PERFORMANCE OF A POTAMODROMOUS CYPRINID NEGOTIATING A SMALL WEIR

AMARAL, SUSANA D.
Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

BRANCO, PAULO
Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

SILVA, ANA T.
Norwegian Institute for Nature Research, P.O Box 5685 Sluppen, 7485 Trondheim, Norway
Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

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

VISEU, TERESA
Departamento de Hidráulica e Ambiente, Laboratório Nacional de Engenharia Civil, Avenida do Brasil 101, 1700-066 Lisboa, Portugal

FERREIRA, MARIA T.
Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

PINHEIRO, ANTÓNIO N.
CEris – Civil Engeneering for Research and Innovation for Sustainability, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais, 1049-001 Lisboa, Portugal

SANTOS, JOSÉ M.
Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

The presence of small man-made barriers like small weirs, far more numerous than dams, alters the river system and negatively affects fish communities, mainly by disturbing fish movements and hindering access to spawning, feeding and refuge locations. However, in contrast to the vast literature on dams, much less is known about the effects of small weirs on fish movements. This study aims to evaluate the upstream passage performance of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*), when encountering small weirs. A total of 16 experiments combining different plunge pool depths (D) with different waterfall heights (Δh) were carried out in an indoor channel. Flow patterns downstream of the weir were characterized with a 3C Acoustic Doppler Velocimeter, in an effort to understand fish behaviour when negotiating the weir. Results demonstrated that both variables and their interaction term (D×Δh) were significantly correlated with the number of successful fish passages (PerMANOVA, $p < 0.01$). Counter-intuitively, an increased number of passages did not occur at higher plunge pool depths in association with a lower waterfall height. Therefore, passage success appears to be a complex phenomenon where both variables interact to set the most effective hydraulic conditions for fish.

1 INTRODUCTION

River fragmentation has been cited as one of the most serious threats to the sustainability of fish populations [1; 2]. For several decades, the number of dams and small hydropower plants has increased along with the number of studies about catchment-scale impacts of such hydraulic structures on ecosystems [2, 3]. However, the impacts on the river system of small instream obstacles (weirs, culverts, and road crossings), which are far more numerous, have received much less attention [4, 5] as they are considered "small barriers" and "*a priori* permeable" to fish movements. Nevertheless, the presence of these barriers changes the hydraulic environment, altering water depth and water velocity patterns, and creates vertical drops that may partially or totally block fish migratory routes, restricting the dispersion of upstream movements to reach feeding, spawning and refuge habitats according to the different life stages needs [6]. Species particularly impacted are those that undergo considerable seasonal upstream migrations within river systems (potamodromy) [5].

This study aims to evaluate the upstream passage performance of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*), when facing an adjustable experimental small weir. According to the literature, plunge pool depth (D) and waterfall height (Δh) are key variables in determining the success of upstream passage by fish [7; 8; 9]. Iberian barbel was selected, since it is considered a representative of at least 8 species of medium-sized benthic potamodromous cyprinids in Iberia and Western Europe, counting the genera *Barbus* and *Luciobarbus* [10]. It was hypothesized that passage success would increase with the decreasing of waterfall height associated with increasing plunge pool depths.

2 MATERIAL AND METHODS

2.1 Experimental setup

The experiments were performed in an indoor experimental channel installed at the National Laboratory for Civil Engineering (LNEC), in Lisbon. The channel consists of a rectangular steel frame (10.0 m long × 1.0 m wide × 1.2 m high) with glass-viewing panels on sidewalls (allowing observation of fish movements within the flume), connected to an upstream chamber and a downstream tank that enable the entry of water in the flume and its recirculation, respectively. The channel was adjusted with a 3% slope, which was considered to be representative of most Iberian rivers. Flow discharge was maintained at 50 $L.s^{-1}$.

An experimental broad crested weir made of polypropylene modules, with a thickness of 20 cm and spanning the entire channel width, was installed in the flume 2.75 m upstream of a 1.0 m^2 acclimation area, created in the downstream zone of the flume by two fine mesh panels 1 m apart. A total of 16 combinations considering: i) four different plunge pool depths (D = 10, 20, 30, 50 cm), and ii) four waterfall heights (Δh = 5, 10, 15, 25 cm) were tested. Plunge pool depths below the weir were maintained by a slot gate located at the downstream tank of the channel, and waterfall heights tested were arranged by adding or removing modules from the weir, considering the total height of the experimental weir (weir height = D + Δh). Immediately downstream of the weir, an approach area of 0.65 m^2 was established in which fish movements were monitored by direct observation and recorded by one video camera (GoPro HERO3).

2.2 Fish experiments

A total of 320 Iberian barbel (mean total length ± SD = 18.7 ± 3.3 cm) were captured in the Lizandro River by wadable electrofishing (Hans Grassl IG-200). During the experiment, five electrofishing episodes were performed collecting around 70 fish per episode. Fish captured in each episode were transported to the laboratory facilities, where they were kept in filtered and aerated acclimation tanks (700 L tanks; Fluval Canister Filter FX5) for a maximum period of six days. Each fish was used only once and was randomly selected.

For each combination of D×Δh tested, 4 replicates were performed with schools of 5. 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 volitionally explore the channel for a maximum of 60 minutes. As downstream passage was permitted, fish were able to negotiate the weir several times. Records from direct observation included: number of fish that approached the weir (fish that entered in the approach area), number of passage attempts (fish that actively tried to negotiate the waterfall), number of upstream passage successes, maximum percentage of success (maximum number of fish that remained upstream the weir), and time taken by fish to successfully negotiate the weir.

Passage efficiency (quotient of number of passages per number of attempts) and attraction efficiency (quotient of number of attempts per number of approaches) were calculated from recorded data. For the statistical analysis, a distance-based MANOVA (PerMANOVA) based on Euclidean distance was performed to determine the influence of D, Δh, and D×Δh, on the number of passages.

2.3 Hydraulic measurements

Hydraulic conditions downstream of the weir were characterized with a 3D Acoustic Doppler Velocimeter (Vectrino ADV; Nortek AS) oriented downwards, perpendicular to the flume bottom. The 3 components of flow velocity (x, y, z) were measured in a total of 108 sampling points, selected according to the expected velocity field variation (36 sampling points carried out on 3 vertical measurement planes). According to requirements previously tested [10], data were acquired for a period of 180 s at a sampling rate of 25 Hz. Turbulence descriptors – turbulent kinetic energy (TKE), turbulence intensity (TI) and Reynolds shear stress (RSS), were calculated based on filtered data (despiking method modified by Wahl [11]) of instantaneous velocity (Vi).

3 RESULTS AND DISCUSSION

On average, 710 movement approaches and 183 attempts were recorded for all combinations of D×Δh, an indication that Iberian barbel were stimulated to pass the weir. All combinations of D×Δh tested were successfully negotiated by fish (Table 1). However, results from passage successes (N), passage efficiency (%PE), attraction efficiency (%AE), maximum percentage of success (%S), and time to negotiate the weir (T; min) were very different among combinations. The combination with the best results was D20Δh10, with 50 successful passages and high values of attraction efficiency (53%), passage efficiency (17%), and percentage of success (80%). On the other hand, D10Δh25 was the combination that presented the poorest results, with only one successful pass and low values of passage efficiency (1%) and percentage of success (20%). This combination actually registered the highest period of time until the first, and only, successful passage occurred (46 min). The combination D50Δh05, which was expected to have the highest number of successful passages due to the high plunge pool depth and the lower waterfall height to overcome, was ranked third with 25 successful weir negotiations. Values of attraction efficiency, passage efficiency, and percentage of success (27%, 13%, and 60%, respectively) were also lower compared with combination D20Δh10.

Table 1. Results from the 16 combinations of D×Δh tested.

	D10 Δh5	D10 Δh10	D10 Δh15	D10 Δh25	D20 Δh5	D20 Δh10	D20 Δh15	D20 Δh25	D30 Δh5	D30 Δh10	D30 Δh15	D30 Δh25	D50 Δh5	D50 Δh10	D50 Δh15	D50 Δh25
N	10	11	18	1	9	50	24	19	17	28	9	3	25	8	18	4
%PE	15	8	20	1	5	17	10	11	5	9	4	3	13	6	11	2
%AE	8	19	12	25	27	53	26	23	48	46	39	15	27	22	17	24
% S	60	40	80	20	40	80	60	40	40	60	20	20	60	20	40	20
T	33	29	15	46	22	15	17	33	15	24	24	13	24	20	9	26

Results of the PerMANOVA analysis on the number of successful fish movements corroborated the previous findings, showing significant effects of both D (F = 5.46; P = 0.004) and Δh (F = 4.68; P = 0.006), and their interaction term D×Δh (F = 3.02; P = 0.005). Pairwise comparisons for each factor indicated 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 depths. Similarly for waterfall height, the lowest number of successful movements was achieved upon using a Δh = 25 cm.

Graphic representation of the hydraulic conditions downstream the weir showed that there are differences between the combinations tested, that may explain the different observed passage successes (Figure 1).

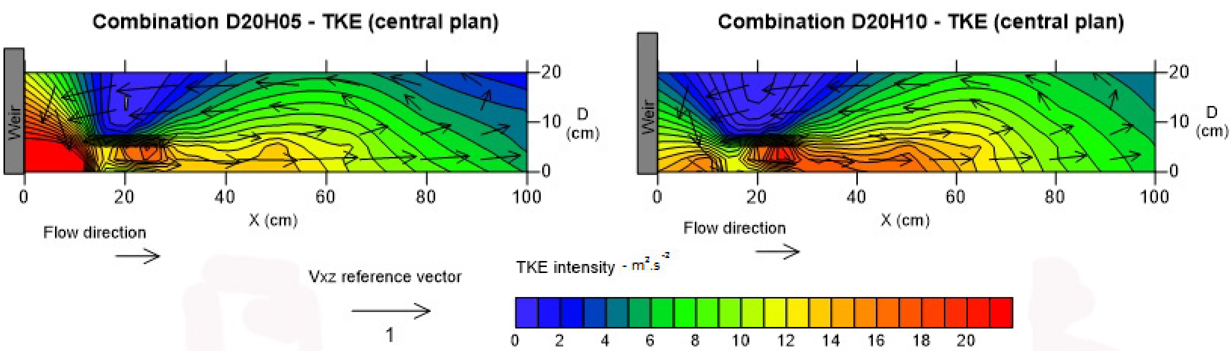

Figure 1. Graphical representation of turbulent kinetic energy (TKE) intensities and velocity vectors (Vxz) for two combinations tested. X is the distance from the weir (cm) and D is the water depth (cm).

4 CONCLUSIONS

Results from attraction efficiency, passage efficiency, and passage success enable us to conclude that both shallow plunge pool depths and high waterfall heights may restrict the successful passage of Iberian barbel. Furthermore, contrary to what was hypothesized, increased passage did not occur at higher plunge pool depths in association with a lower waterfall height, although combination D50Δh05 provided reasonable results. These results lead us to postulate that successful passage of small instream obstacles seems to be a more complex phenomenon where both variables, plunge pool depth and waterfall height, interact to set the most effective hydraulic conditions for fish.

As emphasized by Kondratieff and Myrick [8], these outcomes are useful to identify potential migration obstacles for fish, and especially to define design criteria for the requalification of small barriers to improve fish passage and consequently habitat connectivity.

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