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Fish Upstream Passage through Gauging Stations: Experiences with Iberian Barbel in Flat-V Weirs

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Abstract: The monitoring of river discharge is vital for the correct management of water resources. Flat-V gauging weirs are facilities used worldwide for measuring discharge. 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 address this concern, 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 the target species. Results showed that fish passage is conditioned by both hydraulic and behavioral processes, providing evidence for scenarios in which 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 of the weir of higher than 0.3 m can be considered an effective passage situation for barbels. These findings are of interest for quantifying flat-V weir impacts, for engineering applications and for establishing managing or retrofitting actions when required.

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

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1. Introduction

Gauging stations are structures that measure and record water levels in rivers or canals in relation to stream discharge [1]. They are usually managed by public institutions and act as crucial river monitoring networks with open 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 common facilities for estimation of 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 and 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 used gauging weir alternative is the short crested triangular profile weir, or often called a flat-V or V-Crump weir [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 the precise measurement of 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]; 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. This ability to handle a broad range of discharges is the reason they have been used 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. Twenty-eight of these gauging weirs are flat-V types (http://www.saihduero.es/, accessed on 28 October 2021).

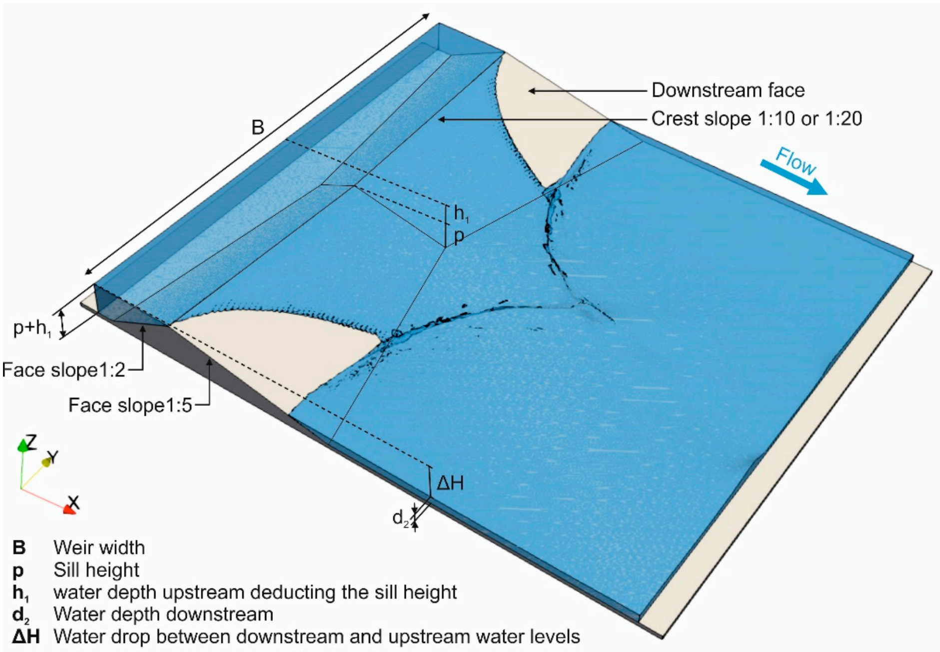

Figure 1. Flat-V weir and its main geometrical parameters. Check ISO Standard 4377:2012 for a broader geometrical description.

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., direct obstructions) 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 depth 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 highly turbulent environment in the center that, together with large eddies on both sides, 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], further reducing, the fish passage probability. Furthermore, weirs can act as selective barriers since the swimming and leaping ability of fish is directly related to fish size and morphology, which may have further implications on the behavioral and dispersal processes of fish populations [16,17].

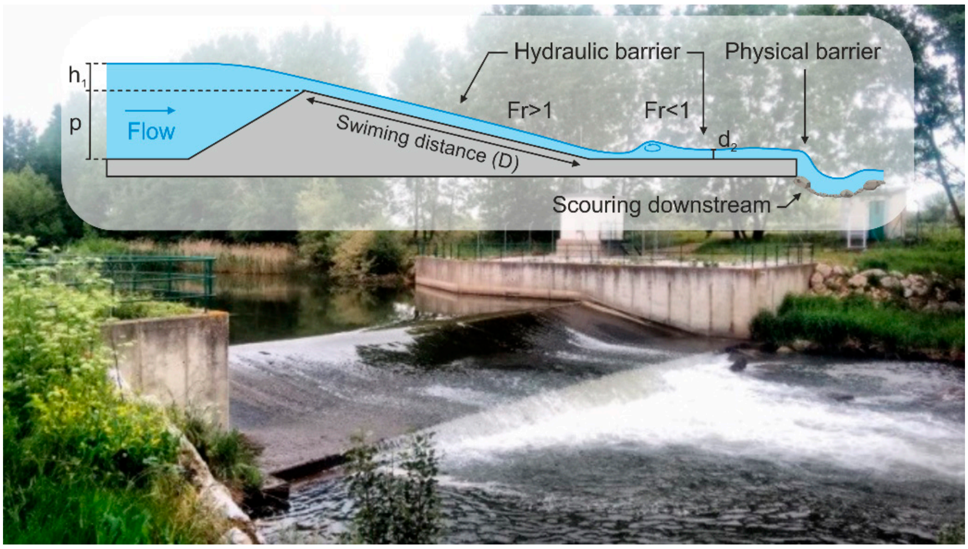

Figure 2. Gauging station with a flat-V weir with scouring problems (Carrión River, Villoldo, Palencia), together with a sketch showing the main problems for the fish ascent. Fr stands for Froude number. See Figure 1 for variable description.

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 have adapted to severe hydrological variability and they must 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 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 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 barbels 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 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 scenarios in which flat-V gauging weirs can act as barriers for upstream fish migration, establishing recommendations for the design of 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): the Bercimuelle weir in the Tormes River (ETRS 89, 40°30′9″ N; 5°31′51″ W; Bercimuelle, Salamanca) and the Palencia weir in the

Carrión River (ETRS 89, 42°2′12″ N; 4°32′30″ W; Palencia, Palencia) (Figure 3a). 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). Palencia's weir is p = 0.7 m and B = 25 m, and has a hydraulic control structure 50 m downstream that influences the base of the gauging weir (backwatering effect).

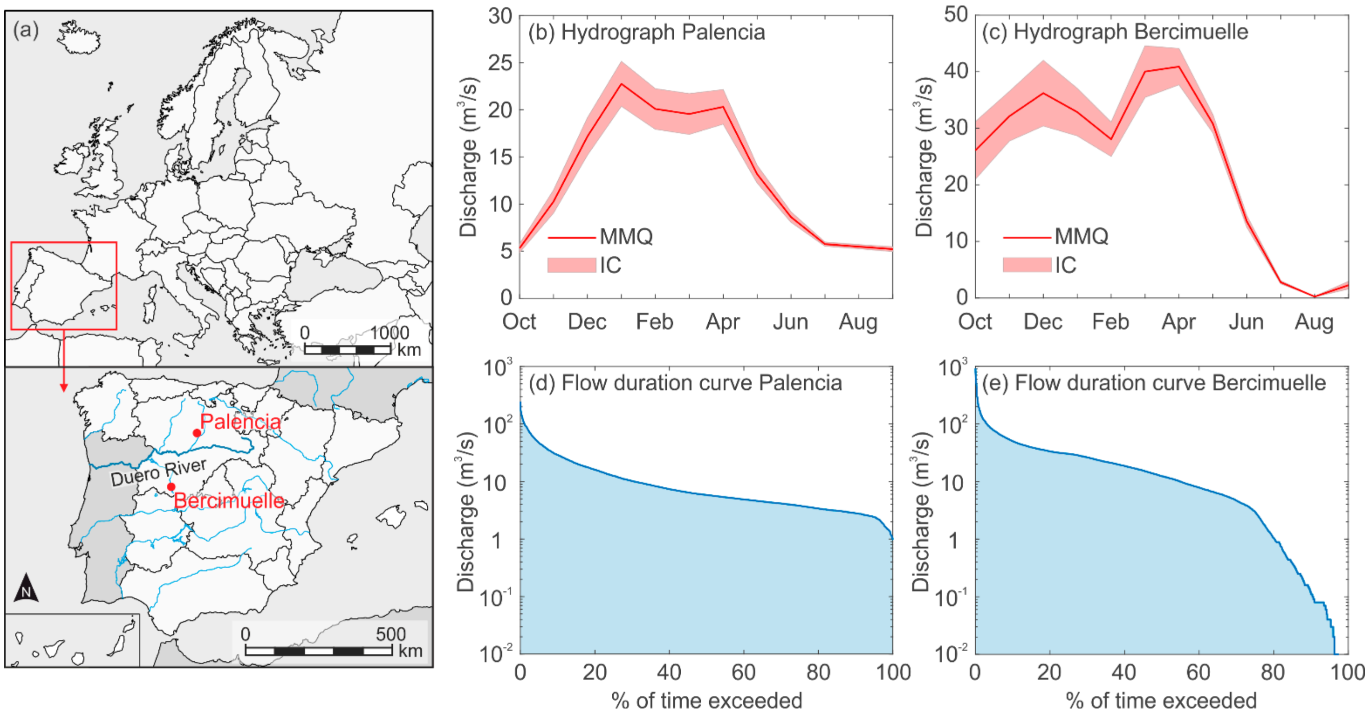

Figure 3. Situation map and hydrograph of the two studied flat-V gauging weirs: (**a**) the Iberian Peninsula with bold-lined Duero River and red dots representing the study sites (Palencia and Bercimuelle); (**b**,**d**) Hydrograph and flow duration curve of the Palencia weir (data series: 1997–2018);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

The Tormes River is a direct tributary of the Duero River and 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 3c). The study river reach comprises a mean annual discharge of 23.74 m^3/s, has an altitude of around 910 m a.s.l., 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, which itself is a direct tributary of the Duero River. It is strongly regulated for irrigation at Palencia and shows an inverted Mediterranean hydrological regime [22], although it is slightly damped by intermediate tributaries, with higher flows than expected during the dry summer (releases for irrigation) and lower flows than the expected during winter (saving water in reservoirs) (Figure 3b). At this study site, the mean annual discharge is 12.80 m^3/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].Iberian barbels and Northern straight-mouth nases are among the most abundant native potamodromous migratory species.

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 of the weirs, are available through Spanish public administration web pages (http://www.saihduero.es/, accessed on 28 October 2021, and https://sig.mapama.gob.es/ accessed on 28 October 2021). Water levels downstream of the weirs were monitored using pressure sensors (MS Pressure Logger; one measurement every 10 min with a typical deviation ±0.1%, https://www.gea-ecohidraulica.org/GEA_en/sensors, accessed on 4 November 2021). The water level was measured by installing one underwater sensor downstream of the weir and another one next to the waterway for barometric pressure compensation. The underwater sensor also recorded water temperature in the same measurement frequency. In addition, 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 the 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 the 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, particularly for 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 models Reynolds-averaged Navier–Stokes (RANS) turbulence modeling was used, which compared to other methods, has been demonstrated to provide a high 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's full volume. Next, 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 free water level oscillation (*variableHeightFlowRate*) and a constant mean velocity in the outlet (*outletPhaseMeanVelocity*) 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).

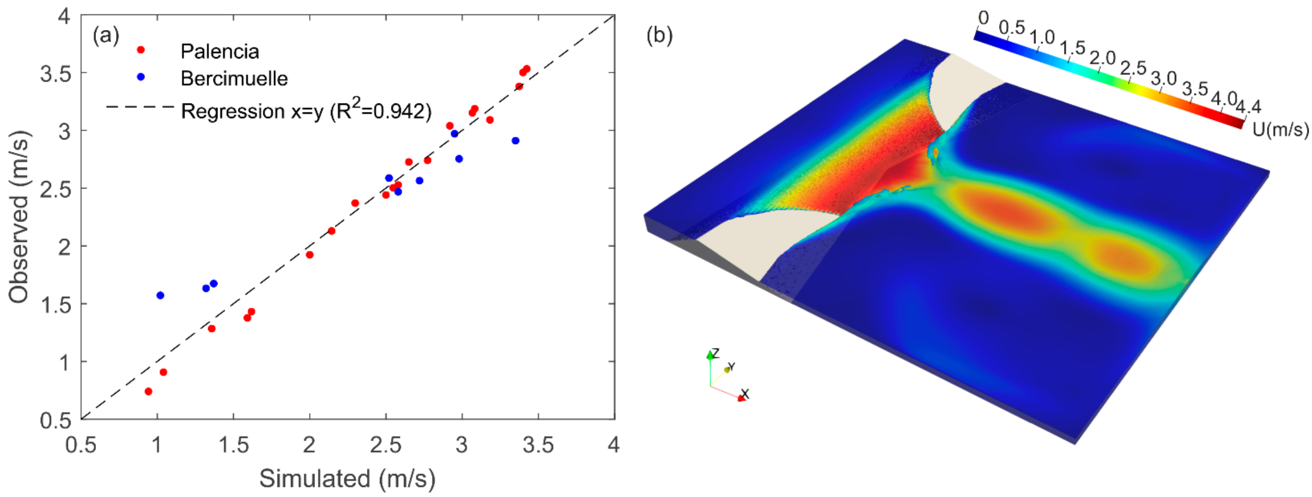

Figure 4. (**a**) Validation of the 3D model results considering field measurements (R^2 stands for determination coefficient); (**b**) Simulation example of the flow velocity (U) for the Palencia weir (p = 0.7 m, h_1 = 1.23 m; Q = 6 m^3/s, d_2 = 0.46 m).

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 across 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) for the downstream face of each weir.

CFD data from OpenFOAM were plotted, visualized and exported to text format with ParaView software (version 5.8.0). Separate data files were obtained for the flat-V weir geometry, the interface between water and air and the hydraulic variables in the water interface. Depth was obtained by directly subtracting the flat-V weir geometry height from 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 the Bercimuelle weir, video camera tracking was employed to detect ascent paths and swimming velocities. However, this technique did not allow us to assess upstream passage efficiency or individual fish identification Thus, for the Palencia weir, radio-tracking was used to complement previous data.

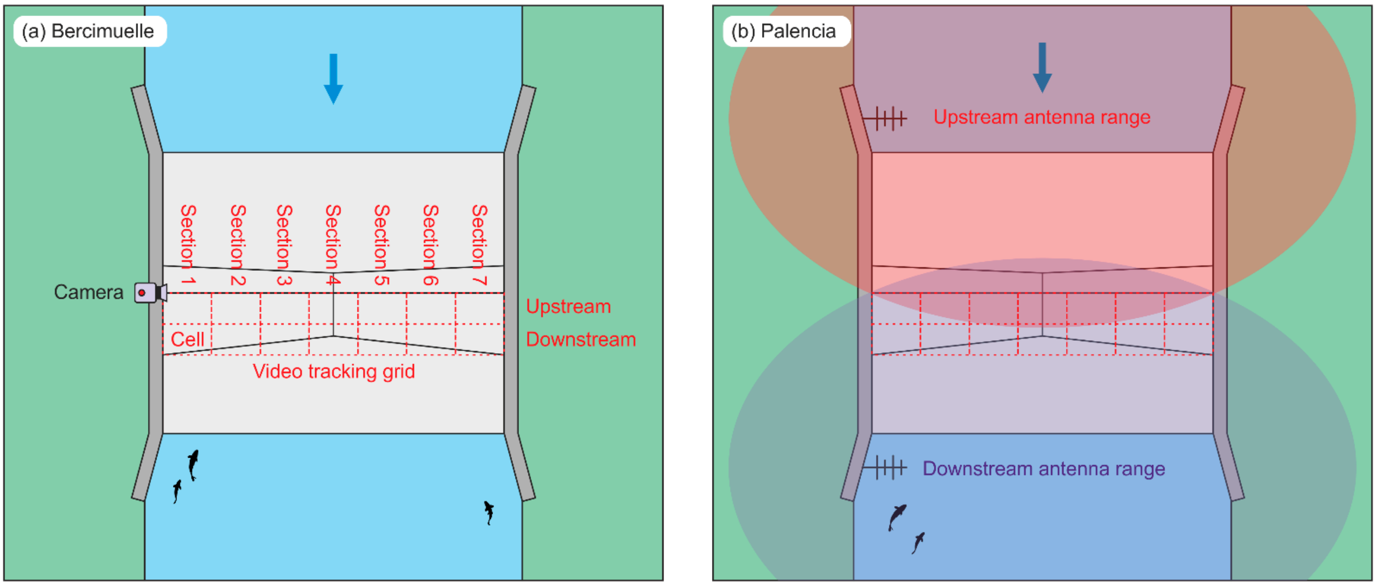

Figure 5. (**a**) Scheme of the video recording in the Bercimuelle weir with the used grid to characterize the ascent paths of the fish. (**b**) Scheme of the radio-tracking in the Palencia weir showing the two fixed radio antennas and their detection range.

2.3.1. Video Tracking—Bercimuelle

The video-tracking experiments were conducted from 1 July to 25 July 2014 between 8 a.m. and 10 p.m. This period aligns 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 resolution was 420 TVL horizontally, or 500 $\times$ 580 pixels (PAL), which resulted in an effective resolution of about 0.5 pixels per cm (the field of the view of the camera was approximately 6 $\times$ 11 m). The camera footage was recorded with a laptop and the recording 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 was presumed 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 area of the weir farthest from the camera, only the half of the weir closest to the camera was analyzed.

All recorded fish tracks were classified in cells of a coarse grid (Figure 5a) 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 along 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 if a fish was able to enter and completely overcome the flat-V weir from downstream to upstream. 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 25 June and 12 December 2020 using Iberian barbel as the 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 1 h 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 23 × 10 mm and weight of 2.5 g, Isanti, Minnesota, EEUU), 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 due to the 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. The surgery process was performed in a surgery box, where barbels stayed 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 weighed <2% of the body mass of the smallest tagged fish; limit which is known to have negligible effects [38–40]. After the surgery, the recovery of fish was confirmed before the release (usual swimming activity and good equilibrium needed to be observed). All fish were released in the same location (500 m downstream of the study site) and on the same 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 readers (Datasika SRX400 Lotek®, Newmarket, ON, Canada) with synchronized timestamps powered by a 220 V AC power point on the gauging station. The detection area of the antennas was fitted via the signal strength, obtaining independent signals downstream and upstream of the weir and overlapping signals in the crest (Figure 5b). During the experiment, the system was dissembled once, during a punctual high flow period (22–26 October) with conditions that made fish migration highly unlikely to avoid damage to.

2.4. Radio Tag Record Analysis

Both receivers recursively scanned each frequency every 5 s, ensuring 2 tag records of the same frequency every scan (total scan time = 5 s × 10 tags). After downloading the data, the selection of valid records and their treatment was done following standardized criteria:

- The burst interval of the registered signal were required to be between 29 and 31 pulses per minute (in accordance with tag 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 by 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 with both antennas together with a logical power variation. Specifically, a strong signal in the downstream antenna followed by a consecutive intensity gain in the upper antenna, a decrease in the intensity of the uppermost antenna and its disappearance in the downstream antenna were required.
- 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).

2.5. 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 (version 18.1). All hydraulic data extraction and visualization was 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. This test was selected due to the non-normal distribution of the data. In addition, to check for the possible influence of fish size/flow rate on the ascent paths, as well as between the radio-tracking events and the daily pattern of movement, the chi-square (χ^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 increased toward the center of the weir, while general velocity pattern of each scenario increased with the discharge. In contrast to the typical performance of this type of structure, in the studied cases the water drop between upstream and downstream water level ($\Delta H = (h_1 + p) - d_2$)) remained more or less constant (0.4 m for Bercimuelle and 0.7 m for Palencia), especially for Palencia. This caused similar velocity profiles between the 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 (m^3/s)	$h_1 + p$ (m)	d_2 (m)	Sections 1 and 7		Sections 2 and 6		Sections 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. An example of each can be seen in the Supplementary Material. Successful events did not show 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 relate significantly with fish size (p-value = 0.517; χ^2 = 0.42) or discharge (p-value = 0.844; χ^2 = 0.04), even though five of them were assigned to small fish and four of them were in the low flow rate category.

Table 2. Swimming velocity (m/s) of successful ascent events recorded in the 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 m^3/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 for either the entrance (downstream cell) (p-value = 0.709; χ^2 = 1.38) or the exit (upstream cell) (p-value = 0.502; χ^2 = 2.36). However, flow rate showed a marginal significant relationship ($\alpha < 0.1$) for both the entrance (p-value = 0.084; χ^2 = 6.65) and the exit zone (p-value = 0.069; χ^2 = 7.09), which drove fish to use of section 1 (Figure 6).

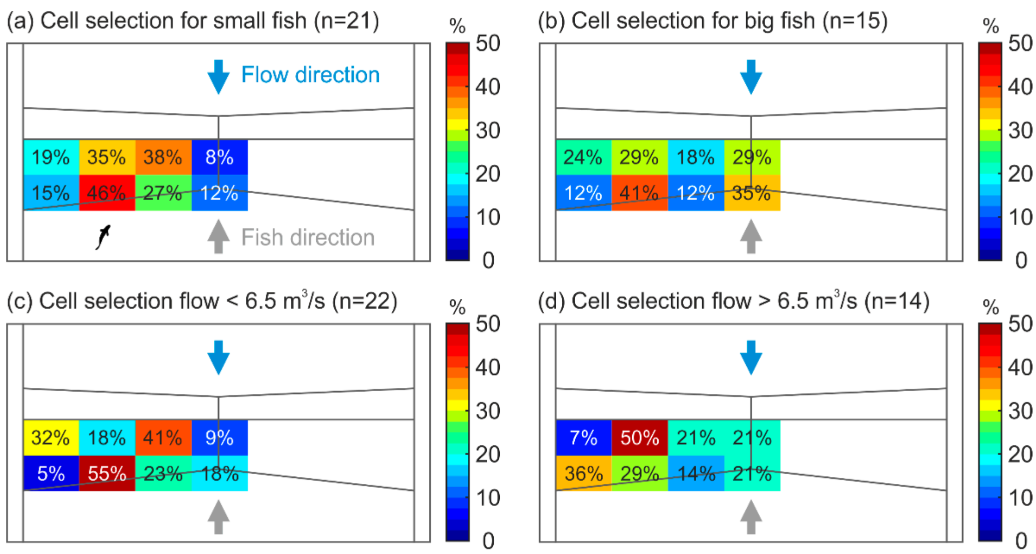

Figure 6. Frequency distributions of fish entry (downstream) and exit (upstream) cells by size (**a**,**b**) and flow rate (**c**,**d**). Due to the symmetrical nature of flat-V weirs and the lower quality of images in the left bank of the weir, only the half of the flat-V weir closest to the camera bank was analyzed.

In total, 47% of recorded fish (17/36) changed section while ascending (i.e., upstream and downstream cells of different sections (Figure 6)). The 47% of fish that 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 remained constant whether the ascent was analyzed according to the flow rate or the fish size; nearly 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 during the dawn–morning period (between 7 a.m. and 11 a.m.; 18/43), with the number detected at the afternoon-dusk period (between 5 p.m. and 9 p.m.; 2/43) being marginal. However, it should be noted that this may be an effect of the luminosity in the event detection procedure. Intense sunny days or darkness in the early dawn and late afternoon may have hindered the passage.

In addition to ascent path identification, during the video analysis, other behavioral observations were made. For instance, there was a lack of evidence that supported fish disorientation triggered by the recirculation zones downstream of 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 the Palencia weir. Despite most of the movements occurring in summer, the events lasted until late fall and no significant relationship was observed between daily hours and events (p-value = 0.563; χ^2 = 8.68); they were evenly distributed throughout the day.

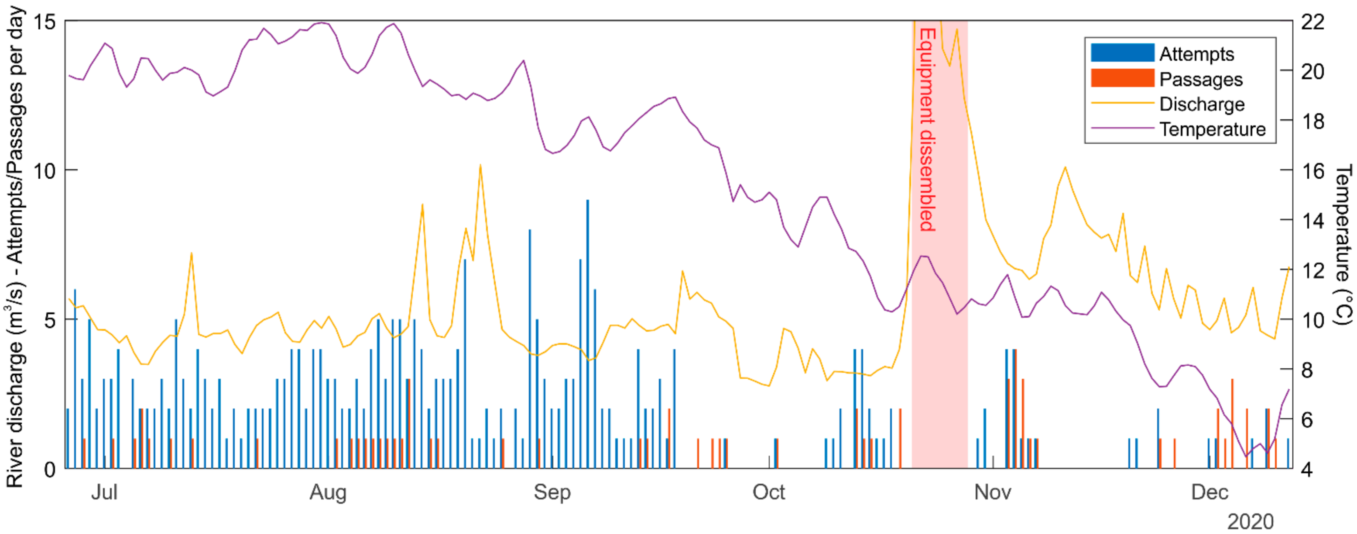

Figure 7. Upstream passage attempts per day and successful passages through the Palencia weir related to the river discharge and water temperature. The time-period with disassembled antennas (due to the damage risk by high flows) has been represented with a shaded area.

The detection rate of the radio-tracking system was high: 9 of 10 fish were registered and all of them succeeded 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 overall upstream passage efficiency (ratio between successful upstream passages and ascent attempts) for different river discharges reveals a maximum success from 5 to 8 m^3/s, with an accelerated decrease outside this range (Figure 8). In addition, the plot of mean velocities of the studied seven 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 m).

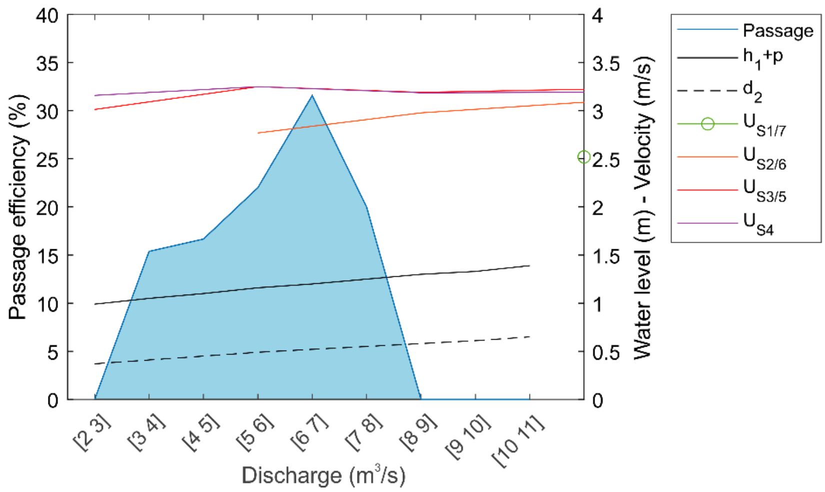

Figure 8. Passage efficiency of the Palencia weir pooled by cubic meter of discharge. Water depth and velocity changes in each section (see Figure 5) according to changes in discharge.

4. Discussion

This study relates fish passage performance to the hydraulic behavior of flat-V gauging stations. Our 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 that 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 when establishing 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 for which the weir is physically and safely accessible. Thus, to characterize the full performance of these structures, it is necessary to 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 were 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 that has previously been used and validated for hydraulic structures with higher geometrical complexity, such as fish passage systems [35,42]. Despite the obtained results being accurate when compared with field data, it is worth mentioning that variables such as the initial upstream velocity or the downstream water level are of crucial interest when performing this type of simulation, 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 variable parameters such as turbulence and luminosity, and manual processing is required in most cases. In the present study, video tracking allowed us 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 may have influenced the number of detections; however, the collected data still serves the exploratory nature of the experiment.

Results from video tracking showed 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 in conditioning fish swimming capacity [16]. However, for short distances, it is possible that significant differences would not be detected. In the present study, for the 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; a longer distance would be required to see effects in fish endurance due to the body size. These 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 of the hydraulic jump before an attempt (see Supplementary Material), possibly taking advantage of the naturally occurring currents to save energy. Nevertheless, specific research would be required to further explore these observations.

Discharge showed a certain influence on the section selection when ascending the downstream face of the weir. 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 passage upstream 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. More centered sections were deeper but faster and more turbulent than those sections close to the banks. Thus, fish were required to 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 barrier tests with Iberian barbels [37,46,47], 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 barbels was reported to be almost halved from 2.5 to 3 m/s [48]. For instance, Sanz-Ronda et al. [37,48], 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. [46] 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 81% ascent success for a 20% slope (i.e., equal to the downstream face of a flat-V) (mean $U \approx 2.5$ 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 36% when the slope increased to 30% (mean $U \approx 2.8$ m/s and $D < 1$ m for $U > 3$ m/s (maximum $U \approx 3.6$ m/s)]. Therefore, flow velocities higher than 3–3.5 m/s in 1 m length could restrict passage for a high percentage of the target fish population.

Complementary radio-tracking information allowed us to determine the ratio of fish upstream passage success in each scenario, although the interpretation of radio signals usually has an assumable bias [49]. Regardless of the origin of used fish, during the study, every fish showed noticeable activity with multiple attempts and ascent success events (3 to 16 times during the experimentation). Their main activity was concentrated in summer throughout all 24 h of the day, with even some marginal activity during autumn with temperatures ranging from 5 °C to 10 °C. Although other works also mention autumn movements for Iberian barbels [26,50], night movements observed in other studied hydraulic structures (e.g., fish passes) are scarce [51].

All radio-tagged fish with recorded attempts managed to pass the weir. The passage efficiency maxima happened between 6 and 7 m^3/s (h_1 = 0.50–0.56 m; d_2 = 0.46–0.51 m; water drop ΔH = 0.77–0.75 m); however, fish needed a mean of three attempts to overcome the weir. Ascent success was concentrated in the range of 3 to 8 m^3/s. However, only 4 days during the study period were observed with a discharge lower than 3 m^3/s (h_1 = 0.39 m; d_2 = 0.30 m; ΔH = 0.69 m); therefore, the lower limit could probably be extended to 0.27 m^3/s (h_1 = 0.15 m). This scenario produces a mean depth of 10 cm in the downstream face, which is the limit for effective swimming [37,46] and similar flow velocity profiles to higher fish-passable discharges. However, there were 21 days with discharges higher than 8 m^3/s (h_1 = 0.58 m; d_2 = 0.59 m; ΔH = 0.69 m), and despite simulated hydraulic parameters being compatible with fish ascent, 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 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 m^3/s (h_1 ranging from 0.33 to about 0.50 m). According to the present study, those hydraulic conditions would likely 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 from the Bercimuelle weir showed successful ascent passage in similar discharges to those in the Palencia weir, between 2.5 and 8 m^3/s. However, it is worth mentioning that the Bercimuelle weir's h_1 values were higher due to its shorter width and, although one would expect higher velocities, the sill height (p) is lower, directly reducing the maximum possible velocities in the downstream face. When there are two weirs with similar downstream water level conditions, the lower the p, the lower the velocities, as it indicates a 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 ΔH: 0.4 m in Bercimuelle and 0.7 m in Palencia. Therefore, even if one would expect a lower range of passable discharges in Bercimuelle due to the hydraulic similarity, the lower p allows successful passages in analogous discharges for both structures. Special attention should be taken when generalizing the observed results, as in addition to weir dimensions, flow conditions are of extreme importance in determining the performance of the weir. Both studied cases are best-case scenarios for fish, due to the low initial velocity upstream and high depths (d_2) in the downstream base. Simulations showed 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 it, 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 [52], which must be considered.

Based on the results, a discharge below 8 m^3/s can be considered an effective scenario for fish to ascend both studied flat-V weirs. This discharge corresponds to a discharge with 26.8% of probability to occur in Bercimuelle and a 62.6% of probability in Palencia considering full-year discharge distribution (or 42.9% in Bercimuelle and of 64.8% 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 appropriate range of discharges may generate delays in fish migration or even provoke demotivation. Moreover, fish migration is a complex process that is influenced by many environmental factors [21,23,53] 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], as well as to face a barrier [13]. However, these scenarios may generate challenging conditions in the studied flat-V weirs. 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 for fish conservation [18], especially for other endemic cyprinids with smaller sizes and weaker swimmers than barbels [37], and enhances the need for variable e-flows to ensure a real passage time window [23].

5. Conclusions

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, in certain scenarios, act as velocity barriers to native fish fauna passage or, in the best-case scenario, delay fish migration. The studied cases and the analysis of hydraulic behavior of these structures under variable simulated flow conditions seem to suggest that effective fish passage is possible for Q = 0.27–8 m^3/s, h_1 = 0.15–0.65 m, d_2 > 0.3 m and AH < 0.7 m. Despite the existence of passable scenarios, their timing 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 for the quantification of flat-V weir impacts (such as barrier effect and migration delay), for engineering applications (such as the construction of fish-friendly small weirs) and for establishing retrofitting actions (such as backwatering [9,11] or increasing roughness over the face by means of baffles or bristle clusters [44,47], among others) when required.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/fishes6040081/s1, Video S1: Small barbel, Video S2: Large barbel and Video S3: Wave-riding.

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Data Availability Statement: Data are available upon reasonable request to the corresponding author.

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

Nomenclature

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)
α	significance level
ΔH	Water drop between upstream and downstream water levels (m)
Δx	mesh size in the x-direction (m)
Δy	mesh size in the y-direction (m)
Δz	mesh size in the z-direction (m)
χ^2	chi-square test value

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