

Article

# Passage Performance of Potamodromous Cyprinids over an Experimental Low-Head Ramped Weir: The Effect of Ramp Length and Slope

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**Abstract:** Low-head ramped weirs are a common instream obstacle to fish movements. Fish passability of these structures, where water passes over but does not generate a waterfall, is primarily related to ramp length and slope, but their relative contribution has seldom been considered. This study aims to assess the passage performance of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*), negotiating an experimental ramped weir with varying ramp length (L) and slope (S). Four configurations were tested, with a constant discharge of 110 L·s<sup>-1</sup>. Results suggest that both factors influenced passage performance of fish. Attraction efficiency (AE) increased with increasing L and S, whereas the number of successes (N) and passage efficiency (PE) decreased upon increasing L. For S, it was found that both N and PE peaked at the intermediate level (20%). These results suggest that configurations with the lowest slopes may not necessarily be the best option because they may be less attractive for the fish and their demand for space is higher. Higher slopes (but not excessive) could be more attractive to fish, less space-demanding, and therefore, more cost-effective. Future studies should investigate how discharge and boulder placement influence fish passage across ramped weirs, to improve habitat connectivity.

**Keywords:** potamodromous cyprinid species; low-head ramped weirs; upstream migration; ecohydraulics

## 1. Introduction

River fragmentation by small engineered structures, far more numerous than dams, has led to severe declines or local extinctions of many fish populations by blocking upstream movements for reproduction, feeding, and refuge needs [1–3]. By identifying the importance of aquatic connectivity for good ecological quality in rivers, the European Water Framework Directive (WFD) emphasized the need to re-establish free movements for all fish species and size classes, regulating that member states should assess all instream obstacles, even small weirs, and minimize their barrier effect [4–6]. Since then, a few studies on small obstacles (considering assessment protocols, e.g., [7–9], or field assessments, e.g., [10–12]) and projects, such as the European project AMBER and other operational programs like the EU LIFE programs, have been developed, aiming to enhance the knowledge on permeability of small obstacles and fish passage, recommend strategies for action, and rehabilitate river habitats [3,13,14].

Portuguese rivers have more than 8000 small weirs [14] that are, in general, less than 5 m in height. Along with small broad-crested weirs (designed with a vertical downstream face, [15]), low-head ramped weirs, with inclined faces that fish may be able to overcome by swimming, are the most usual design [8,16]. In fact, some old broad-crested weirs that, after assessment, could not be removed have undergone rehabilitation works to include ramps in their designs, in order to enhance fish passability (e.g., [17]). However, the effectiveness and efficiency of these structures remains poorly understood, particularly for potamodromous cyprinids, which are an important component of Mediterranean European fish assemblages [18].

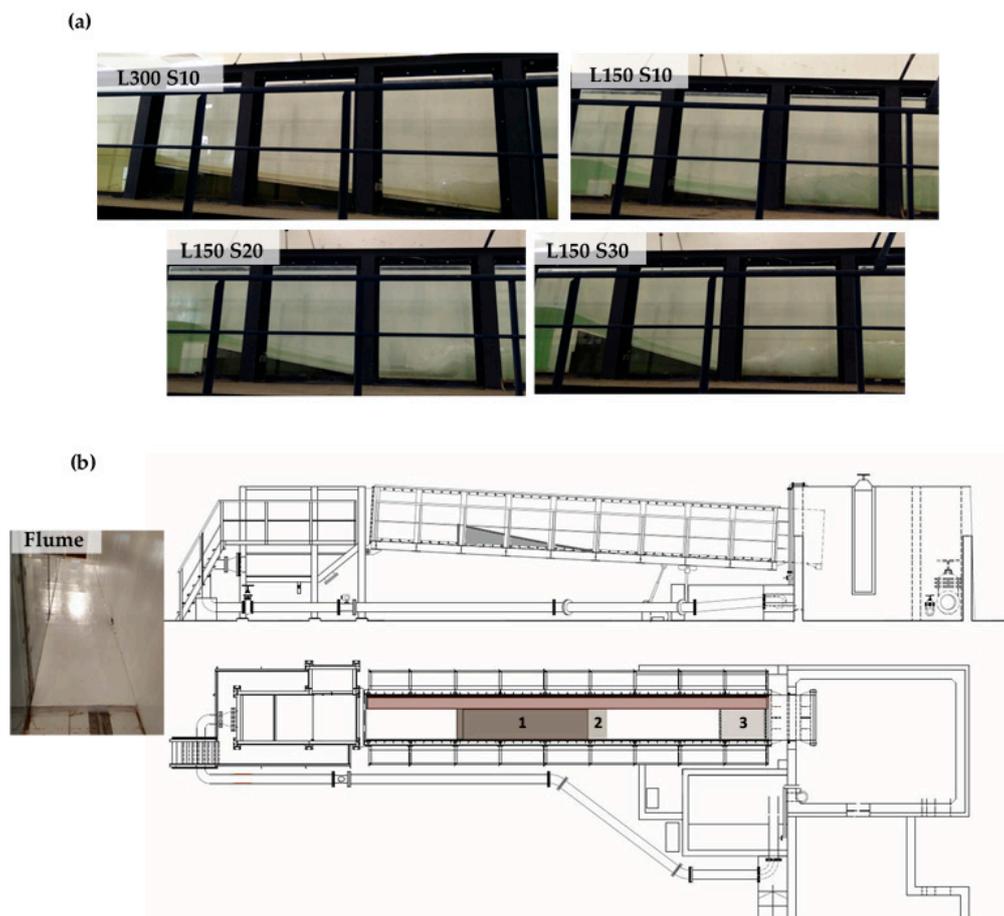
In low-head ramped weirs, water passes over the ramp and does not generate a waterfall [8,19]. The permeability of such structures to fish movements is usually site-, season-, and species-specific, depending on the effect of hydraulic boundary conditions (e.g., roughness of the ramp surface, conditions at the ramp toe related with erosion processes, and/or structure maintenance), hydrodynamics (e.g., water depth, discharge, and turbulence) present in the vicinity of the structure [19,20], and on fish swimming abilities, which are closely related to fish species groups and body size [21–23]. Nevertheless, in the physical design of a ramped weir, length and slope play an important role on the efficiency of these structures to successful upstream passage of fish [9,19,24]. As mentioned by Baker [24], although the effect of ramp length and slope is difficult to discriminate and their relative contribution 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* (Steindachner, 1864), negotiating an experimental low-head ramped weir with varying ramp length (L) and slope (S). Iberian barbel was selected as the target species for being considered a representative of several species from the genera *Barbus* and *Luciobarbus*, commonly present in rivers from Mediterranean and Western Europe [25,26]. It is expected that (i) passage performance of fish, considering the attraction as well as upstream successful passages, will be influenced by the different combinations of L and S; (ii) attraction efficiency would increase with increasing L and S, due to increasing water velocity near the ramp that may act as an attraction factor for fish; and (iii) successful passages, and consequently passage efficiency, would decrease with increasing L and increasing S, hampered by the increasing water velocity present downstream and over the ramped weir.

## 2. Materials and Methods

To study the influence of L and S on the passage performance of Iberian barbel, four configurations encompassing two ramp lengths (L = 1.50 and 3.00 m) and three different slopes (S = 10%, 20%, 30%) were assessed (L150 S10; L150 S20; L150 S30; L300 S10). The experimental ramped weirs (Figure 1a), made of maritime plywood, were tested in an indoor ecohydraulic flume (a rectangular steel frame 10.00 m long × 1.20 m high × 0.60 m wide, with glass-viewing panels on sidewalls that allow direct observation of fish where, due to its dimensions and facilities, it is possible to preform ecohydraulic studies, assessing the influence of key hydraulic variables on the behavior of specimens) installed at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon. The flume (Figure 1b) includes an upstream and a downstream tank, separated from the channel by mesh panels (from where the water enters the flume and is recirculated), and it was tilted at a 3% slope to represent the average slope of central and southern Iberian rivers (Catchment Characterisation and Modelling, version 2 [CCM2]; [27]). The experimental ramped weir (Figure 1b), spanning the entire channel width, was fixed in the flume at 2.50 m upstream of the acclimation area, a 0.60 m<sup>2</sup> area created by two mesh panels in the downstream zone of the flume. Immediately downstream of the ramp toe, a zone 0.50 m in length was established as the approach area. Discharge was measured by a flow meter installed in the supply pipe and maintained constant at 110 L·s<sup>-1</sup>. Consequently, in all the configurations tested, the water depths at the weir crest and along the

ramps, measured using rulers placed along the glass-viewing panels of the channel, were similar. Values registered at the weir crest varied from 0.19 to 0.20 m (observed in L150 S10 and L300 S10, respectively). Along the ramp, water depths decreased from 0.10–0.11 m (registered in L300 S10 and L150 S10, respectively), registered at the upper part of the ramp, to 0.06–0.08 m (observed in L150 S30 and L150 S10, respectively). A minimum water depth of 0.20 m, which was found to be the most suitable according to literature [17,19] and previous studies by Amaral et al. [15,28], was maintained in the approach area to standardize that condition throughout the experiments. Since the water column over the tested ramps was not deep enough ( $\approx 0.10$  m) to use a 3D acoustic Doppler velocimeter and there was too much aeration and turbulence downstream of the ramp, especially at the ramp toe, the water velocity along the ramps, as well as upstream and downstream of the ramp, was instead measured with a flow probe (model FP 101, Global Water Instrumentation) in 21 and 27 sampling points for  $L = 1.50$  m and  $L = 3.00$  m, respectively. Sampling points were established along three longitudinal planes—a plane along the center of the ramp and two lateral planes spaced 0.05 m from the walls, and at intervals of 0.75 m along the ramp. Measurements were also taken in the middle of the weir crest, as well as 0.50 m upstream and downstream (0.50 and 1.00 m) of the ramped weir. These measurements ( $V_x$ ) were represented graphically by contour maps, to illustrate water velocity variation along the tested combinations.



**Figure 1.** Images of (a) the four configurations tested (L represents the length (cm), while S the slope (%) of the ramp); (b) the experimental flume, representing a side view of the channel on a slope of 3% (scheme above), and a top view (scheme below) with the location of (1) the experimental low-head ramped weir (2.50 m upstream the acclimation area), (2) the approach area (the  $0.30 \text{ m}^2$  shaded area immediately downstream of the ramp toe), and (3) the acclimation area (the  $0.60 \text{ m}^2$  shaded area between the two removable fine mesh panels located downstream).

Adult Iberian barbel used in the experiments ( $n = 80$ ; mean total length (TL)  $\pm$  standard deviation (SD) =  $16.3 \pm 2.1$  cm) were captured by wadeable electrofishing (Hans Grassl IG-200) in the Lisandro River, a small Atlantic coastal river near Lisbon. Fishing and handling permits for capture of wild fish (40/2017 and 222/2017/CAPT; 41/2017 and 223/2017/CAPT; 42/2017 and 224/2017/CAPT, respectively) were issued by the Portuguese Institute for Nature Conservation and Forests (ICNF, I.P.). A total of four electrofishing episodes were performed (two episodes per week during two consecutive weeks to not bias the fish motivation, collecting 20 fish per episode) according to the protocol adopted by the European Committee for Standardization (CEN 2003). To transport the fish to the laboratory facilities at LNEC, a fish transport box (Hans Grassl, 190 L) with external aeration was used. At LNEC, fish were maintained in filtered and aerated acclimation tanks (700 L tanks; Fluval Canister Filter FX5), where water quality was daily monitored (temperature =  $23 \pm 1$  °C, pH =  $7.7 \pm 0.1$ , and conductivity =  $174 \pm 14$   $\mu\text{s}\cdot\text{cm}^{-1}$ ), using a multiparametric probe (HANNA, HI 9812-5), and high-quality levels (i.e., active fish, no mortality) were guaranteed by the mechanical and biological filtration system, with a turnover rate of  $2300 \text{ L}\cdot\text{h}^{-1}$ . Fish were only tested after an acclimation period of 48 h from the holding conditions in the laboratory.

The study was conducted in agreement with national and international guidelines to maintain the welfare of the tested animals and minimise stress (J. M. Santos holds FELASA Level C certification ([www.felasa.eu](http://www.felasa.eu)) to direct animal experiments). Fish experiments and maintenance in the laboratory and experimental facility were authorized (reference DGAV: 0420/000/000/2012) by the Department for Health and Animal Protection (Direcção de Serviços de Saúde e Protecção Animal) in accordance with the recommendations of the “Protection of animal use for experimental and scientific work”. No fish were sacrificed during this study and, after finishing the experiments, all fish were taken back and released in their natural habitat.

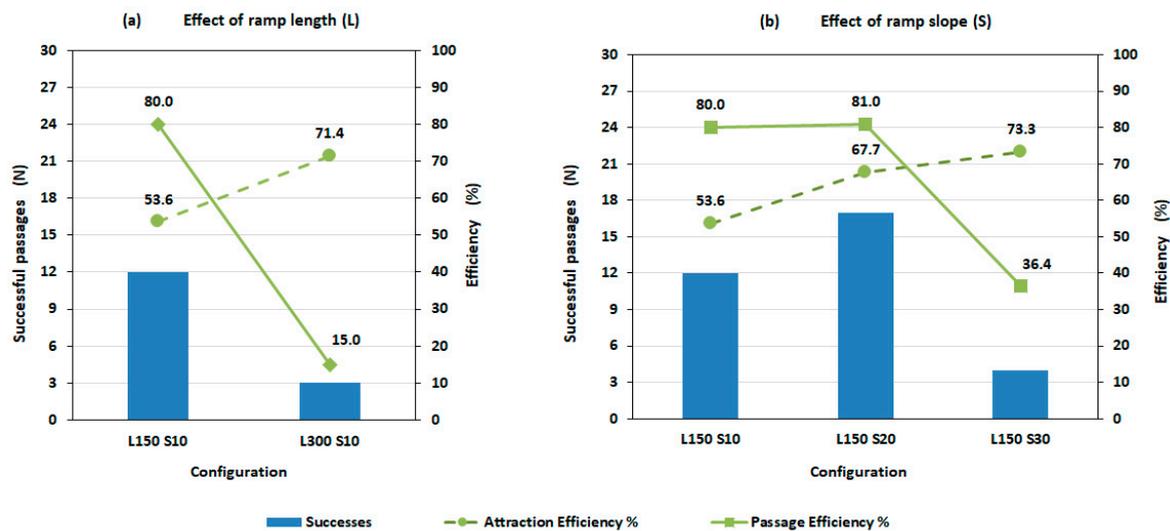
Experiments were performed during late spring–early summer, reported by some authors as the main reproductive season for this species [19,29]. For each configuration tested (L150 S10; L150 S20; L150 S30; L300 S10), 4 replicates were carried out with schools of 5 fish ( $n = 20$  fish) that were haphazardly selected from the acclimation tanks and were used only once. The unit of analysis was therefore a school of five adult Iberian barbel with similar size, as this species tends to move in schools, rather than individually, as observed in other studies by Amaral et al. [15,28] and Romão et al. [26,30], to increase hydrodynamic efficiency [31]. For fish to adapt to the conditions in the flume, each replicate started with an acclimation period of 15 min (period previously tested by Amaral et al. [15,28,32] and considered to be appropriate for the acclimation of fish to the flume). After that time, the upstream mesh panel of the acclimation area was removed, and fish were able to volitionally explore the channel for a maximum of 60 min. Since both upstream and downstream passages were allowed, fish could approach, attempt to pass, and successfully negotiate the ramp multiple times. Fish movements were monitored by direct observation and recorded (top view) by a video camera (GoPro HERO5). The number of fish that entered the approach area ( $A_p$ ), the number of fish that entered into the ramp and actively tried to negotiate it ( $A_t$ ), and the number of fish that completely passed the ramp to upstream, i.e., completed successful passages ( $N$ ), were registered. Metrics of passage performance, such as percentage of attraction efficiency (AE%) and percentage of passage efficiency (PE%), were then calculated from Equations (1) and (2), adapted from Amaral et al. [15]. For the statistical analysis, because this study did not have a full factorial design, and data were not homoscedastic nor normally distributed, a nonparametric Kruskal–Wallis  $H$  test was performed to analyze the influence of L and S on the successful negotiation of the experimental ramps, pondering the results for  $N$ , AE%, and PE%. The *dunn.test* package [33], from the open-source software R [34], was used to compute the analysis.

$$\text{AE\%} = 100 \times A_t/A_p, \quad (1)$$

$$\text{PE\%} = 100 \times N/A_t, \quad (2)$$

### 3. Results

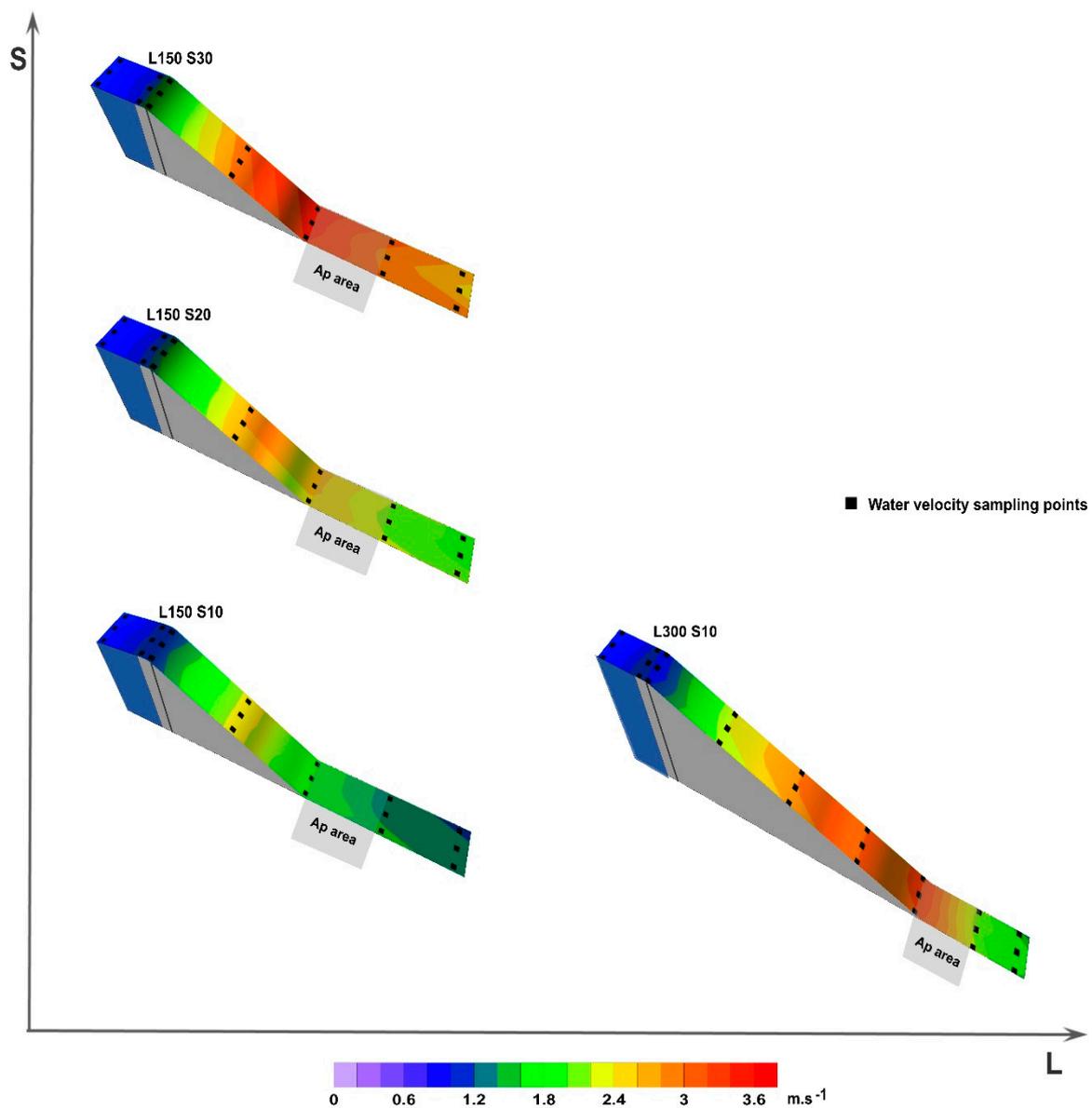
Upstream successful passages were registered in all the configurations tested. However, the number of N, Ap, and At, and consequently values of AE% and PE%, varied according to the tested configurations, highlighting the effect that factors L and S may have had on the passage performance of Iberian barbel. The total number of N, together with values of PE%, mainly decreased with the increase of tested L (Figure 2a) and S (Figure 2b). On the contrary, values of AE% registered an increase with the increasing values of both L and S (Figure 2a,b). Configuration L150 S20 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 L150 S30 registered the lowest numbers, with only Ap = 15, At = 11, and N = 4. However, it was the most attractive configuration for fish, with AE% = 73.3%, followed by L300 S10 (71.4%), which in turn was the least efficient configuration in terms of PE%, registering only 15% (Ap = 28, At = 20, N = 3). Configuration L150 S10 was the least attractive for fish (AE% = 53.6%), registering several approaches (Ap = 28) but few attempts (At = 15) to negotiate the experimental ramp.



**Figure 2.** Results for the number of successful passages (N; bars), and attraction efficiency (AE%; dotted line) and passage efficiency (PE%; solid line) for the configurations tested, considering the variation of (a) ramp length (L); (b) ramp slope (S).

Results from the Kruskal–Wallis  $H$  test suggest a marginally significant influence (i.e.,  $P \leq 0.10$ ) 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.*,  $P = 0.05$ ). The ramp with L = 1.50 m achieved better results than the one with L = 3.00 m and, in terms of slope, S = 20% stood out from the other slopes tested as the most successful. As for AE%, however, 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.*,  $P = 0.31$ ).

Figure 3 displays the variation of water velocity ( $V_x$ ) for the different tested ramps. Contour maps revealed that water velocity values increased with L and S. This increase was particularly important in the case of L150 S30 and L300 S10, where values of water velocity above  $3 \text{ m}\cdot\text{s}^{-1}$  were registered close to the toe of the ramp. On the contrary, configuration L150 S10 was the one with the lowest water velocities ( $1.8 \text{ m}\cdot\text{s}^{-1}$  close to the toe of the ramp, and a maximum of  $2.3 \text{ m}\cdot\text{s}^{-1}$  over the ramp).



**Figure 3.** Contour maps of water velocity ( $V_x$ ) for the configurations tested, considering the variation of ramp length ( $L$ ) and slope ( $S$ ). Measurements were made with a flow probe (model FP 101, Global Water Instrumentation). Black dots represent water velocity sampling points. The approach area, located immediately downstream of the ramp toe between two lines of sampling points, is identified by the tag below (Ap area).

#### 4. Discussion

In situ studies on the negotiation of small instream obstacles by fish—that must associate the assessment of fish movements and an extensive characterization of all the hydrodynamic conditions that fish need to overcome in order to successfully pass the obstacle—can be very complex and onerous [35–37]. All the requirements needed to carry out such studies, in terms of human resources and time, field equipment, and robust technology, may strongly constrain their developments [35,38], unless a long period of execution and provision of funding is ensured, conditions that most scientific field experiments often fail to achieve. Therefore, the use of full-scale or even scaled-down laboratory facilities, such as the ecohydraulic flume used in the present study, is presented as a more expeditious parallel approach to study fish behavior and negotiation of small instream obstacles [25,39,40]. Inherent to laboratory conditions, these ecohydraulic flumes provide the opportunity to easily manipulate

important factors, control for confounding variables and effects that could bias the results, and observe responses that should improve the knowledge of events occurring in the wild [25,39,41].

In this study, the influence of L and S on the passage performance of the Iberian barbel negotiating an experimental low-head ramped weir was assessed, maintaining a constant discharge of  $110 \text{ L}\cdot\text{s}^{-1}$ . Although experimental conditions tested in the flume were a simplification of what fish may encounter in nature, they allowed detailed observation of fish behavior (e.g., fish approaching the ramp, attempts to negotiate it, and successful passages) as well as the control and analysis of physical and hydraulic variables, such as ramp length and slope, discharge and consequently water velocity, and water depth at the toe of the ramp that, along with fish swimming abilities and other boundary conditions (e.g., roughness of the ramp surface, structural conditions of the ramp toe), are referred by some authors [8,9,19,20,24] as preponderant factors for the successful upstream passage of fish along ramped weirs.

Results of this experiment suggest that both factors L and S had a marginally significant influence on the number of N, and consequently on values of PE%, but their influence on AE% was not significantly determined. As in other experiments by Amaral et al. [15,32], and in Goering and Castro-Santos [42], the “fish passage paradox”—concerning the influence of water velocity and, consequently, of turbulence and energy dissipation present on these small barriers [9,19] in the attraction of fish and on the successful negotiation of the obstacle—was also observed in the present study. 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 successful upstream passage—what attracts fish is what hampers movements.

Contrary to what was initially expected, configuration L150 S10, that combined the smallest L with the lowest S, and thus the one that registered the lowest values of water velocities, was not the configuration that recorded the highest values of N or PE%, and was also the least attractive (AE% ca. 50%). In this configuration, only half the fish that entered the approach area ( $A_p = 28$ ) went into the ramp and actively tried to negotiate it, a fact that may suggest that the water velocity ( $V_x = 1.7 \text{ m}\cdot\text{s}^{-1}$ ) was not the most appropriate to establish an attractive path for fish to proceed and successfully pass the obstacle [42–44]. On the other hand, configurations L150 S30 and L300 S10, which displayed high water velocity (registering values of  $3.6$  and  $3.4 \text{ m}\cdot\text{s}^{-1}$ , respectively, at the ramp toe) due to the correspondingly steeper S and the longer L, achieved the highest values of AE% but registered a low number of N (only 4 and 3 successful passages, respectively) and, consequently, the lowest values of PE% (36% and 15%, respectively), suggesting that water velocity, and the potential turbulence associated to these type of obstacles [9,19], had a positive influence on the attraction of fish to the ramp but, at the same time, might have hampered their successful upstream passage possibly due to fish disorientation and fatigue [43–45]. This was especially observed in configuration L300 S10 where, in some attempts, fish were able to negotiate the ramp up to its half-length by sprinting (maximum-speed swimming), overcoming values of water velocity around  $3 \text{ m}\cdot\text{s}^{-1}$ . However, most likely due to fatigue, fish stopped swimming and were dragged down to the end of the ramp.. Therefore, to enhance fish passage along long low-head ramped weirs, it would probably be important to retrofit these types of obstacles with substrates, such as different types of blocks or rocks for a more nature-like design, in order to create areas with diverse hydraulic conditions along the ramp [46,47], allowing fish to rest and to recover energy to continue successful negotiation of the ramp [22,47]. Since the swimming performance of the Iberian barbel is quite similar to the swimming performance of other rheophilic cyprinids and salmonids of the same length [22], these results may be more broadly applicable. Nevertheless, species swimming traits and the different strategies to negotiate obstacles should always be considered [30,48,49]. Finally, configuration L150 S20, which displayed intermediate values of water velocity when compared to the other configurations tested, was the combination that recorded the best results for N and PE%, and registered also nearly 70% of AE%, a value that may be considered as a reasonable percentage for attraction. Taken together, these results may suggest that, upon designing ramped-weirs, configurations with the lowest slopes may not necessarily be the

best option, because they are less attractive for the fish and their demand for space is higher, thereby increasing construction costs. Conversely, as the present study shows, higher (but not excessive) slopes, though yielding a similar PE%, can be more attractive to fish, less expensive and, therefore, more cost-effective.

In conclusion, this study is in line with the outcomes of Baker [24] about the importance that L and S may have on the permeability of low-head ramped weirs for upstream movements of fish, both in terms of the attraction of fish to the ramp and especially regarding successful negotiation. However, the negotiation of ramped weirs by potamodromous fish species should be further investigated. Future studies should explore discharge variation and boulder placement, featuring different arrangements and geometries that influence fish passage across low-head ramped weirs, to further improve habitat connectivity. Thereby, the outcomes from the present work, complemented with future research pondering the above considerations, may significantly contribute to help engineers and biologists to design more appropriate passage structures for low-head instream obstacles.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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