THE EFFECT OF SLOPE AND RAMP LENGTH ON THE UPSTREAM PASSAGE PERFORMANCE OF POTAMODROMOUS CYPRINIDS NEGOTIATING LOW-HEAD RAMPED WEIRS

SUSANA DIAS AMARAL(1), PAULO BRANCO(2), CHRISTOS KATOPDIS(3), MARIA TERESA FERREIRA(4), ANTÓNIO NASCIMENTO PINHEIRO(5) & JOSÉ MARIA SANTOS(6)

1,2,4,6 Forest Research Centre, School of Agriculture - University of Lisbon, Lisbon, Portugal, samaral@isa.ulisboa.pt; pbranco@isa.ulisboa.pt; terferreira@isa.ulisboa.pt; jmsantos@isa.ulisboa.pt
3 Katopdis Ecohydraulics Ltd., Winnipeg, Canada, katopdisecohydraulics@live.ca
5 Civil Engineering for Research and Innovation for Sustainability, Técnico - University of Lisbon, Lisbon, Portugal, antonio.pinheiro@tecnico.ulisboa.pt

ABSTRACT

Low-head ramped weirs are one of the most common small engineered structures present in Iberian rivers. Fish passability of these obstacles, where water passes over but does not generate a waterfall, is primarily related to ramp length and slope. However, the relative contribution of these factors has seldom been investigated. This study aims to assess the upstream passage performance of a medium-size potamodromous cyprinid, the Iberian barbel (Luciobarbus bocagei), negotiating an experimental low-head ramped weir with varying ramp length (L), slope (S), and discharge (Q). A total of 4 configurations were initially tested contemplating different combinations of L (1.50, 3.00 m) and S (10, 20, 30 %), with a constant Q of 110 L.s⁻¹. The configuration with the lowest number of successful upstream passages was then assessed for an additional Q of 55 L.s⁻¹. Results suggest that both factors L and S, as well as Q, influenced passage performance of fish. While attraction efficiency increased with increasing L and S, the number of successful negotiations, and consequently passage efficiency, decreased upon increasing L, and peaked at the intermediate value of S. Regarding Q, although its reduction contributed to the presence of a smaller water column on the ramp, the number of successful passages increased significantly. However, both attraction and passage efficiencies registered lower values, suggesting that it is rather difficult to determine the most suitable combination of hydrodynamic conditions downstream and over the ramp for efficient fish passage. These results may be useful for designing appropriate passage structures for low-head instream obstacles.

Keywords: Potamodromous cyprinid species, low-head ramped weirs, upstream migration, ecohydraulics

1 INTRODUCTION

River fragmentation caused by the presence of small engineered structures, estimated as 2-4 orders of magnitude more numerous than dams, has been considered one of the main threats to the sustainability of fish populations (Nilsson et al., 2005; King et al., 2017). In Portuguese rivers, more than 8000 small weirs, with less than 5m in height, were identified (Ordeix et al., 2018). Along with small broad-crested weirs, that have the downstream face vertical, low-head ramped weirs, with inclined faces that fish may be able to overcome by swimming, are the most usual design (Solà et al., 2011; Branco et al. 2017).

In low-head ramped weirs, water passes over the ramp and does not generate a waterfall (Solà et al., 2011; Baudoin et al., 2014). The permeability of such structures to fish movements is normally site-, season-, and species-specific. Besides the importance of fish swimming abilities, which are closely related to fish species groups and body size (Katopdis and Gervais, 2016; Newton et al., 2018), the efficiency of these structures to successful upstream passage of fish is mainly dependent on hydrodynamic conditions present in the vicinity of the structure, such as discharge and turbulence (Baudoin et al., 2014; Harris et al., 2016), and on the physical design of the ramped weir, with ramp length and slope being key factors (Baker, 2014; Baudoin et al., 2014). So, since the efficiency of low-head ramped weirs has seldom been assessed, it is particularly important to study the interaction of these key factors in order to establish more appropriate design considerations for these types of obstacles.

The goal of this study was to assess the passage performance of a medium-size potamodromous cyprinid, the Iberian barbel (Luciobarbus bocagei), negotiating an experimental low-head ramped weir, considering the effect of physical and hydraulic factors – ramp length (L) and slope (S), and discharge (Q). Iberian barbel was...
selected, since it is considered a representative of few species of medium-sized benthic potamodromous cyprinids commonly present in Iberian and Western European rivers, counting the genera *Barbus* and *Luciobarbus* (Santos et al., 2014). It was hypothesized that: i) passage performance of fish, considering the attraction as well as upstream successful passages, will be influenced by the different combinations of $L \times S$, and $Q$ tested; ii) attraction efficiency would increase with increasing $L$, $S$, and $Q$; and iii) successful passages, and consequently passage efficiency, would decrease with increasing $L$, $S$, and $Q$.

2 MATERIAL AND METHODS

Experiments were carried out in an indoor ecohydraulic flume (a rectangular steel frame 10.00 m long x 1.20 m high x 0.60 m wide, with glass-viewing panels on the sidewall that allow direct observation of fish) installed at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon. Four configurations, encompassing two ramp lengths ($L = 1.50$ m, $3.00$ m) and three different slopes ($S = 10\%$, $20\%$, $30\%$), were initially tested ($L150$ $S10$; $L150$ $S20$; $L150$ $S30$; $L300$ $S10$) maintaining a constant discharge of $110$ L.s$^{-1}$. The configuration with the lowest number of successful upstream passages was then assessed for an additional discharge of $55$ L.s$^{-1}$.

Each experimental ramped weir tested (Figure 1), made of maritime plywood, spanned the entire channel width and was fixed in the flume at 2.50 m upstream of the acclimation area, a $0.60$ m$^2$ area created by two mesh panels in the downstream zone of the channel. Immediately downstream of the ramp toe, a $0.50$ m long zone was established as the approach area. A minimum water depth of $0.20$ m was maintained in the approach area, to standardize that condition throughout the experiments. Discharge was measured by a flow meter installed in the supply pipe. Water velocity ($V_x$) along the ramps, as well as upstream and downstream of the ramp, was measured with a flow probe (model FP 101, Global Water Instrumentation; for more details see Amaral et al., 2019).

![Figure 1](image_url). Scheme of the experimental flume (above), representing a side view of the channel, and a top view with the location of (1) the experimental low-head ramped weir (2.50 m upstream the acclimation area), (2) the approach area (the $0.30$ m$^2$ shaded area immediately downstream of the ramp toe), and (3) the acclimation area (the $0.60$ m$^2$ shaded area between the two removable fine mesh panels located downstream); and images (photos below) of the four configurations tested ($L$ represents the length (cm), and $S$ the slope (%) of the ramp).

A total of 100 adult Iberian barbel was used in the experiments ($n = 100$; mean total length (TL) ± standard deviation (SD) = $16.3 \pm 2.1$ cm). Fish were captured by electrofishing (Hans Grassl IG-200) in the Lisandro River, according to the protocol adopted by the European Committee for Standardization (CEN, 2003). Five electrofishing episodes were performed (maximum two episodes per week), collecting 20 fish per episode. At LNEC, fish were maintained in filtered and aerated acclimation tanks (700 L tanks), where water quality was guaranteed by the mechanical and biological filtration system (Fluval Canister Filter FX5), and daily monitored (temperature = $23 \pm 1$ °C, pH = $7.7 \pm 0.1$, and conductivity = $174 \pm 14$ μS.cm$^{-1}$) using a multiparametric probe (HANNA, HI 9812-5). Fish were only tested after an acclimation period to the conditions in the laboratory of 48 hours.
Experiments were performed during late spring-early summer, reported as the main reproductive season for this species (Santos et al., 2005; Baudoin et al., 2014). For each configuration tested, 4 replicates were carried out with schools of 5 fish (n = 20 fish). Fish were randomly selected from the acclimation tanks and were used only once. Prior to each replicate, fish were held 15 minutes in the acclimation area, for adaptation to the flume conditions. After this period, the upstream mesh panel was removed, and fish were allowed to voluntarily explore the channel for 60 minutes. Fish movements, such as number of times fish approach the ramp (Ap), number of attempts to actively negotiate it (At), and number of successful upstream passages (N), were monitored by direct observation and recorded by a video camera (GoPro HERO5). Both upstream and downstream passages were allowed, so fish could approach, attempt to pass, and successfully negotiate the ramp several times. Metrics of passage performance – attraction efficiency (AE%; quotient of number of attempts per number of approaches), and passage efficiency (PE%; quotient of number of passages per number of attempts), were calculated according to equations from Amaral et al. (2016).

For the statistical analysis, a nonparametric Kruskal-Wallis H test was performed to analyze the influence of L, S, and Q on the successful negotiation of the experimental ramps, pondering the results for N, AE% and PE%. The dunn.test package (Dinno, 2015), from the open-source software R (R Core Team, 2017), was used to compute the analysis.

3 RESULTS AND DISCUSSION

Upstream successful passages were registered in all 5 configurations tested (Figure 2). Nevertheless, the effect that factors L, S, and Q may have had on the passage performance of Iberian barbel was highlighted, due to the different number of Ap, At, and N registered in each configuration tested. Consequently, the metrics of passage performance assessed, AE% and PE%, also varied according to the tested configurations.

![Figure 2](image-url) 

**Figure 2.** Results for the number of successful upstream passages (N), and for the performance metrics attraction efficiency (AE%) and passage efficiency (PE%) for the configurations tested, considering the variation
of: a) ramp length (L), with Q = 110 L.s\(^{-1}\); b) ramp slope (S), with Q = 110 L.s\(^{-1}\); and c) discharge (Q), with Q55 = 55 L.s\(^{-1}\) and Q110 = 110 L.s\(^{-1}\).

Regarding the effect of factors L (Figure 2a) and S (Figure 2b) on the passage performance of fish, with Q = 110 L.s\(^{-1}\), the total number of N and, consequentially, values of PE\% mainly decreased with the increase of tested factors. However, values of AE\% registered an increase with the increasing values of both L and S. Contrary to what was initially expected, configuration L150 S10, that combined the smallest L with the lowest S, and registered values of V\text{X} over the ramp and at its toe, below 2 m.s\(^{-1}\), was not the most successful configuration. Instead, configuration L150 S20, where values of V\text{X} ranged from 2 to 3 m.s\(^{-1}\), recorded the highest number of Ap, At and N (totals of 31, 21 and 17, respectively), being the configuration with higher PE\% (81\%). On the other hand, configuration L300 S10, that displayed values of V\text{X} above 3 m.s\(^{-1}\), registered the lowest number of N, with only 3 successful passages, and was the configuration least efficient in terms of PE\% (15\%). Nevertheless, considering the results for AE\%, configuration L300 S10 was the second most attractive for fish, with AE\% = 71.4\%, being only surpassed by configuration L150 S30 (AE\% = 73.3\%). These results corroborate the outcomes of previous studies from Amaral et al. (2016; 2018) and from Goering and Castro-Santos (2017) about the “fish passage paradox”, considering the influence of water velocity and, consequently, of turbulence and energy dissipation present on these small barriers (Baudoin et al., 2014) in the attraction of fish and on the successful negotiation of the obstacle. Like in the mentioned studies, fish were attracted to the ramped weir by high values of water velocity but, at the same time, it might have been a limiting factor for the successful upstream passage – thus, what attracted the fish may have hampered their movements. Results from the Kruskal-Wallis H test suggest a marginally significant influence (i.e., P ≤ 0.10) of both factors L and S on the number of N (L: H = 1.85, 1 d.f., P = 0.10; S: H = 4.47, 2 d.f., P = 0.10), as well as on values of PE\% (L: H = 3.19, 1 d.f., P = 0.07; S: H = 5.71, 2 d.f., P = 0.05). However, for AE\%, results reveal no significant influence of factors L (H = 0.004, 1 d.f., P = 0.90) and S (H = 2.30, 2 d.f., P = 0.31).

Concerning the effect of Q (Figure 2c), assessed in the configuration with the lowest number of successful upstream passages L300 S10, the total number of N increased with decreasing Q, recording four times upstream successful passages with Q = 55 L.s\(^{-1}\), despite the smaller water column on the ramp. However, in terms of AE\% and PE\%, this lower Q, which displayed values of V\text{X} below 2 m.s\(^{-1}\), proved to be less efficient, attaining values of only 35% and 9.1\%, respectively. These results are related to the large number of non-oriented entries in the approach area (Ap = 377), of which only ⅓ resulted in attempts to actively negotiate the ramped weir (At = 132), and of these attempts, only 12 were successful upstream passages. So, overall, these numbers may evidence the fact that water velocity at the toe of the ramped weir (V\text{X} = 1.4 m.s\(^{-1}\)) was not the most appropriate to establish an attractive path for fish to actively attempt to negotiate the obstacle and successfully overcome it (Pavlov et al., 2000; Elder and Coombs, 2015; Goering and Castro-Santos, 2017). Results from the Kruskal-Wallis H test revealed a significant influence of Q on the number of N (H = 4.86, 1 d.f., P = 0.02) and on values of AE\% (H = 5.33, 1 d.f., P = 0.02), but values of PE\% were not discharge related, at least in the configuration tested (L300 S10).

4 CONCLUSIONS

Although the experimental conditions tested in the flume were a simplification of what fish may encounter in nature, they allowed the analysis of physical and hydraulic factors, such as ramp length and slope, discharge and consequently water velocity, that are referred by some authors (Solà et al., 2011; Baker, 2014; Baudoin et al., 2014) as preponderant factors for the successful upstream passage of fish along low-head ramped weirs. Moreover, due to the structural characteristics of the experimental flume, a detailed observation of fish behavior negotiating the obstacle was possible to perform.

Results from the present study corroborates the outcomes of Baker (2014) about the importance that L and S, as well as Q, may have on the permeability of ramped weirs for upstream movements of fish. Results suggest that, together, these three factors (L, S, and Q) may have influenced the negotiation performance of barbel, both in terms of attraction of fish to the ramp and especially on its successful upstream passage. However, the negotiation of low-head ramped weirs by potamodromous fish species should be further investigated, focusing on retrofitting such structures with different boulder geometries and arrangements, in order to improve fish passability and, consequently, habitat connectivity.

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