EUROMECH Colloquium 523
Clermont-Ferrand, France, 15-17 June 2011
ISBN - 978-2-84516-529-8

Substrate density influences fish passage success in pool-type fishways

P. BRANCO[1], A. SILVA[1], J.M. SANTOS[1], T. FERREIRA[1]
T. VISEU[2], C. KATOPODIS[3] & A. PINHEIRO[4]

ABSTRACT. Several authors state that heterogeneity on the bottom of fishways (logs, boulders or stones) may potentiate fish passage. The aim of this work is to study the behaviour and performance of the Iberian barbel (*Luciobarbus bocagei*) in a full-scale experimental pool-type fishway with different bottom substrata arrangements. Water velocity and Reynold's shear stress (RSS) were used as independent hydraulic variables and related to fish swimming behaviour. Results show that, hydraulically, boulders seem to favour fish, by reducing water velocities and RSS. Fish responded with greater success to higher discharges (Q) independently of substrate density. Density proved to be important only for low discharges, where low density yielded better results. These findings express that substrata placed at the bottom of fishways may potentiate fish negotiation of such devices. With low discharges care must be taken to accommodate substrates in low density arrangements.

KEYWORDS: *Pool-type fishway, substrate density, boulders, potamodromous fish, cyprinids, vectrino, connectivity.*

1. Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade Técnica de Lisboa.
2. Departamento de Hidráulica e Ambiente, Laboratório Nacional de Engenharia Civil, Lisboa.
3. Katopodis Ecohydraulics Ltd., Winnipeg, Manitoba, Canada.
4. Departamento de Engenharia Civil, Instituto Superior Técnico, Universidade Técnica de Lisboa.

1. Introduction

Connectivity, or more correctly isolation, is considered one of the primary factors influencing the distribution of species (MacArthur & Wilson, 1967), especially in riverine environments, where a single barrier isolates contiguous segments of river (Jager *et al.*, 2001). Numerous studies have documented dramatic changes in the persistence and abundance of fish populations as a result of human-induced disturbances, particularly dam construction (Marmulla, 2001). Dams and weirs can block or delay fish movements and are responsible for the decline or extirpation of many native species throughout Europe (Mader & Maier, 2008). The fragmentation of the river continuum by such obstacles negatively affects fish populations by increasing loss of genetic variability and risk of extinction through demographic, environmental and genetic stochasticity (Nicola *et al.*, 1996; Peňáz *et al.*, 1999).

Migratory fish are particularly sensitive to connectivity loss caused by habitat fragmentation as their ability to reach spawning grounds is seriously affected. Although diadromous fish are amongst the most studied fish species concerning the impacts of man-made structures on the persistence and abundance of their populations, much less is known on the migratory ecology of potamodromous cyprinids (Lucas & Batley, 1997) and on their behaviour in the vicinity and within fishways.

The re-establishment of a systems' longitudinal connectivity is essential for accomplishing the main goal of the WFD (European Commission, 2000). The most common way to circumvent an obstacle, and to mitigate its impacts, is to implant a fish passage device. However, a great number of these facilities are not suited for most native cyprinids, since they were built based on guidelines created for salmonids (*e.g.* Pinheiro & Ferreira, 2001) which have movement and jumping abilities quite different from those of non-salmonid fish. There is the need to determine optimum dimensioning values and hydraulic parameters for native freshwater species with different morphological and ecological characteristics. Several authors (*e.g.* Hinch & Rand, 2000; FAO/DVWK, 2002; Baker & Boubée, 2003) state that the inclusion of heterogeneity through the use of structures like logs, boulders or stones at the base of fish passes may potentiate fish negotiation of such devices.

The purpose of this work is to study the behaviour and performance of a potamodromous species, the Iberian barbel (*Luciobarbus bocagei*) in a full-scale indoor model of a pool-type fishway with different bottom substrate arrangements and variable discharges.

2. Materials and methods

2.1. Experimental model

The study was conducted in a full scale experimental pool-type fishway. The model is composed of a steal frame with lateral acrylic glass panels, allowing a simple visualization of the processes occurring within the fishway. The flume is composed by six pools (1,9 m long x 1 m wide x 1.2 m wide) divided by compact polypropylene crosswalls with bottom orifices of variable area. The channel was set with an 8.5% slope creating a constant head drop between pools of 16.2cm. Bottom orifices were placed in an off-set pattern.

2.2. Experiments

Four different configurations (Table 1) were tested by changing the discharge (Q) of the fishway and substrate density changed by placing bottom substrates (boulders - 15 cm x 15 cm x 10 cm high) at different densities (high and low). The boulders were positioned in five even spaced lines in symmetrical arrangements (Figure 1), and oriented according to the prevailing flow pattern to reduce recirculation behind the boulders. Low density configurations were obtained by removing one third of the boulders, and by turning high boulder density lines into low density lines.

For each configuration 20 Iberian barbel (*Luciobarbus bocagei*) were studied individually. The fish were collected on the field, during the migration season, following electrofishing protocols. Fish were stabilized in acclimation tanks (800 L) for at least 48h before they were tested. Feeding stopped 24h prior to the experiment. Each experiment had a maximum duration of 90 minutes ending as soon as the fish successfully negotiated the boulder pool. Two independent observers and two video cameras (top and side view) registered the fish movements within the substrate pool. Fish transit times were also recorded: *Entrance time* - time span since the beginning of the test until the successful entrance of the fish in the substrate pool; *Negotiation time* - time span between the beginning of the experiment to the successful negotiation of the substrate pool.

Water velocity was measured, in its three components (x, y and z), with a Vectrino 3D ADV (Nortek AS) oriented downwards. Measurements were taken at a rate of 25 Hz for a period of 90s. A mesh of sampling points was created to cover the entire pool and velocity measurements were performed at two horizontal planes parallel to the flume bed (boulders mid height and 25% of pool mean depth (*h*m)). Velocity measures were also taken for both flow discharges, at 25% of *h*m, in a situation of smooth bottom (*ie* without substrates – control treatment). Instantaneous measures of velocity were filtered using the Goring & Nicora (2002), modified by Wahl (2003), phase-space threshold despiking. Reynold's shear stress (RSS) was calculated for the horizontal plane xy, using the following formula:

$$-\rho\,\overline{u'v'} \qquad (1)$$

where ρ = fluid density, u' = fluctuating component of the velocity in the x direction, and v' = fluctuating component of the velocity in the y direction.

Table 1. Description of the four tested configurations. Conf. – configuration; Q – flow discharge; A_o – area of the orifice; *h*m – pool mean depth; P_v – volumetric power dissipation

Conf.	Q ($L.s^{-1}$)	A_o (m^2)	Boulder density	*h*m (m)	P_v ($W.m^{-3}$)
A1	62.7	0.053	High*	0.84	62.37
A2	62.7	0.053	Low**	0.84	62.37
B1	38.5	0.032	High	0.88	36.56
B2	38.5	0.032	Low	0.88	36.56

* 12 boulders; **8 boulders

3. Results

3.1. Hydraulics

The Figure 1 shows the velocity contours of the horizontal plane (xy) at 25% of *h*m. There is a clear decrease in water velocity (Kruskal-Wallis ANOVA: $A_{(configurations)}$ – H = 2.66, d.f. = 2, N = 224, p = 0.0001; $B_{(configurations)}$ – H = 29.43, d.f. = 2, N = 214, p = 0.0001) and flow pattern alterations between the control treatments and the tested configurations. The same happens with RSS values (Kruskal-Wallis ANOVA: $A_{(configurations)}$ – H = 10.72, d.f. = 2, N = 224, p = 0.005; $B_{(configurations)}$ – H = 14.32, d.f. = 2, N = 214, p = 0.0008). For the same discharge, water velocity and RSS do not vary significantly between high and low boulder density (Mann-Whitney U Test: A – N1 = 88, N2 = 88, Vxy-p = 0.955, RSS-p = 0.418; B –N1 = 83, N2 = 83, Vxy-p = 0.054, RSS-p = 0.566). In control treatments (smooth bottom) the flow pattern was characterized by a jet stream close to the side-wall adjacent to the orifice and a recirculation zone from the jet stream to the opposite side-wall. Velocity vectors and contours show that boulders homogenized water velocity in the planes above the substrate, creating a large circulation region, occupying the whole pool area. The flow pattern at boulders mid height was drastically altered for the configuration with high density of boulders. Because, flow was diverged, by the two boulders in front of the orifice, in a way that the jet stream was interrupted and velocities decreased. There was also a detectable transformation in flow direction, with small recirculation patterns near each boulder.

3.2. Fish

A total of 80 fish were tested on the four considered configurations. Table 2 summarizes the time results of the experiments. Transit times traduced significant differences among configurations (Entrance time - Kruskal-Wallis ANOVA d.f. = 3, N = 31, p = 0.0205; Negotiation time Kruskal-Wallis ANOVA - d.f. = 3, N = 31, p = 0.008). B1 was the configuration with the lowest transit times, and configuration B2 was its counterpart by having the higher transit times. Fish negotiation of the fishway had a higher success rate in both configurations with the higher discharge (A1 and A2) independently of boulder density. In terms of density, there were only noticeable differences for the low discharge situation, where B2 had a higher success rate than B1.

Table 2. Summary table of the mean values of the fish transit times in the four tested configurations. The rate of successful negotiations is also presented. Conf. - configuration.

Conf.	Entrance time (min)	Negotiation time (min)	Rate of success (%)
A1	41.4 ± 17.5	55.9 ± 17.3	0.45
A2	32.2 ± 14.2	47.1 ± 15.8	0.45
B1	22.8 ± 20.5	32.4 ± 17.2	0.25
B2	56 ± 17.3	71.9 ± 19.3	0.4

4. Discussion

This study allowed a laboratory test of the behaviour of *L. bocagei* within a pool-type fishway with varying boulder density and flow discharge configurations. Studies on fish transposition devices often lack balanced experimental designs, in which, contrarily to those conducted in the wild, the variables of interest can be manipulated while controlling for confounding effects (Kondratieff & Myrick, 2005).

The results show that boulders had a significant effect in reducing water velocity and RSS. These substrates alter the flow pattern and homogenize the upper portions of the pool by turning the area above the substrates into a circulation area without jet streams and by reducing RSS values. This creates a less turbulent flow with less eddy formation and annulling fish disorientation phenomena (Odeh *et al.*, 2002). Bottom heterogeneity transforms

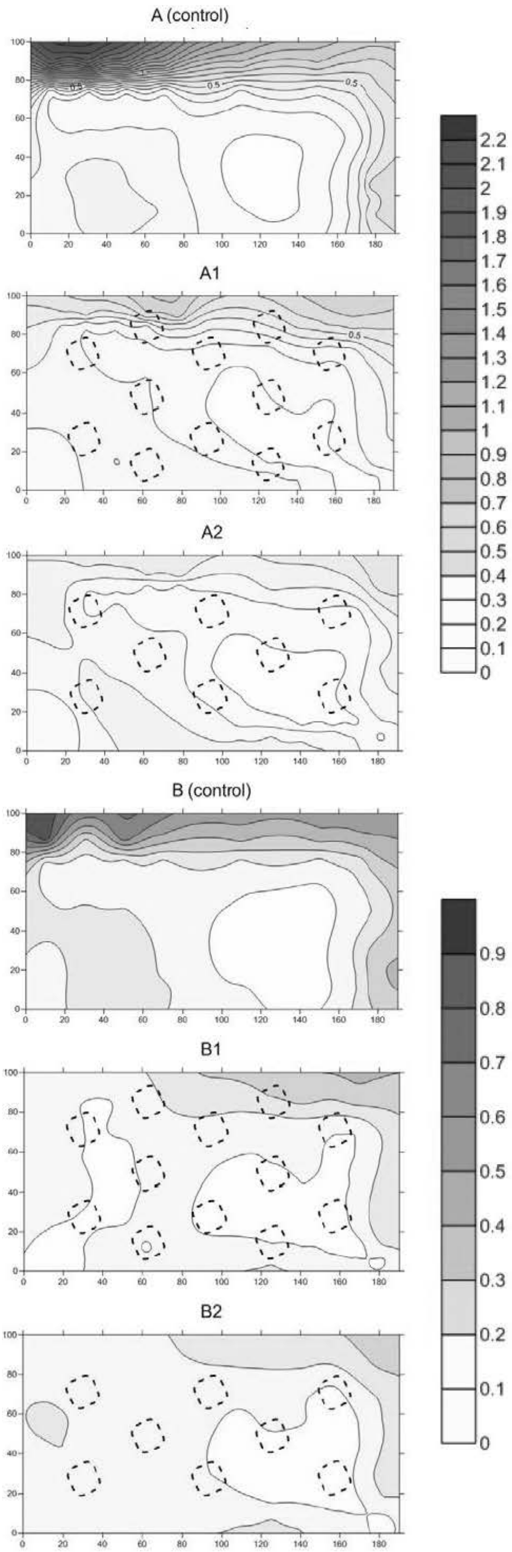

Figure 1. Velocity (m s^{-1}) contours of the xy plane, measured at 25% pool mean depth (*h*m), in the four tested configurations and in "control" situations without substrates. Dotted squares represent the boulders and show their position and alignment. Flow enters the pool at the top left corner of the diagram.

the pool into a more agreeable environment for fish. Which can have a veiled effect - increase of recirculation areas allied with decrease of water velocity can produce an ecological trap, increasing transit times by removing the migratory cue that uses water velocity to orientate potamodromous fish upwards (Tarrade *et al.*, 2008). Hydraulically, there were no statistical differences, in water velocities between low and high boulder density for the same flow discharge. So, while there are clear differences between a smooth bottom and a heterogeneous bottom, there are no differences between degrees of bottom heterogeneity.

Fish results show that high discharge configurations (A1 and A2) have higher rate of successful negotiation of the boulders pool. This occurred primarily due to the greater attractiveness promoted by the discharge in these configurations. When looking at boulder density, differences can only be found for the low discharge situation where B2 had clearly a higher success rate than B1. Boulders create recirculation patterns near the bottom that might have movement implications for fish, especially for benthic species. Fewer boulders create less recirculation and eddy formation, increasing fishway negotiation.

This work demonstrates that boulder placement on the bottom of fishways creates a better pool environment for fish species, while turning the fishway into a nature-mimicking structure. To achieve higher negotiation success, discharges have to be tendentially higher than the ones tested here. If, by water constrains, fishway discharges should be lower, boulders should be placed in a low density arrangement in order to potentiate fish passage.

This was the first study where different densities allied with different flow discharges were tested with fish. Future works should be focused on testing higher discharges associated with boulders; and fish species with different uses of the water column. Another important issue, that should be studied, is the bottom fine heterogeneity – probably beneficial for benthic species due to the increase in friction forces.

References

Baker, C. & Boubée, J., 2003. Using ramps for fish passage past small barriers. Water & Atmosphere, 11(2): 12-13.

European Commission, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for the Community action in the field of water policy. Official Journal of the European Commission - Legis. 327: 1-72.

FAO/DVWK, 2002. Fish Passes – Design, Dimensions and Monitoring. FAO, Rome.

Goring, D.G. & Nikora, V.I., 2002. Despiking acoustic Doppler velocimeter data. J. Hydraul. Eng., 128: 117-126.

Hinch, S.G. & Rand, P.S., 2000. Optimal swimming speeds and forward-assisted propulsion: energyconserving behaviours of upriver-migrating adult salmon. Canadian Journal of Fisheries and Aquatic Sciences, 57: 2470-2478.

Jager, H.I., Chandler, J.A., Lepla, K.B., Winkle, W.V., 2001. A theoretical study of river fragmentation by dams and its effects on white sturgeon populations. Environmental Biology of Fishes 60: 347-361.

Kondratieff, M.C. & Myrick, C.A., 2005. Two adjustable waterfalls for evaluating fish jumping performance. Transactions of the American Fisheries Society, 134(2): 503–508.

Lucas, M.C. & Batley, E., 1997. Seasonal movements and behaviour of adult barbel *Barbus bocagei*, a riverine cyprinid fish: implications for river management. Journal of Applied Ecology, 33: 1345-1358.

MacArthur, R.H. & Wilson, E.O., 1967. The Theory of Island Biogeography. Princeton University Press: Princeton, NJ.

Mader, H. & Maier, C., 2008. A method for prioritizing the restablishment of river continuity in Austrian rivers. Hydrobiologia, 609: 277-288.

Marmulla, G., 2001. Dams, fish and fisheries. Opportunities, challenges and conflict resolution. FAO Fisheries Technical Paper, No. 419. Rome, FAO: 166 p.

Nicola, G.G., Elvira, B., Almodóvar, A., 1996. Dams and fish passage facilities in the large rivers of Spain: effects on migratory species.Archive fur Hydrobiloguie (Suppl. 113) Large Rivers, 10: 375-379.

Odeh, M, Noreika, JF, Haro, A, Maynard, A, Castro-Santos, T., 2002. Evaluation of the effects of turbulence on the behavior of migratory fish. Final Report to the Bonneville Power Administration, Contract 00000022, Project 200005700, Portland, Oregon.

Peňáz, M., Baruš, V., Prokeš, M. 1999. Changes in the structure of fish assemblages in a river used for energy production. Regulated Rivers: Research and Management, 15: 169-180.

Pinheiro, A. & Ferreira, T., 2001. Portuguese fish ladders operating conditions: an overview. XXIV IAHR Congress, Beijing: 377-383.

Tarrade, L., Texier, A., David, L., Larinier, M., 2008. Topologies and measurements of turbulent flow in vertical slot fishways. Hydrobiologia, 609: 177-188.

Wahl, T.L., 2003. Discussion of "Despiking Acoustic Doppler Velocimeter Data". Journal of Hydraulic Engineering, Vol. 129, No. 6.