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Vertical slot versus submerged notch with bottom orifice: Looking for the best technical fishway type for Mediterranean barbels

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ABSTRACT

When engineers and ecologists face a fishway design, many issues need to be considered, the type of fishway being the first and foremost. It is an especially complex issue in areas with species whose migratory and swimming behavior are as yet poorly known as Mediterranean barbels. The present study focuses on the fish passage of two of the most common types of technical fishways: Vertical Slot (VS), and Submerged Notch with Bottom Orifice (SNBO). Both types were studied and compared in terms of ascent ability (as the success rate and transit time) and motivation (as the proportion of attempts and attempt rate), with Iberian barbel (*Luciobarbus bocagei*) as the target species.

Ascent ability in VS and SNBO were similar. More than 90% of fish ascended the fishways successfully and the median transit time to ascend a total water height of 2.25 m was less than 23 min. Fish length had an effect on ascent time, with the biggest ones being faster. Motivation was greater for VS, although not seeming to have a relevant influence in the passage.

These results support the use of VS and SNBO in areas with Iberian barbel and provide new data of fishways performance helping ecologists and engineers with their decision making, mainly in Mediterranean areas with similar habitats and species.

1. Introduction

Man-made transverse structures in the rivers (dams, weirs, gauging stations, culverts, and others) have been increasingly used in recent decades worldwide, fragmenting riverine fish populations (Baudoin et al., 2014). At the same time, there is progressively more knowledge and environmental awareness about the necessity for free movement of ichthyofauna along watercourses in order to complete their lifecycles. Moreover, the Water Framework Directive points to the need for undisturbed migration of fish species as a key component of watershed restoration.

In the case of the circum-Mediterranean region, barriers to movement are among the principal threats affecting endemic potamodromous fish (Doadrio, 2011; Smith and Darwall, 2006; Vila-Gispert et al., 2005). Mediterranean fish fauna is mainly composed by cyprinids species and barbels (genus *Barbus* and *Luciobarbus*) are one of the most widely distributed and abundant (Doadrio et al., 2002; Kottelat and Freyhof, 2007; Tsigenopoulos and Berrebi, 2000). They occupy a variety of riverine habitats, ranging from floodplains to headwaters, and play an important role in trophic interactions within their ecosystems (Collares-Pereira et al., 1996; Kottelat and Freyhof, 2007). Like other potamodromous cyprinids, barbels usually ascend to headwaters in spring for spawning.

Many fish passage solutions have been designed in recent years to improve longitudinal connectivity in this region. Technical stepped fishways have been the most popular designs worldwide (FAO/DVWK, 2002) and even in Mediterranean areas (Elvira et al., 1998; Santos et al., 2012), used first in salmonid zones and in cyprinid reaches since the last century. Vertical slot fishways (VS) and submerged notch with bottom orifice fishways (SNBO) are very common types. For instance, in the Spanish Duero River basin, the largest basin of the Iberian Peninsula, about 60 fishways of these types have been built the last

Abbreviations: VS, Vertical Slot; SNBO, Submerged Notch with Bottom Orifice; VED, Volumetric Energy Dissipation

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decade and more than 100 have been designed (and several of them have been built) in the rest of the country (own data).

Both types are designed following the optimal criteria recommended by FAO/DVWK (2002) and Larinier (2002) for cyprinids. They are standardized for a discharge of about 0.25–0.30 m^3/s and a Volumetric Energy Dissipation (VED; energy generated due to the water drop between pools that is dissipated in the volume of water of each pool) lower than 150 W/m^3 (CHD, 2016), not having important differences in building costs per unit of height between them (Sanz Ronda et al., 2013). There are many references about the hydraulic performance and design of VS and SNBO fishways (Clay, 1994; Fuentes-Pérez et al., 2016, 2014; Larinier, 2002). In general, VS tolerate major variations in the upstream water levels and they allow fish movements at any depth. However, for large migrators (> 60 cm), they can only be used where a significant flow is available (> 0.70 m^3/s) because of the minimum slot dimensions required for such fish, and pool depth for low flows is not often suitable. On the other hand, SNBO accept a wide range of design flow discharge (several tens of L/s to several m^3/s), ensure a minimum depth in the pool and, if the notches are deep enough, they accommodate relatively significant upstream water level variations. The bottom orifice allows benthic fish passage, but depending on its dimensions, it could be easily clogged by debris (DVWK, 2002; Larinier, 2002).

Fish passage assessment of VS and SNBO are scarce (Aparicio et al., 2012; Bravo-Córdoba et al., 2018; Ordeix et al., 2011; Sanz-Ronda et al., 2016) and non exist comparing the two. The characteristics of Mediterranean rivers including seasonal and annual flow variation and the ichthyofauna which includes a high number of endemic and endangered species emphasize the importance of fish passage assessments. This means an added difficulty for engineers and biologists when choosing the best fishway option.

Fishway overall efficiency must be assessed considering fish attraction to the device, their entry and passage into it and also the exit (Castro-Santos and Haro, 2010; Valbuena-Castro et al., 2017). Attraction and entrance are mostly influenced by the presence of attraction flows close to the fishway and its location in the river/weir complex (DVWK, 2002; Larinier, 2002), and the main factor influencing fish passage is the proper typology of the fishway (Bunt et al., 2012).

Therefore, the purpose of this paper is to evaluate and compare the passage of Mediterranean barbels facing two of the most common technical stepped fishway types: VS and SNBO, with a theoretical optimal design and similar VED, discharge and building cost. Iberian barbel (*Luciobarbus bocagei*, Steindachner) was considered as target species due to its broad distribution and similarities with several potamodromous barbels from the Mediterranean area (Branco et al., 2017). Its passage performance was measured attending to ascent motivation, ascent time and passage success in field conditions. The aim of this paper is to aid engineering design, implementation and management decisions in many Mediterranean watercourses with similar species.

2. Materials and methods

2.1. Study site and fishways

The experiments were carried out in two fishways at the Vadocondes (VS) and Guma (SNBO) hydropower plants; 41°38′16.1″N 3°34′18.1″W; 41°38′13.5″N 3°32′37.2″W; (Fig. 1). Both are located on the main course of Duero River, Castilla y León region, province of Burgos in north-central Spain, they are spaced by about 3.5 km, sharing the same environmental characteristics (flow discharge, substrate, vegetation and fish population) and operate in synchronized mode. At these locations, the river drains a watershed of approximately 7400 km^2 with a mean annual discharge of 17.5 m^3/s (data from the Vadocondes gauging station, code: 2522; www.saihduero.es). This river reach belongs to the epipotamon area with an average altitude of around 810 m above sea level. The zone corresponds to category C6, i.e. a silt-clay bed stream of moderate sinuosity with a slope of 0.001–0.02 m/m (Rosgen and Silvey, 1996). The most abundant native fish species is the Iberian barbel, also having presence Northern straight-mouth nase (*Pseudochondrostoma duriense)* and Northern Iberian chub (*Squalius carolitertii)*.

Both fishways are the standard type of fishways most frequently built at the Duero river basin and they comply with the (existing) recommendations for these species (FAO/DVWK, 2002; Larinier, 2002) (Table 1; design details). Their bottoms were covered by substrate from the riverbed to increase roughness, and discharge can be regulated by a sluice gate located in the flow entrance. At each fishway, a section with the same head of 2.25 m was selected for fish ascending tests (difference between the headwater level and tailwater level).

Drop between pools is higher in SNBO than in VS. Recommendations on FAO/DVWK (2002) for Cyprinids: 0.2–0.25 m in SNBO vs. 0.15–0.2 m in VS, but water velocity at the slot is higher than the notch for the same drop, due to the lower coefficient of discharge (Fuentes-Pérez et al., 2016, 2014).

SNBO is steeper than the VS, although pool dimensions are larger, meaning a similar workload and economic cost, for the same VED and discharge (Sanz Ronda et al., 2013).

2.2. Fish testing

The test was carried out during the spawning season (between 2nd and 7th June 2012), when barbels seemingly exhibit strong migratory activity in this area. Experimental fish for all trials were captured by electrofishing (Erreka Model; DC 300 V) one day prior to testing in a river branch of the same stretch of Duero River, less than 5 km downstream of both fishways location. Within 2 h after capture, fish were transported to the corresponding fishway in 100 L aerated tanks and then held in an acclimation tank (staging pools, Fig. 2) at ambient temperatures. This tank consisted of two consecutive fish ladder ponds. They were supplied with water (50 L/s) directly from the river. All fish were anaesthetized (solution of 0.20 g/L MS-222), measured (mass and fork length) and Passive Integrated Transponder-tagged intraperitoneally by an incision posterior to the left pectoral fin (Castro-Santos and Vono, 2013). These tags measured 23 mm long by 3.85 mm diameter, and weighed 0.6 g (< 2% of the body weight of the smallest tagged fish) (Half-duplex tags, TIRIS model RI-TRP-WRHP). This method has been shown to have negligible effects on growth, survival, and behavior of many species (Ostrand et al., 2011). Fish were not fed during experiments, although the river water that supplied the experiment contained numerous food items that fish could eat.

2.3. Trials

Fish were confined in a fishway section and released in the most downstream pool at least 12 h for acclimation (staging pool, Fig. 2). We used a PIT-tag antenna system (pass-through antennas) to study fish movements during the ascent. Antennas were placed at slots in VS, and notches and orifices in SNBO, covering in both cases the same head = 2.25 m (Fig. 2). Each antenna was connected to a dedicated reader (ORFID® Half Duplex multiplexer reader), programmed to query the antennas at 14 Hz (3.5 Hz or 0.29 s per antenna). Two multiplexer readers were used in all tests, both being synchronized to avoid cross-talking phenomenon.

In both fishways, just before each trial started, the flow gate was opened to achieve the desired water level into the pools. It corresponds with the design flow for optimum theoretical operation during the spawning period with the discharge and VED similar for both fishways. Once established, a mesh placed at the upstream end of the staging area was removed and fish were allowed to ascend the fishway volitionally. Two homogenous groups of barbel per fishway did so, each trial lasting 24 h, and taking part in both fishways each group of barbel (Table 2).