth by 0.5–1 cm, ten-spined stickleback (*Pungitius pungitius*) have these reactions when changing the depth by 3 –6 cm, and goldfish by 0.5–2.0 cm. This is consistent with visual and video observations from the present study, where, upon entering the pools during regime 1, fish were frequently seen to be immediately displaced to the upper portions, above the substrata, and thereafter swimming in circles (a clear sign of the presence of a recirculation flow) before proceeding to the submerged orifice in an attempt to proceed upstream. In contrast, during regime 2, fish tended to swim within the pathways created by the boulders. These pathways, often referred to as micro-channels, are expected to provide interconnected, preferential low stress routes along which fish may swim (Acharya et al., 2001). The present authors therefore believe that such behaviour reflected the adoption of an energy-minimizing tactic in which fish selected the paths with higher spatial hydraulic heterogeneity, i.e. where velocity vectors were more likely to be opposite to the direction of bulk flow, thus facilitating fish movements. It is clear that future studies should focus on testing the effect of density, with different combinations of boulder spacing and height to optimize the timing and success of fish passage and to understand how the resulting micro-channels can be specifically incorporated into future fishway designs.

The results of this study showed that in spite of similar proportions of successful fishway negotiation, flow regimes with lower relative depth can be more beneficial to fish passage in pool-type fishways since they reduce the fish transit time. The approach used can also be a template for river restoration studies that try to quantify relations between fish passage and instream boulder placement.

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Author's address: José Maria Santos, Departamento de Recursos Naturais Ambiente e Território, Pavilhão Florestal, Instituto Superior de Agronomia, Tapada da Ajuda, P-1349-017 Lisboa, Portugal.
E-mail: jmsantos@isa.utl.pt