*Article*

# Fish upstream passage through gauging stations. Experiences with Iberian barbel in flat-V weirs

**Francisco Javier Sanz-Ronda[1,*], Francisco Javier Bravo-Córdoba[2], Ana García-Vega[2], Jorge Valbuena-Castro[1], Andrés Martínez-de-Azagra[1], and, Juan Francisco Fuentes-Pérez[1]**

[1]  GEA Ecohidráulica, Department of Agriculture and Forestry Engineering, ETSIIAA, University of Valladolid, Palencia, Spain; jsanz@uva.es; Jorge.valbuena@uva.es; amap@uva.es; juanfrancisco.fuentes@uva.es

[2]  Centro Tecnológico Agrario y Agroalimentario Itagra.ct, Palencia, Spain; agarvega@itagra.com, fjbravo@itagra.com

*   Correspondence: jsanz@uva.es

**Abstract:** The monitoring of river discharge is vital for the correct management of water resources. A worldwide facility used for measuring discharge are flat-V gauging weirs. These structures consist of a small weir, with a triangular cross-section and a flat "V"-shaped notch. Their extensive use is a consequence of their utility in the measurement of both low and high flow conditions. However, depending on their size, local morphology and river discharge can act as full or partial hydraulic barriers to fish migration. To give answer to this question, the present work studies fish passage performance over flat-V weirs considering their hydraulic performance. For this, radio-tracking and video monitoring observations were combined with computational fluid dynamics (CFD) models in two flat-V weirs, using Iberian barbel (*Luciobarbus bocagei*) as target species. Results show that fish passage is conditioned by both hydraulic and behavioral processes, providing evidences about the scenarios where flat-V weirs may act as full or partial barriers to upstream movements. For the studied flat-V weirs, a discharge range of 0.27-8 $m^3$/s, with a water drop difference between upstream and downstream water levels lower than 0.7 m and a depth downstream the weir higher than 0.30 m can be considered as an effective passage situation for barbels. These findings are of interest to quantify flat-V weir impacts, for engineering applications and to establish managing or retrofitting actions when required.

**Keywords:** gauging weirs; impact; swimming performance; hydraulic barriers

## 1. Introduction

Gauging stations are structures that measure and record water levels in rivers or canals relating them to stream discharge [1]. They are usually managed by public institutions and act as a crucial river monitoring network with openly and real-time accessible data to ensure human safety (flood and drought control), provide correct management of water resources (for domestic, industrial, and agricultural supply), to design and plan river-related engineering projects or to monitor environmental flows [2,3].

One of the most extended facilities for estimation of the river discharge is the use of gauging weirs [1]. They consist of well-known hydraulic control structures, that make discharge estimation possible by means of discharge-water level relationships [3], together with a monitoring system to record and transmit water level (or discharge after transformation) data. Gauging weirs can be classified into three main types of structures [2]: 1) sharp-crested or thin-plate weirs (e.g., rectangular, trapezoidal, V-notch), 2) broad-crested weirs (e.g. rectangular, triangular) and 3) short-crested weirs (e.g. triangular profile, nappe-profile spillways). The first group of weirs is recommended in small and

low carrying debris streams, when accuracy is desired and maintenance is possible, while the second and third groups are preferred for larger streams and rougher conditions [4].

A commonly worldwide used gauging weir alternative is that consisting of a short crested triangular profile weir, or commonly named as flat-V or V-Crump weirs [1,5,6]. These gauging stations consist of a small weir, with a triangular cross-section (upstream slope of 1:2 - vertical:horizontal - and downstream 1:5) and an open or flat "V"-shaped notch (side slopes of 1:10 or 1:20) (ISO Standard 4377:2012) (**Figure 1**). Its extensive use is justified by its geometry, which allows measuring precisely a wide range of water levels and discharge. During low discharge events, a V-shape can maintain an acceptable depth upstream for the water level logging system [7]; meanwhile, during high discharge events, it provides a wide opening, that together with the water acceleration produced in its downstream face, limits the backwatering effect in the upstream water level. That capacity of handling a broad range of discharges justifies the widely use   of this type of structure in Spain since the 1990s [6], usually in the range of 1 to 25 m$^3$/s. For instance, in the Spanish side of the Duero River basin (78,952 km$^2$, the largest Iberian river) there are 167 gauging stations, 40 of which have gauging weirs and where 28 of these gauging weirs are flat-V types (http://www.saihduero.es/, accessed on 28/10/21).



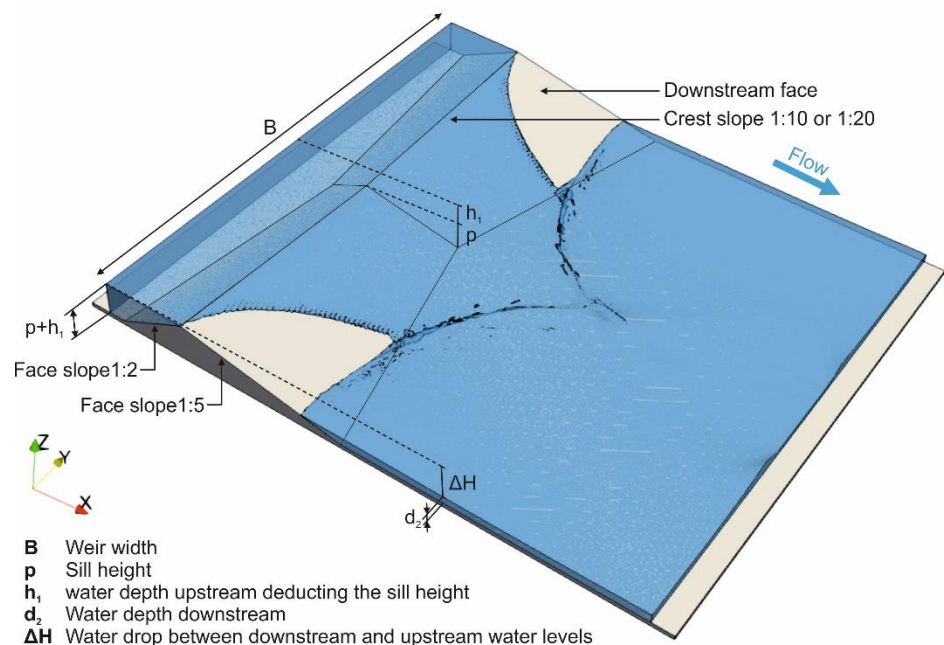| | |
|---|---|
| **B** | Weir width |
| **p** | Sill height |
| **$h_1$** | water depth upstream deducting the sill height |
| **$d_2$** | Water depth downstream |
| **$\Delta H$** | Water drop between downstream and upstream water levels |

**Figure 1.** Flat-V weir and its main geometrical parameters. Check ISO Standard 4377:2012 for a broader geometrical description.

Despite the great social usefulness of river monitoring, gauging stations can have a negative effect on upstream fish passage, since they can act as full or partial physical barriers (i.e. a direct obstruction) or hydraulic barriers (i.e. triggering hydraulic parameters outside the swimming limits of fish) [8–10]. Fish ascent through gauging weirs depends on fish swimming and leaping ability, motivation, the type and size of the weir, and the flow conditions [11–13]. In the case of those stations consisting of flat-V weirs, some discharge rates can produce excessive velocities and low depths conditions over the downstream face, which may constitute a hydraulic barrier for fish. Additionally, they may generate a hydraulic jump downstream (i.e. a rapid and short spaced change from supercritical to subcritical velocity [14]) which produces a high turbulent environment in the center together with large eddies on both sides, which may disorient fish [12,15]. In the worst-case scenario, the installation of a gauging station can cause a scouring process downstream of the weir (**Figure 2**), generating a water drop (physical barrier) and directly reducing the downstream water depth ($d_2$). This enlarges the area with high velocities and low depths (hydraulic barrier) below the weir [11], reducing even more the fish passage

probability. Furthermore, weirs can act as selective barriers since the swimming and leaping ability of fish are directly related to the fish size and morphology, which may have further implications in the behavioral and dispersal processes of fish populations [16,17].
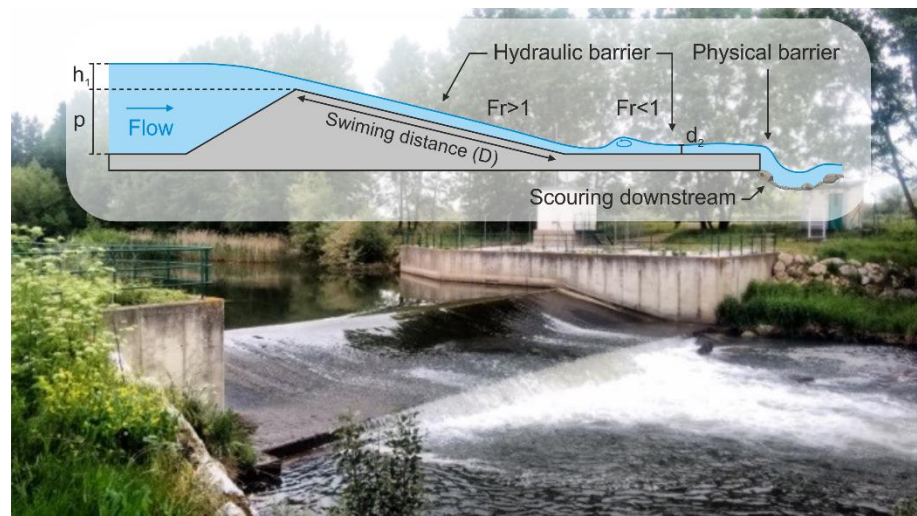


**Figure 2.** Gauging station with a flat-V weir with scouring problems (Carrión River, Villoldo, Palencia), together with a sketch showing the main problems for the fish ascent. Fr stands for Froude number. See **Figure 1** for variable description.

Habitat fragmentation caused by river barriers is among the main causes of the global decline in freshwater biodiversity [18]. River connectivity is an essential requirement for the effective functioning of freshwater ecosystems and for allowing fish to complete their life cycles [19]. River connectivity is particularly important for Iberian fish fauna, as they are adapted to severe hydrological variability and they require to move along the river systems seasonally for reproduction, feeding, and thermal refuge searching [20–23].

One of the most representative species of the Iberian fish fauna is the Iberian barbel (*Luciobarbus bocagei* Steindachner 1864). This endemic species has a broad distribution over the Iberian Peninsula and it shares similarities with several potamodromous barbels from the Mediterranean area [24]. Barbels are rheophilic cyprinids [25] that display migratory behavior with reproductive and overwinter movements from spring to late autumn [23,26] and play an important role in trophic interactions within their ecosystems [27,28]. Therefore, it is vital to determine which gauging stations, and under which hydraulic scenarios, act as barriers to fish movements, to propose management strategies and retrofitting actions when required, to ensure fish conservation.

Considering the above, this study aims to (1) analyze the upstream passage performance of Iberian barbel through flat-V gauging weirs depending on hydraulic conditions, (2) identify ascent paths and describe fish behavior during these movements and (3) define a range of effective hydraulic conditions for maximizing the upstream passage. To achieve this, radio-tracking and video monitoring observations are combined with computational fluid dynamics (CFD) models in two flat-V weirs, relating results with hydraulic conditions. Among other results, this work highlights the scenarios on which flat-V gauging weirs can act as a barrier for fish upstream migration, establishing recommendations to design fish-friendly flat-V gauging weirs.

## 2. Materials and Methods

### 2.1. Study sites

The experiments were carried out in two flat-V gauging weirs located in the Duero River basin (northwest of Iberian Peninsula): Bercimuelle weir in the Tormes River (ETRS 89, 40° 30′ 9′′ N; 5° 31′ 51′′ W; Bercimuelle, Salamanca) and Palencia weir in the Carrión River (ETRS 89, 42° 2′ 12′′ N; 4° 32′ 30′′ W; Palencia, Palencia) (**Figure 3**a). Both weirs were

constructed as a part of the SAIH Duero project (Hydrological Information and Alert Service of the Spanish Duero Basin Water Authority), following the standard ISO 4377:2012 design guidelines. Bercimuelle is a p=0.5 m height and B=12 m width weir, with an end-sill of 0.2 m high at the end of the downstream horizontal apron and a ≈0.4 m water drop formed later by a scouring process (Figure 2); while Palencia's weir is p=0.7 m and B=25 m and there is a hydraulic control structure 50 m downstream which influences the base of the gauging weir (backwatering effect).
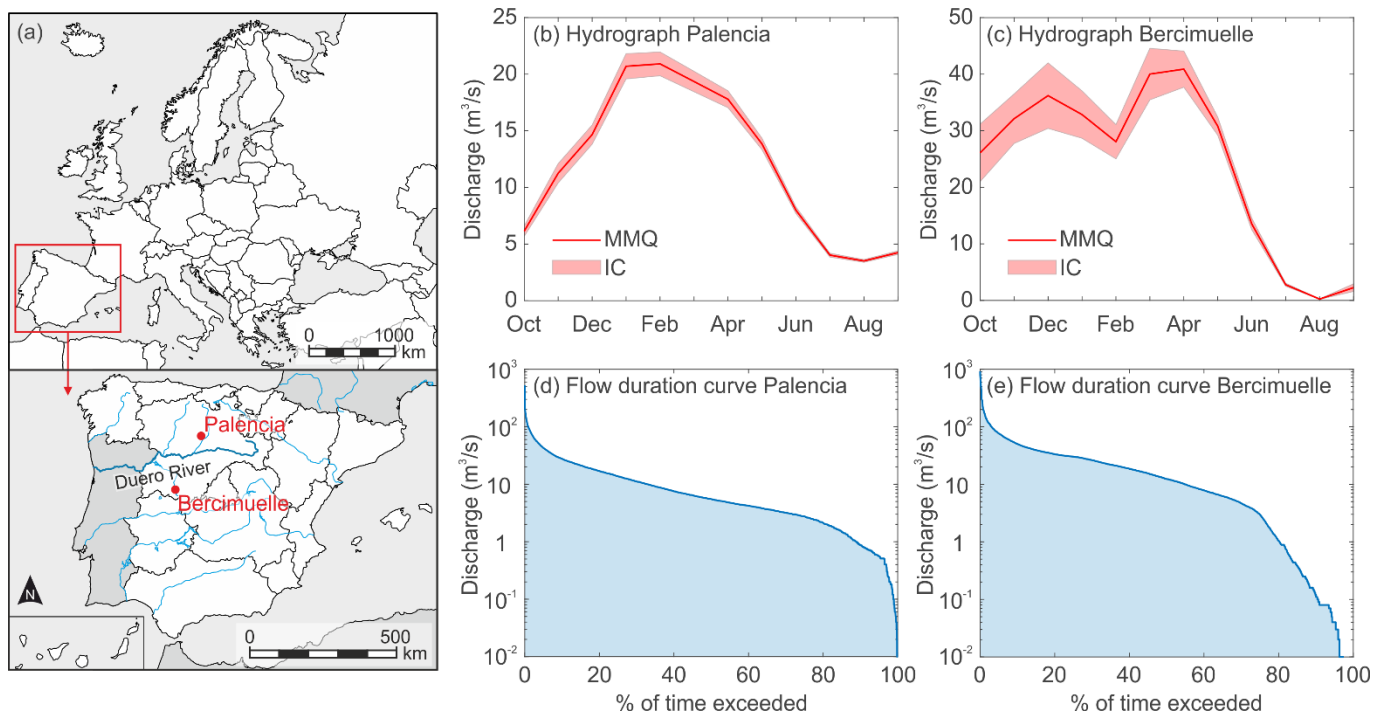


**Figure 3.** Situation map and hydrograph of the two studied flat-V gauging weirs: (a) Iberian Peninsula with bold lined Duero River and red dots representing the study sites (Palencia and Bercimuelle); (c) Hydrograph of Palencia weir (data series: 1912-2018); (d) Hydrograph of Bercimuelle weir (data series: 1997-2018). MMQ stands for mean monthly discharge and IC for confidence interval.

The Tormes River is a direct tributary of the Duero River and it is not regulated at Bercimuelle. It presents a typical Mediterranean hydrological regime: high flows and sporadic floods during late autumn, winter, and early spring, as well as strong summer droughts [29] (**Figure 3**c). The study river reach comprises a mean annual discharge of 23.74 m³/s, its altitude is around 910 m a.s.l., it is placed in the Epipotamon zone [30], and corresponds to a B1 category: bedrock and gravel bed stream of moderate sinuosity with a slope of 0.02–0.04 m/m [31]. The most abundant potamodromous fish species are Iberian barbel, Northern straight-mouth nase (*Pseudochondrostoma duriense* Coelho 1985), and brown trout (*Salmo trutta* Linnaeus 1758).

The Carrión River is a tributary of the Pisuerga River, being the latter a direct tributary of the Duero River. It is strongly regulated for irrigation at Palencia and shows an inverted Mediterranean hydrological regime [22] although slightly damped by intermediate tributaries, with higher flows than expected during the dry summer (releases for irrigation) and lower flows than the expected ones during winter (saving water in reservoirs) (**Figure 3**b). The mean annual discharge in the study site is 12.03 m³/s, the altitude is around 735 m a.s.l., it is placed in the Epipotamon zone [30] and corresponds to E4 category: gravel-bed stream of high sinuosity with a slope of 0.001–0.02 m/m [31]. As in many Iberian rivers, the fish community is altered due to the modification of the hydrological regime and the introduction of non-native invasive species [32]. Among the most abundant native potamodromous migratory species, there are Iberian barbel and Northern straight-mouth nase.

*2.2. Hydraulic data collection and CFD model*

### 2.2.1.    Hydraulic data

Discharge distribution of the study sites, as well as the associated water level upstream the weirs, are available through the Spanish public administration web pages (http://www.saihduero.es/, accessed on 28/10/21, and https://sig.mapama.gob.es/ accessed on 28/10/21). Water levels downstream the weirs were monitored using own pressure sensors (MS Pressure Logger; one measurement every 10 minutes with a typical deviation ± 0.1%, https://www.gea-ecohidraulica.org/GEA_en/sensors, accessed on 04/11/21). The water level was measured by installing one underwater sensor downstream of the weir and another one outside for barometric pressure compensation. The underwater sensor also recorded water temperature in the same measurement frequency. In addition, to validate to validate the results of the hydraulic model, velocity and depth measurements were manually collected: 1) in the center of the downstream face every meter for multiple discharges (Q = 0.08, 0.32, 1.8, 2.57, and 2.96 m$^3$/s) in Palencia weir, and 2) in a coarse mesh of $\Delta$x=1 m and $\Delta$y=2 m for a discharge of Q = 3.00 m$^3$/s in Bercimuelle weir. These discharges allowed for manual measurements in situ whereas greater discharges could compromise the safety of the field staff. Velocity was measured using a propeller-type current meter (Swoffer Model 2100 Current Velocity Meter) and water depth was measured by means of a metal ruler.

### 2.2.2.    CFD Methods

The 3D models were implemented to gather hydraulic data in a thinner mesh and particularly in those non-accessible scenarios (i.e. high discharges). To develop them, the open-source numerical C++ toolbox OpenFOAM (release 3.0.1) was used. The resolution of the transient flow of two fluids separated by a sharp interface (water-air) was achieved using the prebuilt Eulerian solver interFoam [33], an implementation of the volume of fluid (VOF) method [34]. A detailed description of the procedure and methods used (flow equations, boundary conditions, and the simulation process applied) for modeling can be found in [35].

To solve turbulence, in all the models Reynolds-Averaged Navier-Stokes (RANS) turbulence modeling method was used, which compared to other methods, has demonstrated to provide a good accuracy/computational cost ratio [35].

### 2.2.3.    Mesh, boundary conditions, and time sensitivity analysis

All studied meshes were generated using a two-step procedure [35]. First, the block-Mesh utility [36] was used to create a structured hexahedral mesh of the gauging station full volume. After, the snappyHexMesh utility [36] was applied to define the flat-V weir, creating a high-quality hex-dominant mesh. After a mesh independency analysis and a comparison with the data collected in the field, the mesh size used to perform the simulations was $\Delta$x = 0.08 m, $\Delta$y = 0.05 m, and $\Delta$z = 0.04 m.

The overall performance of each scenario (see **Table 1** in Results) was controlled by defining a constant flow rate at the inlet (*variableHeightFlowRateInletVelocity*) in accordance with the observed discharges in the field, enabling the free water level oscillation (*variableHeightFlowRate*) and a constant mean velocity in the outlet (o*utletPhaseMeanVelocity*) to achieve the observed water-levels downstream [35]. These boundary conditions were iteratively varied until the observed behavior matched the conditions observed in the field. In all the simulations, the differences between time-steps on water levels and mass flow were monitored to ensure that an asymptotic behavior was reached. Obtained results were in accordance with the field observations and theoretical equations of flat-V weirs (Figure 4).
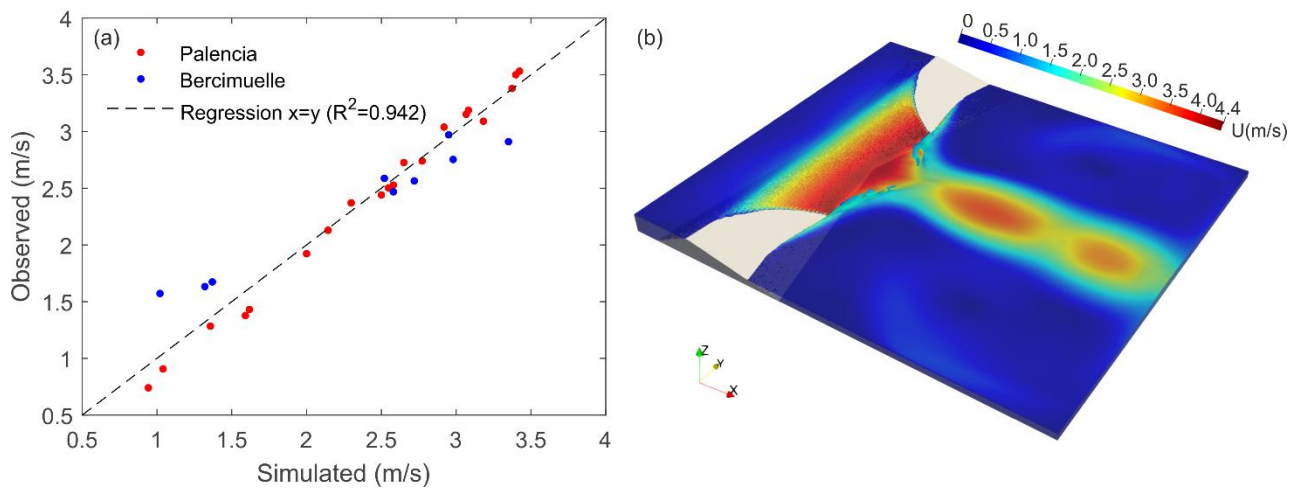
**Figure 4.** (a) Validation of the 3D model results considering field measurements ($R^2$ stands for determination coefficient); (b) Simulation example of the flow velocity (U) for Palencia weir (p = 0.7 m, $h_1$ = 1.23 m; Q = 6 $m^3$/s, $d_2$ = 0.46 m).

### 2.2.4.  CFD data extraction

Once all scenarios were simulated and validated, mean depth and velocity values were extracted considering the coarse grid used for fish data collection (section 2.3.). The grid was situated in the downstream face of the weir and outside the hydraulic jump influence (**Figure 5**). This area was divided into 7 sections evenly distributed in the full width (B) of the weirs (y-direction) and each section was divided evenly into up and down areas (x-direction). Finally, a grid of 14 cells was obtained representing the hydraulic conditions (mean depth and mean velocity) on the downstream face of each weir.

To achieve this, CFD data from OpenFOAM were plotted, visualized, and exported to text format with Paraview software (version 5.8.0), obtaining separate data files for the flat-V weir geometry, interface between water and air, and hydraulic variables in the water interface. Depth was obtained by subtracting directly the flat-V weir geometry height to the interface between water and air height, and by calculating mean values in the target grid. Mean velocity magnitudes were directly obtained by delimiting hydraulic variables files in the target grid.

### 2.3. *Fish data collection*

For each of the study sites, a different fish data collection technique was used. In Bercimuelle weir, video camera tracking was employed to detect ascent paths and swimming velocities, meanwhile, in Palencia weir, radio-tracking was used to allow for individual fish identification and evaluate the upstream passage efficiency.
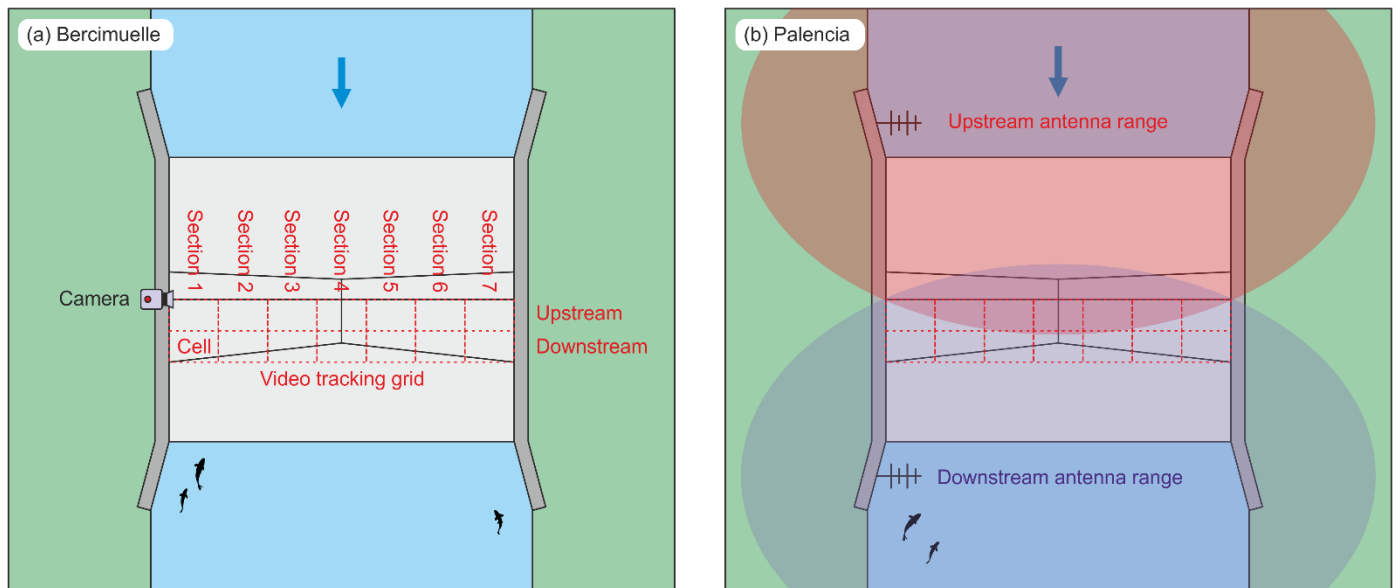
**Figure 5.** (a) Scheme of the video recording in Bercimuelle weir with the used grid to characterize the ascent paths of the fish. (b) Scheme of the radio-tracking in Palencia weir showing the two fixed radio antennas and their detection range.

### 2.3.1    Video-tracking - Bercimuelle

The video-tracking experiments were conducted from July 1 to July 25 of 2014 between 8 a.m. and 10 p.m. This period matches with Iberian barbel upstream migration maxima in the area [23]. Video tracks were recorded by means of a camera (Sony 420 TVL CCD; 15 fps) placed in the right bank wall of the flat-V weir, 2 m above the weir crest. The camera footage was recorded with a laptop and all the system was solar-powered (3 solar panels of 200 W and 2 batteries of 12 V and 250 Ah).

Camera tracking did not allow fish species identification; therefore, both migratory species in the area (could be included in the track analysis. Nevertheless, it is expected that fish movements were mostly from Iberian barbels due to the studied time frame [23]. Likewise, due to the symmetrical nature of flat-V weirs and the lower quality of images in the farthest area of the weir, only the closest half of the weir was analyzed.

All recorded fish tracks were classified in cells of a coarse grid (**Figure 5**a) over the downstream face of the weir in order to relate them with simulated mean depths and velocities on each cell, as well as, to identify the ascent and entrance cells together with the time of ascent and swimming distance. In addition, the length of individuals was roughly classified into two categories: >25 cm "large" and <25 cm "small".

A successful ascent event was defined for those fish that were able to enter and completely overcome the flat-V weir from downstream to upstream. After, considering the swimming distances, ascent times, and simulated mean flow velocities in each cell, fish swimming velocity was calculated as in [37].

### 2.3.2    Radio-tracking - Palencia

Radio-tracking experiments were conducted between June 25 and December 12 of 2020 using Iberian barbel as target species. Fish were captured by electrofishing (Hans-Grassl ELT60II backpack equipment; 180-200 V DC and 1.8-2.0 A) in the Arlanza River, a tributary of the Pisuerga River near the Palencia weir. Within one hour after the capture, fish were transported to the study site in 100 L aerated tanks. They were held in acclimation tanks at ambient temperature with a continuous oxygen supply.

In total, 10 barbels were radio-tagged (model F1040 of ATS® with internal coil antenna; dimension of 23x10mm and weight of 2.5 g), with fork lengths ranging from 21.5 to 32.5 cm (weight from 130 to 514 g). According to tag suppliers, the battery life of each

tag was about 5 months (30 pulses per minute) and they allowed the individual detection of each fish thanks to a unique frequency emitted by each tag (frequency ranged between 164.200 and 164.400 MHz).

The implantation of tags to anesthetized fish (eugenol 80 mg/L diluted in ethanol 1:10) was made through an incision in the intraperitoneal cavity. The incision was closed with absorbable stitches and liquid cutaneous sutures. All the surgery process was performed in a surgery box, where barbels stay in a fixed position maintaining the gills completely submerged in fresh water with oxygenation and a maintenance dose of anesthetic (50 mg/L). Radio tags weight < 2% of the body mass of the smallest tagged fish, which is known to have negligible effects [38–40]. After the surgery, the recovery of fish was confirmed before the release (looking for the usual swimming activity and good equilibrium). All fish were released in the same location (500 m downstream of the study site) and date (25 June 2020).

To monitor the fish passage through the weir, two stationary radio antennas were installed upstream and downstream of the flat-V weir (in the left bank) (Figure 5b). Antennas (threefold element Yagi type) were connected to independent (but with synchronized timestamp) readers (Datasika SRX400 Lotek®) powered by a 220V AC power point of the gauging station. The detection area of the antennas was fitted via the signal strength, obtaining independent signals downstream and upstream the weir and overlapping signal in the crest (Figure 5b). During the experiment, the system was dissembled once, during a punctual high flow period (22-26 October) to avoid damage of equipment and with conditions that made fish migration highly unlikely.

*Radio tag record analysis:*

Both receivers were recursively scanning each frequency every 5 seconds, ensuring 2 tag records of the same frequency every scan (total scan time = 5 seconds x 10 tags). After downloading the data, the selection of valid records and their treatment was done following a standardized criterion:

- The burst interval of the registered signal should be between 29 and 31 pulses per minute (in accordance with tags frequency).
- Only signals with a power of at least 60 (power scale of the reader between 0 and 255) were considered. This was determined based on on-site tests during the installation and considering the levels of ambient noise.
- In order to consider a positive record, at least two consecutive records were required.
- A successful ascent through the weir was defined as a positive detection of a fish in both antennas together with a logical power variation. That is to say, first a strong signal in the downstream antenna, then a consecutive intensity gain in the upper antenna, followed by a decrease in the intensity of the uppermost antenna, and finally its disappearance in the downstream antenna.
- Ascent attempt without success was defined as 1) a strong positive detection in the downstream antenna, followed by a weak detection in upstream antenna and finishing with a detection only in the downstream antenna, or 2) fish detection only in the downstream antenna.
- Downstream movements were also identified whenever an inverse sequence of signals occurred. However, they were discarded for the analyses.
- Overall upstream passage efficiency was defined as the ratio between the successful upstream passages and the total number of registered events (successful upstream passages + ascent attempts).

### 2.6. Data management and statistical analyses

Fish video-tracking analysis, as well as radio data filtering, were done manually by experienced researchers. All biological analyses were performed in Statgraphics Centurion statistical software (Statgraphics Technologies, Inc., The Plains, Virginia, USA; Version 18.1). All hydraulic data extraction and visualization were done in Matlab R2019a.

To detect significant differences in swimming velocity between fish size as well as among flow rate categories, Mann-Whitney tests were carried out. The selection of this test was motivated due to the non-normal distribution of the data. In addition, to check for a possible influence of fish size / flow rate on the ascent paths and also between the radio-tracking events and the daily pattern of movement, the chi-square ($\chi^2$) test of independence was used.

## 3. Results

### 3.1. Hydraulic modeling

**Table 1** summarizes the main hydraulic variables in the grid used for fish passage data assessment. As can be seen, velocity and depth increase toward the center of the weir, while general velocity pattern of each scenario increases with the discharge. In contrast to the typical performance of this type of structures, in studied cases the water drop between upstream and downstream water level ($\Delta H = (h_1 + p)\text{-}d_2$)) remains more or less constant (0.4 m for Bercimuelle and 0.7 m for Palencia), especially for Palencia, what causes similar velocity profiles between same sections of each scenario.

**Table 1.** Mean velocities and water levels (± S.D.) according to simulations in the coarse grid used for analysis. For a simpler layout and considering the symmetry of the flow rate over the weir only half of the mesh results are shown. – stands for cells without water for the specific scenario.

| Flat-V | | Grid position | Q (m³/s) | h₁ + p (m) | d₂ (m) | Section 1 and 7 | | Section 2 and 6 | | Section 3 and 5 | | Section 4 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | U (m/s) | h (m) | U (m/s) | h (m) | U (m/s) | h (m) | U (m/s) | h (m) |
| Bercimuelle (p=0.5 m) | | Upstream | 4 | 0.94 | 0.57 | 2.00±0.38 | 0.10±0.03 | 2.16±0.37 | 0.15±0.03 | 2.21±0.36 | 0.21±0.04 | 2.19±0.34 | 0.26±0.03 |
| | | Downstream | | | | 2.81±0.16 | 0.06±0.01 | 2.94±0.09 | 0.10±0.02 | 2.93±0.08 | 0.16±0.03 | 2.93±0.07 | 0.22±0.01 |
| | | Upstream | 6 | 1.03 | 0.64 | 2.31±0.42 | 0.15±0.04 | 2.41±0.41 | 0.20±0.04 | 2.44±0.39 | 0.26±0.04 | 2.41±0.38 | 0.32±0.04 |
| | | Downstream | | | | 3.23±0.17 | 0.10±0.02 | 3.30±0.12 | 0.14±0.02 | 3.28±0.11 | 0.20±0.03 | 3.25±0.08 | 0.26±0.02 |
| | | Upstream | 8 | 1.10 | 0.71 | 2.46±0.41 | 0.21±0.05 | 2.53±0.39 | 0.26±0.05 | 2.54±0.38 | 0.33±0.05 | 2.50±0.36 | 0.38±0.04 |
| | | Downstream | | | | 3.42±0.21 | 0.13±0.02 | 3.49±0.14 | 0.18±0.02 | 3.48±0.13 | 0.25±0.03 | 3.42±0.12 | 0.31±0.01 |
| Palencia (p=0.7 m) | | Upstream | 3 | 1.09 | 0.30 | - | - | 1.30±0.51 | 0.03±0.01 | 2.49±0.44 | 0.09±0.04 | 2.68±0.37 | 0.17±0.03 |
| | | Downstream | | | | - | - | - | - | 3.54±0.41 | 0.07±0.03 | 3.64±0.18 | 0.14±0.02 |
| | | Upstream | 6 | 1.23 | 0.46 | 0.77±0.27 | 0.03±0.01 | 2.3±0.52 | 0.06±0.03 | 2.78±0.37 | 0.15±0.04 | 2.81±0.38 | 0.25±0.04 |
| | | Downstream | | | | - | - | 3.27±0.47 | 0.04±0.01 | 3.71±0.18 | 0.12±0.03 | 3.70±0.15 | 0.20±0.03 |
| | | Upstream | 9 | 1.33 | 0.62 | 1.76±0.59 | 0.04±0.01 | 2.70±0.36 | 0.10±0.03 | 2.87±0.35 | 0.20±0.05 | 2.84±0.36 | 0.31±0.04 |
| | | Downstream | | | | - | - | 3.35±0.28 | 0.08±0.03 | 3.52±0.08 | 0.17±0.03 | 3.54±0.1 | 0.27±0.03 |
| | | Upstream | 12 | 1.40 | 0.75 | 2.33±0.54 | 0.06±0.03 | 2.82±0.35 | 0.14±0.03 | 2.93±0.35 | 0.25±0.05 | 2.88±0.36 | 0.36±0.05 |
| | | Downstream | | | | 2.71±0.91 | 0.07±0.1 | 3.36±0.11 | 0.12±0.02 | 3.52±0.07 | 0.21±0.04 | 3.51±0.11 | 0.33±0.03 |

### 3.2. Video-tracking

In total, 36 successful and 7 unsuccessful ascents were recorded. Successful events did not show significant differences in swimming velocity due to size (p-value = 0.833) or discharge (p-value = 0.336) (**Table 2**). In the same way, unsuccessful events did not show significant relation with fish size (p-value = 0.517; $\chi^2$ = 0.42) or discharge (p-value = 0.844; $\chi^2$ = 0.04), even though five of them were assigned to small fish and four of them categorized in low flow rate.

**Table 2.** Swimming velocity (m/s) of successful ascent events recorded in Bercimuelle weir. Size classes based on fish smaller or larger than 25 cm length. Flow rate classes based on discharge lower or higher than 6.5 m³/s (IQR = Interquartile Range; n = number of fish).

| Swimming velocity (m/s) | | Median | IQR | Min-Max |
|---|---|---|---|---|
| Size | Small (n = 21) | 5.03 | 4.53 – 5.31 | 3.97 – 6.50 |

| | | | | |
|---|---|---|---|---|
| | Large(n = 15) | 4.95 | 4.51 – 5.90 | 4.13 – 7.31 |
| Discharge | Low (n = 22) | 4.86 | 4.53 – 5.65 | 3.97 – 6.02 |
| | Medium (n = 14) | 5.04 | 4.51 – 5.61 | 4.13 – 7.31 |

Regarding the ascent paths, fish size did not have a significant correlation with the ascent zones, neither for the entrance (downstream cell) (p-value = 0.709; $\chi^2$ = 1.38) nor the exit (upstream cell) (p-value = 0.502; $\chi^2$ = 2.36). However, flow rate showed a marginal significant relationship ($\alpha$ < 0.1) for both the entrance (p-value = 0.084; $\chi^2$ = 6.65) and the exit zone (p-value = 0.069; $\chi^2$ = 7.09), driven to use of section 1 (**Figure 6**).



**Figure 6. Frequency** distributions of fish entry (downstream) and exit (upstream) cells by size (a and b) and flow rate (c and d).

The 47% of recorded fish (17/36) changed the section while ascending [i.e. upstream and downstream cells of different sections (**Figure 5**)]. The 47% of those who changed (8/17) moved to the middle of the gauging while the remaining 53% (9/17) moved to an outer section when ascending. The percentage remains constant whether the ascent is analyzed according to the flow rate or the fish size, that is to say, near the half of the fish remained in the same section during the ascent event while the other half changed section.

Most of the successful ascents happened in the central hours of the day (between 12 a.m. and 4 p.m.; 23/43) and at the dawn-morning period (between 7 a.m. and 11 a.m.; 18/43), being marginal those detected at the afternoon-dusk period (between 5 p.m. and 9 p.m.; 2/43). However, it should be noted a possible effect of the luminosity in the event detection procedure.

In addition to ascent path identification, during the video analysis, other behavioral observations were made. For instance, the lack of evidence that supports fish disorientation triggered by the recirculation zones downstream the weir or the use of the wave generated immediately before the hydraulic jump by several fish to glide upstream.

*3.3. Radio-tracking*

**Figure 7** provides a general overview of ascent movements together with the main environmental variables for Palencia weir. Despite most of the movements occurred in summer, the events lasted until late fall and no significant relationship was observed between daily hours and events (p-value = 0.563; $\chi^2$ = 8.68), that is to say, they were evenly distributed throughout the day.
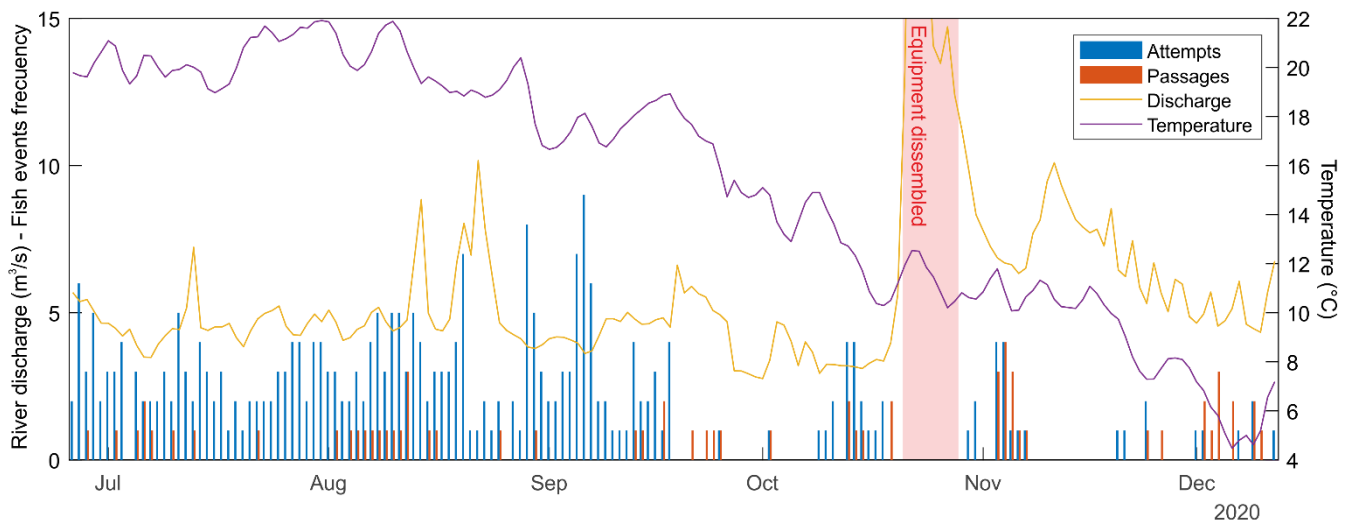
**Figure 7.** Frequency of attempts and successful upstream passages over the Palencia weir related to the river discharge and water temperature. The time-period with disassembled antennas (due to the damage risk by high flows) has been represented with a shaded area.

The detection rate of the radio-tracking system was high: 9 of 10 fish were registered and all of them succeed at least once in the ascent of the flat-V weir. The first upstream passages were distributed from the end of June to the beginning of October and the number of attempts exceeded the number of passages. The plot of the overall upstream passage efficiency (ratio between successful upstream passages and ascent attempts) for different river discharges reveals a maximum success in the range from 5 to 8 m³/s, with an accelerated decrease outside this range (**Figure 8**). In addition, the plot of mean velocities of the studied 7 sections of the downstream face of the weir (**Figure 5**) shows a progressive increase in the velocity of each section with the discharge until they reach an equilibrium near 3.25 m/s. The maximum overall upstream passage efficiency occurred when mean velocities in center sections (sections 4 and 3-5) reached an equilibrium and water started flowing through sections 2-6 (depth over the face ≈ 0.09 cm).
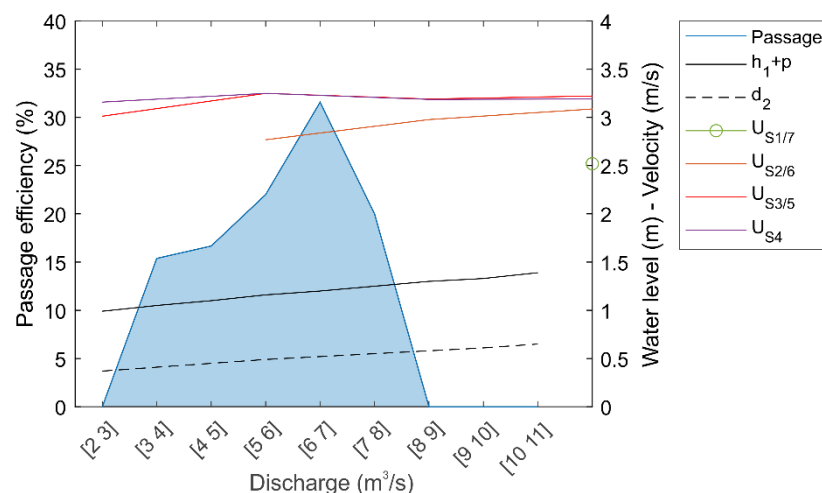


**Figure 8.** Passage efficiency of Palencia weir pooled by cubic meter of discharge. Water depth and velocity changes in each section (see Figure 5) according to changes in discharge.

## 4. Discussion

To the best of our knowledge, this study is the first one trying to relate fish passage performance to the hydraulic behavior of flat-V gauging stations. This work demonstrates that under a broad range of river scenarios, these gauging structures can act as total, or partial and selective barriers for upstream fish migration and shows the limited hydraulic

ranges which permit Iberian barbel passage. This is particularly relevant in Mediterranean areas where high hydrological variability is expected as well as in regulated rivers where fish migration has not been considered to stablish environmental flows.

Measuring hydraulic variables (i.e. flow velocity and water depth) in flat-V weirs is usually challenging, as classical measuring techniques are only useful for a small range of discharges where the weir is physically and safely accessible. Thus, to characterize the full performance of these structures, it is necessary the use alternative techniques such as CFD simulations or large-scale particle image velocimetry [41]. In this work, field measurements (flow velocities and water levels) and CFD simulations developed with OpenFOAM have been combined to obtain an accurate representation of the target scenarios in order to relate them to biological observations of migrating fish. This is a well known approach and it has been previously used and validated for hydraulic structures with higher geometrical complexity, such as fish passage systems [35,42]. Despite the obtained accurate results when comparing with field data, it is worth mentioning that variables such as the upstream initial velocity or the downstream water level are of crucial interest when performing this type of simulations, as they directly influence the accuracy of the results and may differ from one structure to another. The downstream water level is easily measurable by means of sensors [43] or manually, while the initial velocity profile can be measured by means of velocity profilers or estimated by comparing the theoretical upstream water level with the observed water level for the same discharge.

Fish video-tracking is always a complex task, due to possible variable parameters such as turbulence or luminosity, and manual processing is required in most cases. In the present study, it allowed to determine fish pathways over the downstream face of the weir and to estimate ascent times, swimming velocity, and categorical fish size. Species identification under the studied conditions and scenarios was nearly impossible. However previous works in the study reach confirmed that, during the studied time frame, fish movements were mostly from Iberian barbels [23]. Both environmental factors and camera position could have biased the number of detections; however, the collected data still serves in the exploratory nature of the experiment.

Results from video-tracking show that fish body size did not influence the ascent success, path selection, or swimming velocity. Body size is known to be one of the most important factors conditioning fish swimming capacity [16]. However, under short distances, it seems possible to not detect significant differences. In the present study, for Bercimuelle weir, the estimated median swimming velocities were near 5 m/s and fish needed less than 1.5 s to negotiate the 2 m tracked of the downstream face, that is to say, a longer distance would be required to see effects in the fish endurance due to the body size. Those swimming values are similar to the ones observed by [37] for the same species in burst swimming mode. In addition, and supplementary to the main analysis, for video tracked scenarios, no disorientation problems as a consequence of the recirculation areas downstream of the weir were detected, although it is usually pointed out as a drawback in flat-V weirs [12,15]. In addition, some large barbels were observed gliding or wave-riding in the wave upstream the hydraulic jump before an attempt, possibly taking advantage of the naturally occurring currents to save energy. Nevertheless, specific research would be required to further advance in those matters.

Discharge showed a certain influence on the section selection when ascending the downstream face of the weir. It seems that fish preferred sections near the banks during high flows and more centered sections for low flows. This behavior could have been induced by the velocity and depth conditions in the downstream face and base of the weir, as fish upstream passage can be limited when there is an insufficient depth for suitable swimming propulsion over the face, or when the velocities experienced by the fish exceed their burst swimming capabilities [8,44]. Moreover, the turbulence conditions associated with the hydraulic jump downstream of the weir increased with the rise in discharge and probably forced fish to avoid central regions. In this sense, more centered sections are deeper but faster and more turbulent than those sections close to the banks. Thus, fish must search for the equilibrium of the hydraulic conditions to successfully negotiate the

obstacle. Specialized references recommend a water depth higher than 20 cm for suitable swimming [15,45], though in velocity barriers tests with Iberian barbel [46–48], it was shown that water depths near 10 cm permitted them to develop burst swimming mode with a fork length (FL) lower than 25 cm. In the case of flow velocity, distance traveled by Iberian barbel was reported to be almost halved from 2.5 to 3 m/s [49]. For instance, Sanz-Ronda et al. [46,49], in a series of experiments in a zero-slope flume with similar hydraulic scenarios to a flat-V weir, estimated that more than the 75% of Iberian barbels larger than 18 cm (FL) were able to pass a velocity barrier of 4 m (estimated distance from the hydraulic jump to the crest of a flat-V weir, larger than our video observations) facing a flow velocity of 2.5 m/s. This percentage dropped to 30% when the flow velocity increased to 3 m/s. Likewise, Amaral et al. [47] for the same species (total length (TL) of 16 cm) in a 1.5 m length ramp with an approaching area of 1 m, observed an 81% of ascent success for a 20% slope (i.e. equal to the downstream face of a flat-V) [mean U ≈ 2,5 m/s, and D < 0,5 m for U > 3 m/s (maximum U in the experiments for this slope ≈ 3,2 m/s)]. This percentage decreased to a 36 % when the slope increased to the 30% [mean U ≈ 2.8 m/s, and D < 1 m for U > 3 m/s (maximum U ≈ 3.6 m/s)]. Therefore, flow velocities higher than 3-3.5 m/s in 1 m length could restrict the passage for a high percentage of the target fish population.

Complementary, radio-tracking information allowed to determine the ratio of fish upstream passage success in each scenario, although the interpretation of radio signals usually has an assumable bias [50]. Despite the origin of used fish, during the study, every fish showed a noticeable activity with multiple attempts and ascent success events (3 to 16 times during the experimentation). Their main activity was concentrated in summer using the 24 h of the day, with even some marginal activity during autumn with temperatures ranging from 10 to 5°C. Although other works also mention autumn movements for Iberian barbels [26,51], night movements observed in other studied hydraulic structures (e.g. fish passes) are scarce [52].

All radio-tagged fish with recorded attempts managed to pass the weir. The passage efficiency maxima happened between 6 and 7 m³/s ($h_1$=0.50-0.56 m; $d_2$=0.46-0.51 m; water drop $\Delta H$=0.77-0.75 m), even so fish needed a mean of three attempts to overcome the weir. Ascent success was concentrated in the range from 3 to 8 m³/s. However, only 4 days during the study period were observed with a discharge lower than 3 m³/s ($h_1$=0.39 m; $d_2$=0.30 m; $\Delta H$=0.69 m), therefore the lower limit could probably be extended to 0.27 m³/s ($h_1$=0.15 m). This scenario produces a mean depth of 10 cm in the downstream face which is the limit for an effective swimming [46,47] and similar flow velocity profiles to higher fish passable discharges. On the other hand, there were 21 days with discharges higher than 8 m³/s ($h_1$=0.58 m; $d_2$=0.59 m; $\Delta H$=0.69 m), and despite simulated hydraulic parameters were compatible with fish ascent, the success was scarce. Therefore, additional hydraulic or behavioral processes must be present to explain the low success of these scenarios. Alternative radio-tracking experiences in flat-V weirs [8] showed a worse passage performance for large (53 cm of TL) common barbels (*Barbus barbus*). In these experiences, the overall ascent success was 40% in a small V weir (p=0.4 m; B=17 m) for discharge between 2 and 5 m³/s ($h_1$ ranging from 0.33 to about 0.50 m). According to the present study, those hydraulic conditions should have allowed the passage of an Iberian barbel of smaller size (at least in multiple attempts), although downstream hydraulic conditions (low water depth or scouring problems), experiment duration, or fish motivation could have influenced their results.

When comparing both studied scenarios, video records in Bercimuelle weir showed successful ascent passage in similar discharges to those in Palencia weir, between 2.5 and 8 m³/s. However, it is worth mentioning that $h_1$ values are higher due to a shorter weir width and, although one would expect higher velocities, the sill height (p) is lower, directly reducing the maximum possible velocities in the downstream face. That is to say, when there are two weirs with similar downstream water level conditions, the lower the p, the lower the velocities, as it means lower water drop between downstream and upstream water level ($\Delta H$ = (p+$h_1$)-$d_2$). In both studied cases, there was a more or less stable $\Delta H$, 0.4 m in Bercimuelle and 0.7 m in Palencia. Therefore, even if one could expect

a lower range of passable discharges in Bercimuelle due to the hydraulic similarity, the lower p allows to have successful passages in analogous discharges for both structures. In this sense, special attention should be taken when generalizing the observed results, as in addition to weir dimensions, flow conditions are of extreme importance to determine the performance of the weir. Both studied cases are best-case scenarios for fish, due to the low initial velocity upstream or high depths ($d_2$) in the downstream base. Simulations show that a high initial velocity or a low downstream water level (e.g. due to scouring or other river geomorphological features) will provoke greater magnitudes of velocities in the downstream face and immediately after, surpassing fish swimming capability even for the observed passable discharge ranges. Moreover, differences in the swimming ability of fish are expected in other reaches and habitats, directly related to their sizes [16], their morphology [17], or their genetic origin [53], which must be considered.

Considering the results, a discharge below 8 $m^3$/s can be considered as an effective scenario for fish to ascend both studied flat-V weirs. This discharge corresponds to a discharge of 26.8% of probability to occur in Bercimuelle while 58.8% in Palencia considering full-year discharge distribution [or 42.9% in Bercimuelle and of 62.8% in Palencia if only considering the migration season of barbels (May-July)] (Figure 3). This means that even if some individuals can pass the studied flat-V weirs in certain hydraulic scenarios, the lack of their occurrence may generate delays in the fish migration or even provoke demotivation. Moreover, fish migration is a complex process, where many environmental factors take part [21,23,54] and, when it comes to discharge, peak flows are usually required not only to improve habitat connectivity but also to motivate fish to ascend [23], and to face a barrier [13] . However, these scenarios may generate challenging conditions in the studied flat-V weirs. All this implies that, even if certain hydraulic scenarios are passable by fish, the real passage time window to ascend is more limited. This has important consequences on fish conservation [18], especially for other endemic cyprinids with smaller sizes and weaker swimmers than barbel [37] and enhances the need of variable e-flows to ensure a real passage time window [23].

Flat-V gauging stations offer precise flow measurements in low water conditions [2], so their installation in Iberian unsteady rivers is very useful as a water resource management and control system [6]. However, this study provides evidence that flat-V gauging weirs can act in certain scenarios as velocity barriers to native fish fauna passage or, in the best scenario, produce a delay to the migration. The studied cases and the analysis of hydraulic behavior of these structures under variable simulated flow conditions seem to suggest that an effective fish passage is possible for Q=0.27-8 $m^3$/s, h1=0.15-0.65 m, d2>0.3 m, and AH<0.7 m. Likewise, despite the existence of passable scenarios, the timing of them and the need for stimuli for migration can drastically reduce the passage time window for fish. Furthermore, it should be noted that swimming requirements are great even under the most favorable conditions. These findings are of interest to quantify flat-V weir impacts, for engineering applications and to establish retrofitting actions (such as backwatering [9,11] or increasing roughness over the face by means of baffles or bristle clusters [44,48], among others) when required.

## Notation

| | |
|---|---|
| B | weir width (m) |
| D | swimming distance (m) |
| $d_2$ | water depth downstream (m) |
| Fr | Froude number |
| $h_1$ | water depth upstream deducting the sill height (m) |
| h | mean water depth (m) |
| n | number of fish |
| p | sill height (m) |
| Q | discharge ($m^3$/s) |
| $R^2$ | determination coefficient |
| U | flow velocity (m/s) |
| $U_{Si}$ | flow velocity at section i (m/s) |
| | |
| $\alpha$ | significance level |
| $\Delta H$ | Water drop between upstream and downstream water levels (m) |
| $\Delta x$ | mesh size in the x-direction (m) |
| $\Delta y$ | mesh size in the y-direction (m) |
| $\Delta z$ | mesh size in the z-direction (m) |
| $\chi^2$ | chi-square test value |

## References

1. Wessels, P.; Rooseboom, A. Flow-gauging structures in South African rivers Part 1: An overview. *Water SA* **2009**, *35*.

2. Bos, M.G. Discharge measurement structures, Publication 20. *Int. Inst. L. Reclam. Improv. Wageningen, Netherlands* **1989**.

3. Organization), W.M.O. (World M. Manual on stream gauging 2010.

4. Rantz, S.E. *Measurement and computation of streamflow*; US Department of the Interior, Geological Survey, 1982; Vol. 2175;.

5. Servais, S.A. Physical modelling of low-cost modifications to the Crump Weir in order to improve fish passage: evelopment of favourable swimming conditions and investigation of the hydrometric effect. **2006**.

6. Ferrer Castillo, C. El SAIH y la modernización de la hidrometría. *Rev. obras públicas* **1996**, *143*, 63–74.

7. Bleckmann, H. Role of the lateral line in fish behaviour. In *The Behaviour ot Teleost Fish*; Pitcher, T.J., Ed.; Springer: Boston MA, 1986 ISBN 978-1-4684-8263-8.

8. Lucas, M.C.; Frear, P.A. Effects of a flow-gauging weir on the migratory behaviour of adult barbel, a riverine cyprinid. *J. Fish Biol.* **1997**, *50*, 382–396.

9. Mulligan, K.B.; Haro, A.; Noreika, J. Effect of backwatering a streamgage weir on the passage performance of adult American Shad (Alosa sapidissima). *J. Ecohydraulics* **2021**, 1–13.

10. White, W.R.; Iredale, R.; Armstrong, G. Fishpasses at flow measurement structures. In Proceedings of the Proceedings of the Institution of Civil Engineers-Water Management; Thomas Telford Ltd, 2006; Vol. 159, pp. 165–171.

11. Ronda, F.J.S.; Córdoba, F.J.B. Estaciones de aforo V-flat y peces migradores de la Península Ibérica: problemas y soluciones. *Ing. Civ.* **2010**, 111–119.

12. Beach, M.H. *Fish pass design-criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fish in rivers. Fisheries research technical report Nº 78*; Ministry of agriculture, fisheries and food. Directorate of fisheries research: Lowestoft, UK, 1984;

13.     Goerig, E.; Castro-Santos, T. Is motivation important to brook trout passage through culverts? *Can. J. Fish. Aquat. Sci.* **2017**, *74*, 885–893.

14.     Chow, V.T. Open-channel hydraulics. *McGraw-Hill Civ. Eng. Ser.* **1959**.

15.     Armstrong, G.; Apahamian, M.; Fewings, G.; Gough, P.; Reader, N.; Varallo, P. *Environment Agency Fish Pass Manual*; Environment Agency: Bristol, 2004;

16.     Beamish, F.W.H. Swimming capacity. In *Fish Physiology, Vol. VII. Locomotion*; Hoar, W.H., Randall, D.J., Eds.; Academic Press: New York, USA, 1978; pp. 101–187.

17.     Sánchez-González, J.R.; Morcillo, F.; Ruiz-Legazpi, J.; Sanz-Ronda, F.J. Fish Morphology and passage through velocity barriers. Experience with Northern straight-mouth nase (*Pseudochondrostoma Duriense* Coelho, 1985) in a open channel flume. *Hydrobiologia* **2021**.

18.     Reid, A.J.; Carlson, A.K.; Creed, I.F.; Eliason, E.J.; Gell, P.A.; Johnson, P.T.J.; Kidd, K.A.; MacCormack, T.J.; Olden, J.D.; Ormerod, S.J.; et al. Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biol. Rev.* **2019**, *94*, 849–873.

19.     Pringle, C. What is hydrologic connectivity and why is it ecologically important? *Hydrol. Process.* **2003**, *17*, 2685–2689.

20.     Doadrio, I. *Atlas y libro rojo de los peces continentales de España*; Ministerio de Medio Ambiente: Madrid, Spain, 2002; ISBN 84-8014-313-4.

21.     Lucas, M.C.; Baras, E.; Thom, T.J.; Duncan, A.; Slavík, O. *Migration of freshwater fishes*; Wiley Online Library: Oxford, UK, 2001;

22.     García-Vega, A.; Sanz-Ronda, F.J.; Fuentes-Pérez, J.F. Seasonal and daily upstream movements of brown trout *Salmo trutta* in an Iberian regulated river. *Knowl. Manag. Aquat. Ecosyst.* **2017**, *418*, 9.

23.     García-Vega, A.; Fuentes-Pérez, J.F.; Bravo-Córdoba, F.J.; Ruiz-Legazpi, J.; Valbuena-Castro, J.; Sanz-Ronda, F.J. Pre-reproductive movements of potamodromous cyprinids in the Iberian Peninsula: when environmental variability meets semipermeable barriers. *Hydrobiologia* **2021**.

24.     Sanz-Ronda, F.J.; Bravo-Córdoba, F.J.; Sánchez-Pérez, A.; García-Vega, A.; Valbuena-Castro, J.; Fernandes-Celestino, L.; Torralva, M.; Oliva-Paterna, F.J. Passage Performance of Technical Pool-Type Fishways for Potamodromous Cyprinids: Novel Experiences in Semiarid Environments. *Water* **2019**, *11*, 2362.

25.     Doadrio, I.; Perea, S.; Garzón-Heydt, P.; González, J.L. *Ictiofauna continental española: bases para su seguimiento*; Ministerio de Medio Ambiente y Medio Rural y Marino, Centro de Publicaciones: Madrid, Spain, 2011;

26.     Sanz-Ronda, F.J.; Fuentes-Pérez, J.F.; García-Vega, A.; Bravo-Córdoba, F.J. Fishways as Downstream Routes in Small Hydropower Plants: Experiences with a Potamodromous Cyprinid. *Water* **2021**, *13*, 1041.

27.     Collares-Pereira, M.J.; Martins, M.J.; Pires, A.M.; Geraldes, A.M.; Coelho, M.M. Feeding behaviour of *Barbus bocagei* assessed under a spatio-temporal approach. *Folia Zool.* **1996**, *45*, 65–76.

28.     Kottelat, M.; Freyhof, J. *Handbook of European freshwater fishes*; Publications Kottelat: Cornol, Switzerland, 2007; Vol. 2008; ISBN 978-2-8399-0298-4.

29.     Gasith, A.; Resh, V.H. Streams in Mediterranean climate regions: abiotic influences and biotic responses to predictable seasonal events. *Annu. Rev. Ecol. Syst.* **1999**, *30*, 51–81.

30.     Illies, J.; Botoseanu, L. Problèmes et méthodes de la classification et de la-zonation écologique des eaux courantes, considérées surtout-du point de vue faunistique. *SIL Commun.* **1963**, *12*, 1–57.

31.     Rosgen, D.L.; Silvey, H.L. *Applied river morphology*; Wildland Hydrology: Pagosa Springs, Colorado, USA, 1996; Vol. 1481;.

32.     Almaça, C. Freshwater fish and their conservation in Portugal. *Biol. Conserv.* **1995**, *72*, 125–127.

33.     Ubbink, O. Numerical prediction of two fluid systems with sharp interfaces, University of London, London, UK, 1997.

34.     Hirt, C.W.; Nichols, B.D. Volume of fluid (VOF) method for the dynamics of free boundaries. *J. Comput. Phys.* **1981**, *39*, 201–225.

35. Fuentes-Pérez, J.F.; Silva, A.T.; Tuhtan, J.A.; García-Vega, A.; Carbonell-Baeza, R.; Musall, M.; Kruusmaa, M. 3D modelling of non-uniform and turbulent flow in vertical slot fishways. *Environ. Model. Softw.* **2018**, *99*, 156–169.

36. Greenshields, C.J. The open source CFD Toolbox User guide 2015.

37. Sanz-Ronda, F.J.; Ruiz-Legazpi, J.; Bravo-Córdoba, F.J.; Makrakis, S.; Castro-Santos, T. Sprinting performance of two Iberian fish: Luciobarbus bocagei and Pseudochondrostoma duriense in an open channel flume. *Ecol. Eng.* **2015**, *83*, 61–70.

38. Brown, R.S.; Cooke, S.J.; Anderson, W.G.; McKinley, R.S. Evidence to Challenge the "2% Rule" for Biotelemetry. *North Am. J. Fish. Manag.* **1999**, *19*, 867–871.

39. Ostrand, K.G.; Zydlewski, G.B.; Gale, W.L.; Zydlewski, J.D. Long term retention, survival, growth, and physiological indicators of salmonids marked with passive integrated transponder tags. *Am. Fish. Soc. Symp.* **2011**, *76*, 1–11.

40. Castro-Santos, T.; Vono, V. Posthandling Survival and PIT Tag Retention by Alewives—A Comparison of Gastric and Surgical Implants. *North Am. J. Fish. Manag.* **2013**, *33*, 790–794.

41. Fujita, I.; Muste, M.; Kruger, A. Large-scale particle image velocimetry for flow analysis in hydraulic engineering applications. *J. Hydraul. Res.* **1998**, *36*, 397–414.

42. Fuentes-Pérez, J.F.; Quaresma, A.L.; Pinheiro, A.; Sanz-Ronda, F.J. OpenFOAM vs FLOW-3D: A comparative study of vertical slot fishway modelling. *Ecol. Eng.* **2022**, *174*, 106446.

43. Fuentes-Pérez, J.F.; García-Vega, A.; Bravo-Córdoba, F.J.; Sanz-Ronda, F.J. A step to Smart Fishways: an autonomous obstruction detection system using hydraulic modelling and sensor networks. *Sensors* **2021**, *21*, 6909.

44. Montali-Ashworth, D.; Vowles, A.S.; De Almeida, G.; Kemp, P.S. Use of Cylindrical Bristle Clusters as a novel multispecies fish pass to facilitate upstream movement at gauging weirs. *Ecol. Eng.* **2020**, *143*, 105634.

45. FAO/DVWK *Fish Passes: Design, Dimensions, and Monitoring*; FAO: Rome, Italy, 2002; ISBN 9251048940.

46. Sanz-Ronda, F.J.; Ruiz-legazpi, J.; Bravo-córdoba, F.J.; Makrakis, S.; Castro-Santos, T. Sprinting performance of two Iberian fish: *Luciobarbus bocagei* and *Pseudochondrostoma duriense* in an open channel flume. *Ecol. Eng.* **2015**, *83*, 61–70.

47. Amaral, S.D.; Quaresma, A.L.; Branco, P.; Romão, F.; Katopodis, C.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. Assessment of retrofitted ramped weirs to improve passage of potamodromous fish. *Water* **2019**, *11*, 2441.

48. Duguay, J.M.; Lacey, R.W.J.; Castro-Santos, T. Influence of baffles on upstream passage of brook trout and brown trout in an experimental box culvert. *Can. J. Fish. Aquat. Sci.* **2019**, *76*, 28–41.

49. Ruiz-Legazpi, J.; Sanz-Ronda, F.J.; Bravo-córdoba, F.J.; Fuentes-Pérez, J.F.; Castro-Santos, T. Influence of environmental and biometric factors on the swimming capacity of the Iberian barbel (*Luciobarbus bocagei* Steindachner, 1864), an endemic potamodromous cyprinid of the Iberian Peninsula. *Limnetica* **2018**, *37*, 251–265.

50. Harbicht, A.B.; Castro-Santos, T.; Ardren, W.R.; Gorsky, D.; Fraser, D.J. Novel, continuous monitoring of fine-scale movement using fixed-position radiotelemetry arrays and random forest location fingerprinting. *Methods Ecol. Evol.* **2017**, *8*, 850–859.

51. Alexandre, C.M.; Almeida, P.R.; Neves, T.; Mateus, C.S.; Costa, J.L.; Quintella, B.R. Effects of flow regulation on the movement patterns and habitat use of a potamodromous cyprinid species. *Ecohydrology* **2016**, *9*, 326–340.

52. Prchalová, M.; Slavík, O.; Bartoš, L. Patterns of cyprinid migration through a fishway in relation to light, water temperature and fish circling behaviour. *Int. J. River Basin Manag.* **2006**, *4*, 213–218.

53. Alexandre, C.M.; Quintella, B.R.; Ferreira, A.F.; Romão, F.A.; Almeida, P.R. Swimming performance and ecomorphology of the Iberian barbel Luciobarbus bocagei (Steindachner, 1864) on permanent and temporary rivers. *Ecol. Freshw. Fish* **2014**, *23*, 244–258.

54. García-Vega, A.; Sanz-Ronda, F.J.; Celestino, L.F.; Makrakis, S.; Leunda, P.M. Potamodromous brown trout movements in the North of the Iberian Peninsula: modelling past, present and future based on continuous fishway monitoring. *Sci. Total Environ.* **2018**, *640*, 1521–1536.