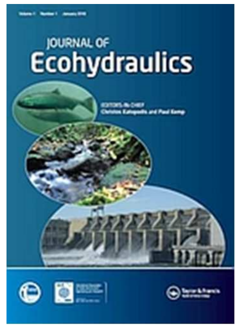

Upstream Passage of Potamodromous Cyprinids Over Small Weirs: the Influence of Key-Hydraulic Parameters

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Complete List of Authors:	Amaral, Susana; Universidade de Lisboa Instituto Superior de Agronomia, CEF - Centro de Estudos Florestais; Universidade de Lisboa Instituto Superior Tecnico, CERIS – Civil Engineering for Research and Innovation for Sustainability Branco, Paulo; Universidade de Lisboa Instituto Superior de Agronomia, CEF - Centro de Estudos Florestais; Universidade de Lisboa Instituto Superior Tecnico, CERIS – Civil Engineering for Research and Innovation for Sustainability Silva, Ana; Norsk Institutt for Naturforskning Katopodis, Christos; Katopodis Ecohydraulics Ltd. Viseu, Teresa; Laboratorio Nacional de Engenharia Civil, Departamento de Hidráulica e Ambiente Ferreira, Teresa; Universidade de Lisboa Instituto Superior de Agronomia, CEF - Centro de Estudos Florestais Pinheiro, Ant�nio; Universidade de Lisboa Instituto Superior Tecnico, CERIS – Civil Engineering for Research and Innovation for Sustainability Santos, José Maria; Universidade de Lisboa Instituto Superior de Agronomia, CEF - Centro de Estudos Florestais
Keywords:	river connectivity, small weirs, potamodromous cyprinid species, upstream migration, ecohydraulics
Abstract:	The presence of small weirs, far more numerous than dams, has increased habitat fragmentation on rivers worldwide. This study aims to evaluate the upstream passage performance of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*), over an experimental broad-crested weir by varying key-hydraulic parameters. Fish passage success was studied for different combinations of waterfall height (Δh), plunge pool depth (D) and flow discharge (Q). The flow pattern downstream of the weir was characterized with a 3D Acoustic Doppler Velocimeter, to assess the effects of hydrodynamics on fish behaviour. Results showed that D, Δh, and their

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interaction D×Δh (PerMANOVA, $p < 0.01$), as well as Q (Kruskal–Wallis H = 10.95; 3 d.f.; $p = 0.01$) were significantly correlated with the number of successful upstream fish passages. However, counter-intuitively, higher fish passage success did not occur at combinations of lower Δh and Q, and higher D. Therefore, upstream fish passage appears to be a complex phenomenon, which is strongly dependent on the hydraulic environment that is produced by the interaction of these parameters. The outcomes of this work will help engineers and biologists to establish design criteria for requalification of small barriers in order to improve fish passage and habitat connectivity.

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Susana Dias Amaral

Forest Research Centre, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

CERIS – Civil Engineering for Research and Innovation for Sustainability, Instituto Superior Técnico, Universidade de Lisboa,

Avenida Rovisco Pais, 1049-001 Lisboa, Portugal

samaral@isa.ulisboa.pt

Paulo Branco

Forest Research Centre, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

CERIS – Civil Engineering for Research and Innovation for Sustainability, Instituto Superior Técnico, Universidade de Lisboa,

Avenida Rovisco Pais, 1049-001 Lisboa, Portugal

pjbranco@isa.ulisboa.pt

Ana Teixeira da Silva

Norwegian Institute for Nature Research, P.O Box 5685 Sluppen, 7485 Trondheim, Norway

ana.silva@nina.no

Christos Katopodis

Katopodis Ecohydraulics Ltd., 122 Valence Avenue, Winnipeg, MB, R3T 3W7, Canada

KatopodisEcohydraulics@live.ca

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Teresa Viseu

Hydraulics and Environment Department, Laboratório Nacional de Engenharia Civil,

Avenida do Brasil 101, 1700-066 Lisboa, Portugal

tviseu@lnec.pt

Maria Teresa Ferreira

Forest Research Centre, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda,

1349-017 Lisboa, Portugal

terferreira@isa.ulisboa.pt

António Nascimento Pinheiro

CERIS – Civil Engineering for Research and Innovation for Sustainability, Instituto Superior Técnico,

Universidade de Lisboa,

Avenida Rovisco Pais, 1049-001 Lisboa, Portugal

antonio.pinheiro@tecnico.ulisboa.pt

José Maria Santos

Forest Research Centre, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda,

1349-017 Lisboa, Portugal

jmsantos@isa.ulisboa.pt

Corresponding author e-mail: samaral@isa.ulisboa.pt

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The presence of small weirs, far more numerous than dams, has increased habitat fragmentation on rivers worldwide. This study aims to evaluate the upstream passage performance of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*), over an experimental broad-crested weir by varying key-hydraulic parameters. Fish passage success was studied for different combinations of waterfall height (Δh), plunge pool depth (D) and flow discharge (Q). The flow pattern downstream of the weir was characterized with a 3D Acoustic Doppler Velocimeter, to assess the effects of hydrodynamics on fish behaviour. Results showed that D, Δh, and their interaction $D \times \Delta h$ (PerMANOVA, $p < 0.01$), as well as Q (Kruskal–Wallis $H = 10.95$; 3 *d.f.*; $p = 0.01$) were significantly correlated with the number of successful upstream fish passages. However, counter-intuitively, higher fish passage success did not occur at combinations of lower Δh and Q, and higher D. Therefore, upstream fish passage appears to be a complex phenomenon, which is strongly dependent on the hydraulic environment that is produced by the interaction of these parameters. The outcomes of this work will help engineers and biologists to establish design criteria for requalification of small barriers in order to improve fish passage and habitat connectivity.

Keywords: river connectivity; small weirs; potamodromous cyprinid species; upstream migration; ecohydraulic

Introduction

River fragmentation caused by the presence of instream obstacles has been considered one of the main threats to the sustainability of fish populations, being responsible for the decline or even extinction of populations through demographic, environmental and genetic stochasticity

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(Aarts et al. 2003; Nilsson et al. 2005). Nevertheless, barriers to fish migration occur not only through the presence of large dams and small hydropower plants, which have recently increased as result of the promotion of renewable forms of energy (Santos et al. 2006; Crook et al. 2015), but also mainly through other artificial obstacles such as small weirs (Lucas and Baras 2001). These obstacles, that are in general less than 5 m in height (ONEMA 2010; Solà et al. 2011) and are considered to be 2-4 orders of magnitude far more numerous than large structures (Lucas et al. 2009), alter the velocity patterns and the water depth, creating vertical drops that change the hydrodynamics of aquatic systems and may prevent the movement of fish species and hence their access to spawning, feeding and rearing areas (Leaniz 2008; Branco et al. 2012). However, compared with large regulated schemes, the effects of small weirs and natural obstacles are much less well quantified, thus deserving greater attention not only due to their much higher numbers (in the Portuguese Tagus basin alone, there are more than 2000 small weirs), but also because they can have a significant effect on fish movements, thereby potentially causing changes in the composition and structure of assemblages (Ovidio and Philippart 2002; Poulet 2007; Ordeix et al. 2011). This is in accordance with recent research lines and European projects, which emphasize the need for additional scientific studies to address the impact of small barriers on fish passage success (Harford and McLaughlin 2007).

Previous studies on the upstream passage of small weirs have been mainly focused on salmonid species (e.g. Brandt et al. 2005; Lauritzen et al. 2005; Kondratieff and Myrick 2006; Kemp et al. 2006; Ovidio et al. 2007) and have shown that fish capacity to negotiate these obstacles is not only related with their swimming and jumping performance, but also with obstacle design and hydrodynamic conditions downstream of the weir (e.g. waterfall height, weir slope, plunge pool depth, flow discharge, turbulence). In this respect, the plunge pool depth (water depth below the weir) and waterfall height (distance from the plunge pool

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surface to the top of the weir crest) emerged as the two most important variables influencing fish movements in broad-crested weirs, which are typically constructed with a vertical downstream face from reinforced concrete, spanning the full width of the river channel (Baudoin et al. 2014).

The effect of plunge pool depth and waterfall height on the successful passage of fish has been investigated in order to improve knowledge on more effective upstream passage of fish. For example, analysing the ratio of plunge pool depth/waterfall height, Stuart (1962) found that for brown trout (*Salmo trutta*), Atlantic salmon (*Salmo salar*) and Euroasian minnow (*Phoxinus phoxinus*), successful passages occurred for a 1.25 ratio, while Lauritzen et al. (2005), for sockeye salmon (*Oncorhynchus nerka*), reported successes in ratios ranging from 0.68 to 1.53. On the other hand, Ovidio and Philippart (2002) assessed the impact of 28 small weirs on the upstream movements of six fish species, and focused on the need of a minimum plunge pool depth for a successful negotiation, postulating that water depth downstream of the obstacle should be at least "twice the size of the fish". Kondratieff and Myrick (2006), and more recently Ficke et al. (2011) also highlighted the importance of plunge pool depth suggesting a minimum threshold not lower than 10 cm, to avoid inhibition of fish movements and minimize predation risk. It is clear that the effect of both plunge pool depth and waterfall height on upstream fish movements needs to be further addressed to quantify fish jumping performance and thus set guidelines for appropriate fish passage designs. This is particularly important for cyprinid fishes that are by far the dominant group of autochthonous freshwater fish in the Iberian Peninsula, and for which performance effectiveness in negotiating small weirs is virtually unknown.

The goal of this study is to evaluate the performance of upstream fish movements over a small experimental broad-crested weir adjustable for different plunge pool depths (D) and waterfall heights (Δh), under different flow discharges (Q). The conditions tested are

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representative of those that fish are expected to overcome when migrating upstream to spawn. Iberian barbel (*Luciobarbus bocagei*) was selected as the target-species, since it is considered representative of at least 8 species of medium-sized benthic potamodromous cyprinids in Iberia and Western Europe, counting the genera *Barbus* and *Luciobarbus* (Santos et al. 2014). It was hypothesized that passage success would increase with decreasing waterfall heights in association with increasing plunge pool depths and low flow discharges.

Material and Methods

Fish and Experimental Facility

Adult Iberian barbel used in the experiments (n = 380; mean total length (TL) ± standard deviation (SD) = 18.7 ± 3.3 cm) were captured in the Lisandro River, a small Atlantic coastal river. Sampling was performed by wadable electrofishing (Hans Grassl IG-200) according to the protocol adopted by the European Committee for Standardization (CEN 2003). Six electrofishing episodes were performed (one episode per week), collecting 65 fish per episode. Fish were transported to the laboratory facilities, at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in a fish transport box (Hans Grassl, 190 L) with external aeration. At LNEC, fish were maintained for a maximum period of six days in filtered and aerated acclimation tanks (700 L tanks; Fluval Canister Filter FX5). To ensure high water quality levels in the acclimation thanks, water temperature (22 ºC ± 1 ºC), pH (≈ 7.3) and conductivity (215 ± 37 $\mu s.cm^{-1}$) were monitored every day using a multiparametric probe (HANNA, HI 9812-5). Water replacement was performed daily with a turnover rate of 150 $L.day^{-1}$. Feeding (Tetra Pond sticks) stopped 24–48 h prior to the experiments.

Experiments were conducted in an indoor experimental ecohydraulic channel installed at LNEC. The channel (Figure 1A) consists of a rectangular steel frame (10.0 m long x 1.0 m

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wide x 1.2 m high) with glass-viewing panels on sidewalls that allow free observation of fish within the flume. The facility includes an upstream and a downstream tank, separated from the flume by mesh panels, from where the water enters the flume and is recirculated. The channel was tilted at a 3% slope, determined to be representative of central and southern Iberian rivers according to the European River and Catchment Database (Catchment Characterisation and Modelling, version 2 [CCM2]; Vogt et al. 2007). Water quality in the flume was also monitored after each experiment. No difference was registered between water temperature in acclimation tanks and in the flume (22 ºC ± 1 ºC); values of pH and conductivity were of ≈ 8.3 and 172 ± 22 µs.cm^{-1}, respectively.

Testing Plunge Pool Depths and Waterfall Heights

To study the effects of plunge pool depths and waterfall heights on upstream passage of Iberian barbel, an experimental broad-crested weir made of polyvinyl chloride (PVC) modules was tested for a factorial design of 16 combinations (Table 1) considering four different plunge pool depths (D = 10, 20, 30, 50 cm), and four waterfall heights (Δh = 5, 10, 15, 25 cm). Minimum plunge pool depth was difficult to setup because it depends on the size and swimming capabilities of fish, and how the plunging jet dissipates downstream of the weir (Baudoin et al. 2014). Nonetheless, for large rheophilic cyprinids, these authors propose a water depth of 10 cm as the minimum to overcome an obstacle, which was therefore the threshold selected for the present study. Maximum waterfall height for the current experiments was determined by carrying out preliminary studies. A lower waterfall height (5 cm) was used initially and, in subsequent trials, fish were presented with increasing heights (5 cm increments) until no fish could negotiate the weir. This final height was taken to be the critical weir height. The maximum waterfall height used in the trials was the critical weir

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height plus 5 cm. Once the maximum waterfall height was determined, trials were assigned randomly, resulting in ratios of D/Δh that ranged from 0.4 to 10.

The experimental weir (Figure 1B) spanned the entire channel width, with a constant thickness of 20 cm, and it was installed in the flume at 2.75 m upstream of the acclimation area, which was created in the downstream zone of the flume by two mesh panels 1 m apart. Immediately downstream of the weir, a 0.65 m long zone was considered as the approach area. Flow discharge was measured by a flow meter installed in the supply pipe and maintained equal to 50 $L.s^{-1}$. The different waterfall heights (Figure 1C) were setup by adding or removing modules from the weir. The plunge pool depth below the weir was controlled by a gate located at the downstream tank of the channel.

Before each trial, fish were held 15 minutes in the acclimation area to allow adaptation to the flume conditions. After that period, the upstream mesh panel was removed and fish were allowed to volitionally explore the channel for 60 minutes. Both upstream and downstream passage was allowed, so fish could negotiate the weir multiple times. Each combination tested had 4 replicates carried out with schools of 5 fish for each replica. Each fish was used only once and was randomly selected. Fish movements were monitored by direct observation and recorded by a video camera (GoPro HERO3). Registered observations included: number of fish that approached the weir (Ap; fish that entered the approach area), number of passage attempts (At; fish that actively tried to negotiate the waterfall), number of passage successes (N), and time taken to achieve the first successful upstream passage (T; min). At the end of each trial, fish were measured (TL ± 0.1 cm) and water temperature and quality (pH and conductivity) in the flume were monitored. All trials were performed during late spring and early summer, in the morning period (07–13h) so that environmental conditions, such as temperature and light, were fairly constant throughout the experiments.

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Effects of Flow Discharge on Upstream Movement of Fish

To study the effects of flow discharge on barbel capacity to successfully negotiate a small weir, 3 additional discharges were tested: 25, 75 and 100 $L.s^{-1}$. These discharges were tested with the combination of waterfall height and plunge pool depth that previously showed the highest passage success with 50 $L.s^{-1}$ and also followed the procedures previously described.

Hydrodynamics Characterization

To characterize the hydrodynamic conditions downstream of the weir, the 3 components of flow velocity (x, y, z) were measured with a downward-looking 3D Acoustic Doppler Velocimeter (Vectrino ADV; Nortek AS). A grid with 27 sampling points was implemented at the centre of the flume, assuming flow symmetry across its width. The sampling points were established according to the expected velocity field variation and taking into account the limitations of the ADV equipment. Such limitations included the minimum distance required at the bottom of the flume (5 cm) and near the obstacle, as well as the need for the probe to be completely immersed during the data acquisition period. This was difficult to ensure near the weir for some combinations due to turbulence derived from the energy dissipation of the plunging jet downstream the weir. Water velocity data were acquired at a sampling rate of 25 Hz for a period of 180 s. The combinations characterized were: the one that registered a lower passage success; the combination expected to achieve the best passage results; and the combination that actually provided the best results.

Data Analysis

In order to determine the potential negotiation of the weir for the combinations tested, similarly to studies on efficiency of fishways (Bunt et al. 1999; Lucas and Baras 2001;

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Aarestrup et al. 2003; Calles and Greenberg 2009), the percentage of attraction efficiency (AE) and passage efficiency (PE) were calculated from equations 1 and 2.

$$\text{AE \%} = 100 \times \frac{\text{number of fish that attempted to negotiate the weir}}{\text{number of fish that entered the approach area}} \quad (1)$$

$$\text{PE \%} = 100 \times \frac{\text{number of successful passages}}{\text{number of fish that attempted to negotiate the weir}} \quad (2)$$

To determine the influence of plunge pool depths, waterfall heights and their interaction (D×Δh) on the number of successful upstream passages of Iberian barbel, a distance-based MANOVA (PerMANOVA) using the Euclidean distance was performed by using PC-ORD 6 (Peck, 2010). Likewise, to test the effect of flow discharge on the successful negotiation of the weir a Kruskal–Wallis ANOVA with a post hoc Dunn's test for pairwise comparison was performed by using the *dunn.test* package (Dinno 2015) from the open-source software R (R Core Team 2014).

Data on instantaneous velocity (V_i) were filtered with WinADV freeware software (Wahl 2001) using the Goring and Nikora (2002) phase-space threshold despiking method, modified by Wahl (2003). Then, to analyse velocity fluctuations and turbulence gradients along the water column in a vertical plane, the resultant V_{xz} and turbulent kinetic energy (TKE; important turbulence descriptor (Wang et al. 2011; Wilkes et al. 2013) in ecohydraulic studies) were calculated and represented graphically, by vector and contour maps, in order to illustrate the hydrodynamic conditions within the test area (*e.g.* areas of high velocity and turbulence gradients) that might have affected fish movements. Additionally, for the tested discharges, differences in flow velocities and turbulence were analysed using a non-parametric Friedman test followed by a Nemenyi post hoc test applying the R package *PMCMR* (Pohlert 2015).

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Results

Plunge Pool Depths and Waterfall Heights

Fish attempted to negotiate all D×Δh tested combinations (Table 2) (an example of a successful attempt is illustrated in Figure 1C). However, successful upstream passage as well as the number of fish approaches, the number of attempts to pass the weir, and the time needed to successfully pass upstream, were markedly variable among combinations. Overall, a total of 254 upstream successful passages were registered for all combinations of D×Δh. Regarding the approach movements and attempts to pass the weir, an average of 710 approaches (max = 1013 approaches, in D50Δh15; min = 293, in D10Δh25) and 183 attempts (max = 328 attempts, in D30Δh05; min = 65, in D10Δh05) were recorded.

The best results were achieved for the combination of D20Δh10 (D/Δh = 2), with 50 successful passages and a PE of 17%. This percentage of PE was only surpassed by combination D10Δh15 (D/Δh = 0.67; 20%), however in D10Δh15 both the number of attempts (90) and the number of successful passages (18) were lower than D20Δh10. Additionally, combination D20Δh10 registered the highest percentage of AE (53%), with a total of 548 approaches that resulted in 291 attempt movements. Having the same D/Δh ratio as combination D20Δh10, D/Δh = 2, combinations D10Δh05, D30Δh15 and D50Δh25 however, recorded very different passage successes (10, 9, and 4 upstream passages, respectively) and the percentages of AE and PE were also lower compared with the results of combination D20Δh10.

The poorest results were registered for combination D10Δh25 (D/Δh = 0.4), with only 1 successful upstream passage and a PE of 1%. This combination registered also the lowest number of approaches, a total of 293, and only 72 attempts. Moreover, it actually registered the highest time until the first (and single one) successful passage occurred (46 min).

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Combination D50Δh05 (D/Δh = 10), which was expected to provide the best results due to its higher plunge pool depth in association to a lower waterfall height to overcome, only ranked third with 25 successful passages, 27% of AE, and 13% of PE.

Results of the PerMANOVA analysis showed significant effects of D ($F = 5.46$; $P = 0.004$), Δh ($F = 4.68$; $P = 0.006$), and the interaction D×Δh ($F = 3.02$; $P = 0.005$) on the number of successful upstream fish passage events. Pairwise comparisons (Table 3) performed for each factor showed that the number of successful fish movements past the weir was significantly different, and higher, for D = 20 cm, in relation to the other tested plunge pool depths. On the contrary, for the tested waterfall heights, Δh = 25 cm was significantly different, registering the lowest number of successful movements.

Flow Discharge

The number of successful upstream passages, as well as fish approaches and attempts to pass the weir were found to decrease with the increment of flow discharge (Table 4). The largest number of attempts (total of 291) and successful passages (50) were registered for 50 $L.s^{-1}$. On the contrary, the discharge of 100 $L.s^{-1}$ proved to be the most limiting for fish, registering only 26 approaches and 12 attempts to negotiate the weir, which resulted in a single successful passage almost at the end of the trial (57 min). For 25 $L.s^{-1}$, there were a high number of fish approaches (a total of 1440), but resulted in only 280 attempts leading to a low AE (19%). PE was also low due to the small number of successful passages (14).

Results of the Kruskal–Wallis test show that flow discharge significantly affected the number of successful passages of barbel ($H = 10.95$; 3 *d.f.*; $P = 0.01$). Further, Dunn's multiple comparison test (Table 5) revealed that for 100 $L.s^{-1}$, the number of successful passages was significantly lower than for 25 $L.s^{-1}$ and especially for 50 $L.s^{-1}$. Likewise,

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successful passages for 75 $L.s^{-1}$ were also significantly lower compared to the ones that occurred for 50 $L.s^{-1}$.

Hydrodynamics

Figures 2 and 3 display the variation of TKE and flow velocity, respectively, for the different conditions tested. Contour maps revealed that both TKE values (Figure 2A, 2B, 2D, and 2E) and velocity (Figure 3A, 3B, 3D, and 3E) increased with flow discharges. This increase was particularly important in the case of 75 $L.s^{-1}$, where values of TKE above 1 $m^2.s^{-2}$ and velocity just above 1 $m.s^{-1}$ were registered close to the foot of the weir, and for the 100 $L.s^{-1}$ which also registered similar values, although these were located furthest from the weir. For combinations D20Δh05 (Figure 2C and Figure 3C; that registered a lower passage success) and D50Δh05 (Figure 2F and Figure 3F; combination that was expected to achieve the best passage results), values of TKE and velocity were slightly higher when compared with D20Δh10 (Figure 2B).

Statistical analysis of hydraulic characterization of combinations D20Δh10, D20Δh05, and D50Δh05, demonstrate that there were significant differences among their respective V*xz* (F_r = 11.76; 2 *d.f.*; $P < 0.01$) and TKE values (F_r = 7.44; 2 *d.f.*; $P < 0.05$). Regarding the flow discharges tested in combination D20Δh10, results of Friedman tests revealed that the four flows were significantly different both in terms of velocity (F_r = 53.73; 3 d.f.; $P < 0.001$) and TKE (F_r = 78.03; 3 d.f.; $P < 0.001$); nevertheless, results of pairwise comparisons for the parameter velocity show that there were no significant differences for 25 $L.s^{-1}$ *vs.* 50 $L.s^{-1}$ (P = 0.46).

Discussion

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This study highlights the importance of plunge pool depth, waterfall height, and flow discharge, as well as their interaction, for the successful negotiation of Iberian barbel over small broad-crested weirs. The high numbers of recorded movements (approaches and attempts) as well as passage successes demonstrated that Iberian barbel were stimulated to move upstream and negotiate the weir. Nevertheless, passage success varied among combinations, indicating that some of the combinations were more favourable for upstream passage as a consequence of suitable hydrodynamic conditions for fish (Liao 2007; Williams et al. 2012; Elder and Coombs 2015).

Similar to other studies (Kondratieff and Myrick 2005; Brandt et al. 2005; Kondratieff and Myrick 2006; Ficke et al. 2011), results from attraction efficiency, passage efficiency, and passage success recorded for $D \times \Delta h$, demonstrate that the combination of shallow plunge pool depths with high waterfall heights, which produce low $D/\Delta h$ ratios, may inhibit the successful passage of Iberian barbel. Generating such unfavourable conditions, combination D10Δh25, which matched the smallest $D/\Delta h$ ratio tested ($D/\Delta h = 0.4$), achieved only one successful upstream passage. However, for combination D10Δh15, the second smallest ratio tested ($D/\Delta h = 0.67$), and similar to the one reported by Lauritzen et al. (2005) as the minimum ratio to allow sockeye salmon to negotiate barriers, the number of passage successes increased to 18. Nevertheless, passage success did not always increase with increasing $D/\Delta h$ ratios – for example, 28 successful passages were recorded for $D/\Delta h = 3$ (combination D30Δh10) and for $D/\Delta h = 6$ (combination D30Δh05) only 17 successes were achieved. Interestingly, and contrary to what might be expected, combination D50Δh05, which represented the maximum $D/\Delta h$ ratio tested ($D/\Delta h = 10$), did not register the highest number of passage successes; it ranked only third.

Another interesting result was that for combinations with the same $D/\Delta h$ ratio ($D/\Delta h$ = 2 for D10Δh05, D20Δh10, D30Δh15 and D50Δh25), different numbers of passage success

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were recorded (N = 10, 50, 9, and 4, respectively). This highlights the fact that, combinations with the same D/Δh ratio generate different hydrodynamic patterns bellow the weir, thereby affecting the successful passage of fish over it. These results corroborate what was postulated by Baudoin et al. (2014) about the energy dissipation of the plunging jet downstream of a weir playing an important role on the attraction and, especially, on the passage success of fish. In fact, in combinations tested, values of PE were, in general, lower than AE estimates, pointing out that passage limitations are more severe than attraction limitations. Additionally to the jet energy dissipation, should also be highlighted that the nappe shape, which depends on the specific flow discharge, and the amount of air entrainment also influence the successful negotiation of these obstacles. Furthermore, other aspects not considered in this study, like the plan shape of the weir and the downstream bottom irregularities, which influence the flow field characteristics (Pasternack et al. 2006; Vallé and Pasternack 2006; Wyrick and Pasternack 2008), may also play a role on the fish performance when negotiating small weirs.

The importance of jet dissipation, nappe profile and air entrainment were also evident in flow discharge tests implemented for combination D20Δh10. Fewer approaches, attempts to pass the weir, and successful passages were recorded with increasing flows and, in addition, fish also required more time to negotiate the weir. The highest number of passage successes was not achieved for the lowest discharge (25 $L.s^{-1}$), although an elevated number of fish approaches were recorded, which lead us to surmise that the plunging jet and the nappe formed in the downstream face of the weir (to vertical and shallow) were not sufficiently efficient to form an attractive path (see Powers and Orsborn 1985) to stimulate fish to negotiate the obstacle. On the other hand, for higher discharges (75 and 100 $L.s^{-1}$), the TKE values created by the plunging jet were considerably high, with intensities above 1 $m^2.s^{-2}$ registered close to the weir. High velocities (> 1 $m.s^{-1}$) were also observed which, together with the high TKE and the consequent aeration, may have decreased the ability of fish to

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negotiate the weir, since cyprinids, like Iberian barbel, are shorter in length and generate lower speeds compared to salmonid species (Doadrio 2001; Silva et al. 2009; Alexandre et al. 2013; Katopodis and Gervais 2016).

Thus, this study showed that the successful passage of small vertical weirs by cyprinid species is a complex phenomenon where not only the plunge pool depth and waterfall height, which have been studied previously, especially for salmonids, are important, but in addition flow discharge contributes to setting the most favourable hydrodynamic conditions for fish to overcome the obstacle. Some results were different than those which might be expected from more simplistic assumptions, as some of the combinations that might have been predicted to be easily negotiated by fish turned out to be more difficult, leading to lower success of passage. This highlights the complexity and importance of the interaction of geometry and hydraulic parameters, as well as fish abilities, to achieve successful negotiation of small obstacles. Although defining $D/\Delta h$ thresholds for successful fish negotiation is important, both nominal values of each parameter should also be taken into account when designing or retrofitting weir-like structures, otherwise their impact on river functional connectivity will not be improved as might be expected.

In nature, all the unfavourable conditions experienced in this study (shallow plunge pool depths, high waterfall heights, low flow discharges, high turbulence and air entrainment) commonly occur. These may lead to an increase in energy expenditures of fish during negotiation of the obstacles (Enders et al. 2005; Tritico and Cotel 2010) that may then reduce swimming performance and possibly cause disorientation (Pavlov et al. 2000; Liao 2007; Tritico and Cotel 2010) and fish fatigue (Katopodis and Gervais 2012). All these conditions may delay fish migration and/or reduce the number of fish that access important upstream habitats for spawning (in addition to other adverse effects; *e.g.* Ovidio and Philippart 2002; Castro-Santos and Haro 2003; Kemp and O'Hanley 2010; McLaughlin et al. 2013).

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The outcomes of this work are expected to be useful to identify potential migration obstacles for potamodromous cyprinids and to define design criteria for the requalification of small barriers (Ovidio and Philippart 2002; Kondratieff and Myrick 2006) improving fish passage and consequently habitat connectivity, and population management (Meixler et al. 2009). Being a laboratory based study, it is recognised that the tested parameters and their respective interactions do not fully explain all the complex situations that fish can encounter in nature (*e.g.* temperature, noise, substrate roughness, weir geometry irregularities, channel complexity, cover, etc.). Furthermore, not all size classes of fish were tested, due to the burden that these experiments would represent (time, number of fish, laboratory conditions), and so, different behaviours and abilities may be expected in experiments, and in the field, with other size classes. However, fish used in the experiments were chosen within the range of 15–25 cm total length that represents the typical size class of natural adult fish, the most active size class in upstream migration of this and other medium-sized benthic potamodromous cyprinids found in Iberian and European river ecosystems (Doadrio et al., 2011; Kottelat and Freyhof, 2007). Nevertheless, this work provided valuable insights that, in future researches, should definitely combine lab and *in situ* studies (Lauritzen et al. 2005; Pasternack et al. 2006; Ovidio et al. 2007; Kemp et al. 2011) to better understand how fish species respond to macro- and micro-hydrodynamic complex conditions downstream of barriers, what attracts them and what repels them. This is the key to enhance knowledge on negotiation of small instream obstacles by fish and to develop and design successful passage facilities (Williams et al. 2012).

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Table 1 – Tested plunge pool depths and waterfall heights (D×Δh) in the experimental weir to assess upstream passage performance of Iberian barbel.

Plunge pool depths (cm) – D		Waterfall heights (cm) – Δh			
		Δh05	Δh10	Δh15	Δh25
	D10	D10Δh05	D10Δh10	D10Δh15	D10Δh25
	D20	D20Δh05	D20Δh10	D20Δh15	D20Δh25
	D30	D30Δh05	D30Δh10	D30Δh15	D30Δh25
	D50	D50Δh05	D50Δh10	D50Δh15	D50Δh25

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Table 2 – Results of the combinations of plunge pool depths and waterfall heights tested (D×Δh). D/Δh, plunge pool depth/ waterfall height ratio; Q, flow discharge ($L.s^{-1}$); n, number of fish tested; Ap, total number of approaches; At, total number of attempts to pass the weir; N, total number of successful passages; % AE, percentage of attraction efficiency (ratio of the number of attempts per number of approaches × 100); %PE, percentage of passage efficiency (ratio of successful passages per number of attempts × 100); T, mean time until the first successful passage (min).

D×Δh	D/Δh	Q	n	Ap	At	N	%AE	%PE	T
D10Δh05	2	50	20	774	65	10	8	15	33
D10Δh10	1	50	20	733	138	11	19	8	29
D10Δh15	0.67	50	20	765	90	18	12	20	15
D10Δh25	0.40	50	20	293	72	1	25	1	46
D20Δh05	4	50	20	687	183	9	27	5	22
D20Δh10	2	50	20	548	291	50	53	17	15
D20Δh15	1.33	50	20	943	248	24	26	10	17
D20Δh25	0.80	50	20	746	173	19	23	11	33
D30Δh05	6	50	20	682	328	17	48	5	15
D30Δh10	3	50	20	650	299	28	46	9	24
D30Δh15	2	50	20	525	204	9	39	4	24
D30Δh25	1.20	50	20	715	110	3	15	3	13
D50Δh05	10	50	20	734	196	25	27	13	24
D50Δh10	5	50	20	676	146	8	22	5	20
D50Δh15	3.33	50	20	1013	171	18	17	11	9
D50Δh25	2	50	20	885	210	4	24	2	26

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Table 3 – Results of the pairwise comparisons, after the main test (PerMANOVA), on the number of successful fish movements for factors: **A)** plunge pool depths (D), and **B)** waterfall height (Δh). Bold values highlight significant differences..

Factor	**Pairwise comparisons**	**Results**	
		t	***P***
D	**D10 *vs.* D20**	3.05	**<0.01**
	D10 *vs.* D30	1.73	0.094
	D10 *vs.* D50	1.34	0.197
	D20 *vs.* D30	2.05	**<0.05**
	D20 *vs.* D50	2.07	**0.05**
	D30 *vs.* D50	0.14	0.871
Δh	Δh05 *vs.* Δh10	1.88	0.070
	Δh05 *vs.* Δh15	0.55	0.572
	Δh05 *vs.* Δh25	2.63	**<0.05**
	Δh10 *vs.* Δh15	1.32	0.192
	Δh10 *vs.* Δh25	3.47	**<0.01**
	Δh15 *vs.* Δh25	2.67	**<0.05**

$\alpha = 0.05$

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Table 4 – Results of the experimental designs to test the influence of flow discharge on the jumping performance of Iberian barbel. D×Δh, tested combination; Q, flow discharge ($L.s^{-1}$); n, number of fish tested; Ap, total number of approaches; At, total number of attempts to pass the weir; N, total number of successful passages; % AE, percentage of attraction efficiency (ratio of the number of attempts per number of approaches × 100); %PE, percentage of passage efficiency (ratio of successful passages per number of attempts × 100); T, mean time until the first successful passage (min).

D×Δh	Q	n	Ap	At	N	%AE	%PE	T
D20Δh10	25	20	1440	280	14	19	5	27
	50	20	548	291	50	53	17	15
	75	20	208	66	8	32	12	40
	100	20	26	12	1	46	8	57

Note: Results from Q = 50 $L.s^{-1}$ are the same presented in Table 1. They are presented here for ease of comparison.

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Table 5 – Results of the pairwise comparisons (Dunn's post-hoc test), after the main test (Kruskal–Wallis), on the number of successful fish movements for factor flow discharge (Q). Bold values represent significant differences.

Factor	Pairwise comparisons	Results	
		Z	***P***
Q	Q25 *vs*. Q50	1.20	0.11
	Q25 *vs*. Q75	-0.86	0.19
	Q25 *vs.* Q100	-1.99	**0.02**
	Q50 *vs.* Q75	-2.07	**0.02**
	Q50 *vs.* Q100	-3.19	**<0.001**
	Q75 *vs*. Q100	-1.13	0.13

α = 0.05

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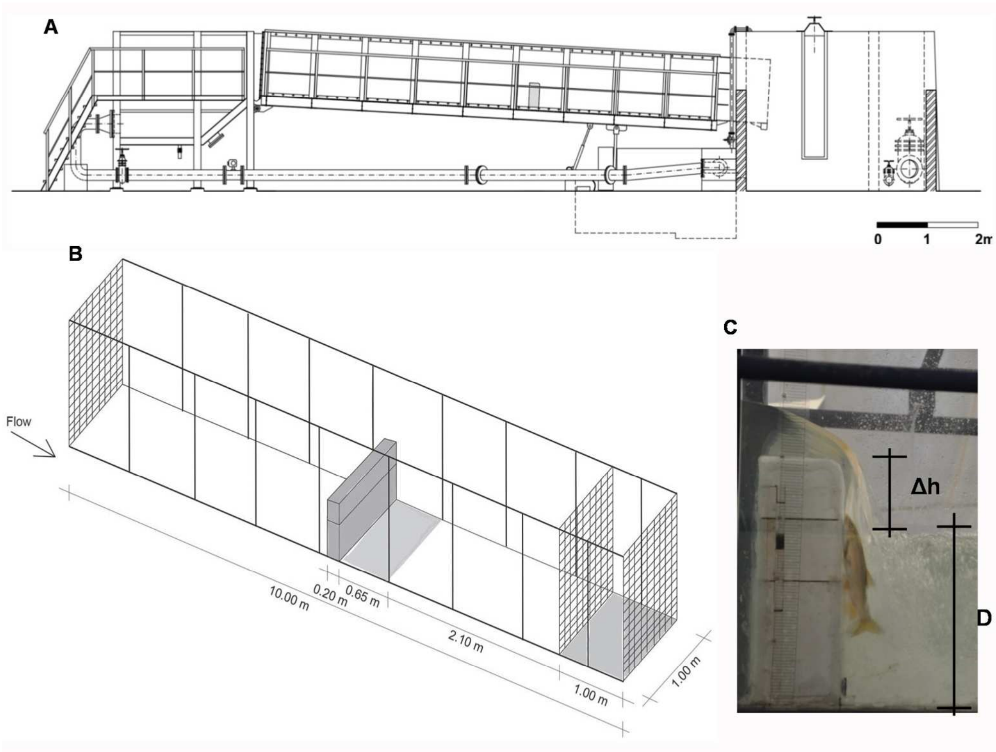

Figure 1 – Representation of: A) side view of the experimental channel on a slope of 3%; B) three dimensional scheme of the experimental ecohydraulic flume showing the location of the experimental weir (2.75 m upstream the acclimation area), the acclimation area (1 m^2 area shown shaded between the two removable fine mesh panels located downstream), and the approach area (0.65 m^2 shaded area immediately downstream the weir); and C) experimental design considering the plunge pool depth (D - distance from the bottom of the flume to the top of the water surface) and waterfall height (Δh – distance from the water surface to the top of the crest of the experimental weir). This picture provides a visible attempt by fish to swim up the skimming flow formed in the downstream face of the weir.

542x410mm (96 x 96 DPI)

Only

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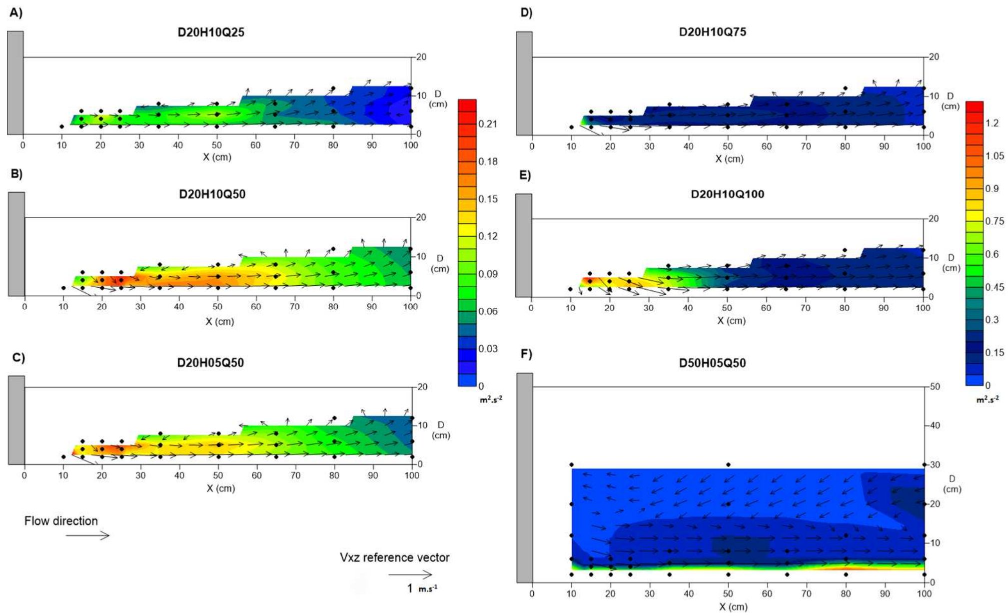

Figure 2 – Graphical representation of turbulent kinetic energy (TKE; $m^2.s^{-2}$) and velocity vectors (V_{xz}; $m.s^{-1}$) for combinations tested: A) D20Δh10 with 25 $L.s^{-1}$; B) D20Δh10 with 50 $L.s^{-1}$; C) D20Δh05 with 50 $L.s^{-1}$; D) D20Δh10 with 75 $L.s^{-1}$; E) D20Δh10 with 100 $L.s^{-1}$; and F) D50Δh05 with 50 $L.s^{-1}$. X is the distance from the weir (cm) and D is the water depth (cm). Points represent the measuring mesh.

294x178mm (145 x 145 DPI)

view Only

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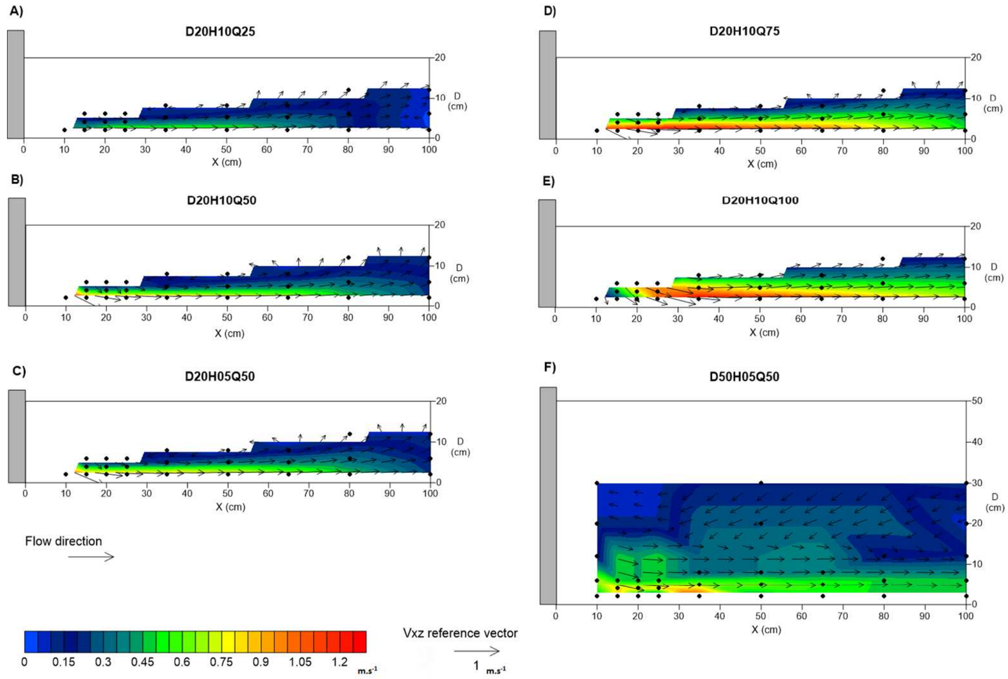

Figure 3 – Magnitude and direction of water velocity (V_{xz}; m.s^{-1}) in combinations tested: A) D20Δh10 with 25 L.s^{-1}; B) D20Δh10 with 50 L.s^{-1}; C) D20Δh05 with 50 L.s^{-1}; D) D20Δh10 with 75 L.s^{-1}; E) D20Δh10 with 100 L.s^{-1}; and F) D50Δh05 with 50 L.s^{-1}. X is the distance from the weir (cm) and D is the water depth (cm). Points represent the measuring mesh.

282x191mm (144 x 144 DPI)

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