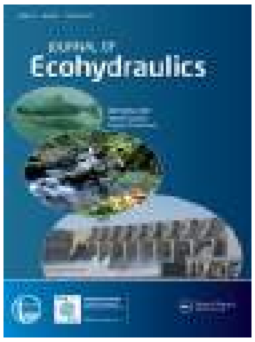

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Brown trout (*Salmo trutta*) passage performance: a quantitative assessment of two vertical slot fishway designs

Filipe Romão[a], Francisco J. Bravo-Córdoba[b], Ana L. Quaresma[a], Ana García-Vega[c], Juan F. Fuentez-Pérez[c] and Francisco J. Sanz-Ronda[c]

[a]CERIS – Civil Engineering for Research and Innovation for Sustainability, Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal; [b]Group of Applied Ecohydraulics, Centro Tecnológico Agrario y Agroalimentario Itagra.ct, Palencia, Spain; [c]Department of Agricultural and Forest Engineering, Group of Applied Ecohydraulics, Sustainable Forest Management Research Institute. University of Valladolid, Palencia, Spain

ABSTRACT

The alteration of natural river flows caused by damming poses a global challenge for fish communities, disrupting life cycles, genetic diversity, and population dynamics. Vertical Slot Fishways (VSFs) are key tools to restore longitudinal connectivity by allowing fish passage across varying flow conditions. However, their success relies on optimising hydrodynamic conditions for fish attraction, passage and minimal energy use. Despite their importance, standardized passage performance assessments remain limited, hindering fishway improvement. This study compared brown trout (*Salmo trutta*) passage performance across two VSF designs: the Revolvo (VS), a commonly used configuration, and the El Arral (DN), featuring a deep notch. Fish trials analysed ascent success, motivation, and transit time under a time-to-event approach. Attempt rates were high (91.4% for VS and 85.7% for DN), with passage success at 87.5% (VS) and 86.7% (DN). Larger trout initiated attempts sooner and had lower transit times, confirming size as a strong performance predictor. Median transit times were relatively low (15.5 min/m for VS and 11.5 min/m for DN), indicating minimal migratory delays. This study identifies suitable hydrodynamic conditions for brown trout and provides insights that may contribute to improving fishway functionality, enhancing understanding of the relationship between fishway design and performance in fish passage engineering.

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Introduction

The disruption of naturally flowing rivers persists as one of the most significant pressures on fish communities throughout the globe (Belletti et al. 2020). The growing number of anthropogenic barriers fragmenting river connectivity results in cumulative impacts on migratory fish, hindering essential life cycle functions, reducing fitness and causing genetic impoverishment of fish stocks (Lucas and Baras 2001; Nilsson et al. 2005; Moccetti et al. 2024). To improve river connectivity, fishways are still, currently, the main mitigation tool employed worldwide when barrier removal is not a viable alternative (Branco et al. 2014). As a driving force, in European water bodies, the EU Water Framework Directive (WFD; 2000/60/EC), the Habitats Directive (HD: 1992/43/EC), the EU Nature Restoration Law 2024/1991, a core element of the Biodiversity Strategy (EC 2020), stand as the main legal frameworks establishing guidance for conservation managers aiming to restore degraded ecosystems and improve river longitudinal connectivity (Hermoso et al. 2022).

Stepped or pool-type fishways are the most widely implemented fish passage systems worldwide (Larinier 2008; Santos et al. 2012). They feature a sloped channel divided into a series of pools by cross-walls, which break the barrier's total height into manageable steps or water drops (ΔH) (Clay 2017). Key design parameters include the size of the pools, the geometric characteristics of the cross-walls – such as the shape and dimensions of slots, orifices, weirs and baffles – and the slope of the structure (Fuentes-Pérez et al. 2024). Among stepped fishways, vertical slot fishways (VSFs) are distinguished by a vertically oriented slot in each cross-wall, extending from the top to the bottom of the channel (FAO/DVWK 2002). This feature allows fish to swim between pools at any depth, eliminating the need for jumping and providing more flexible passage through varying water levels and flow conditions (Larinier 2008; Branco et al. 2023). There

CONTACT Filipe Romão filipe.romao@tecnico.ulisboa.pt CERIS – Civil Engineering for Research and Innovation for Sustainability, Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal; Francisco J. Bravo-Córdoba fjbravo@itagra.com Department of Agricultural and Forest Engineering, Group of Applied Ecohydraulics, Sustainable Forest Management Research Institute. University of Valladolid, Palencia, Spain

are different configurations of VSFs, depending mainly on the size and placement of the downstream and upstream baffles, as well as the relationship between the pool length and width (Rajaratnam et al. 1986, 1992). In some cases, as seen in Design #2 described by Rajaratnam et al. (1986), the design may include a sill at the bottom of the slot, resembling a deep notch (Romão et al. 2024). According to Larinier (2002), this feature serves two main purposes: reducing discharge and providing better guidance and stabilization of the jet passing through the slot. This allows for preventing a short-circuiting or by-passing of the dissipation pool (Clay 2017) and theoretically could assist the passage of smaller-sized fish (Wang et al. 2010). Nevertheless, there is currently no empirical evidence in the scientific literature supporting its effectiveness for salmonid species.

The effectiveness of the fishway design depends on two key factors: its ability to attract fish to the entrance (i.e. attraction efficiency) and its capacity to provide the hydraulic conditions necessary for fish to successfully pass through the fishway (i.e. passage efficiency) (White et al. 2011; Cooke and Hinch 2013). Equally important is ensuring that fish retain enough energy to pursue their migration, avoiding migratory delays and phenotypic selectivity (Roscoe and Hinch 2010; Nyqvist et al. 2017; Lothian et al. 2020).

Fishway design has gradually progressed towards holistic systems aimed at supporting multiple fish species, with the ultimate goal of facilitating effective passage for fish assemblages (Thiem et al. 2013; Sánchez-Pérez et al. 2022). This is particularly challenging in ecosystems with complex fish communities that exhibit distinct migratory requirements across different life stages and diverse swimming mechanics (Liao 2007; Ovidio et al. 2023). A successful design must consider the interplay between flow hydrodynamics, species-specific behaviour and environmental conditions (Williams et al. 2012). Therefore, a critical first step is to conduct site- and species-specific evaluations to identify the most efficient design for effective restoration. Unfortunately, this approach is seldom applied, and fishways are often installed without sufficient prior assessment (Mallen-Cooper and Brand 2007; Katopodis and Williams 2012). To address this issue, adopting an adaptive management framework is key (Castro-Santos et al. 2009). This approach involves comprehensive and ongoing monitoring to evaluate the performance of different designs under varying environmental and operational conditions. By systematically analysing these data, managers can identify context-specific solutions and implement iterative adjustments to optimize fishway effectiveness. Where necessary, adaptive interventions can be applied to improve performance in response to ecological, hydrological or design-specific factors (Santos et al. 2014, 2016; Fuentes-Pérez et al. 2024).

Fish passage monitoring efforts remain limited (Pompeu et al. 2012; Błońska et al. 2024) and often skewed by qualitative methods, which hinders comparisons across different designs due to inconsistent approaches (Bunt et al. 2012; Noonan et al. 2012; Hershey 2021). Quantitative assessments using standardized passage metrics, though still scarce, are crucial for evaluating and improving fishways (Bravo-Córdoba et al. 2021; O'Connor et al. 2022). This is especially important when studying broadly distributed species such as brown trout (*Salmo trutta*, Linnaeus 1758), due to its applicability in many other regions where the species occurs.

The brown trout is a salmonid species native to Europe, North Africa and Western Asia, but due to several anthropogenic displacements, it has a worldwide distribution (Elliott 1994; Klemetsen et al. 2003). This species occupies a wide spectrum of ecological niches, from fresh to salt water and lotic to lentic environments, making it an integral component of aquatic ecosystems as well as a valuable resource for recreational and commercial fishing (Elliott 1994). Their reproductive migratory movements also exhibit comprehensive phenotypic plasticity and may occur within inland waters (i.e. potamodromous – riverine trout) but also between freshwater and marine ecosystems (i.e. anadromous – sea trout) depending on their life traits, behaviour and physiology (Lucas and Baras 2001; Klemetsen et al. 2003; Cucherousset et al. 2005). Considering the habitat requirements as well as the number of biotic and abiotic factors affecting its selection, this species is particularly vulnerable to habitat degradation, due to river fragmentation (Armstrong et al. 2003; García-Vega et al. 2022). Moreover, near-future scenarios of rising water temperatures and altered hydrological regimes are predicted to affect brown trout populations (Almodóvar et al. 2012; García-Vega et al. 2018), particularly in southern regions where water temperatures are approaching critical limits for the species, thereby reducing habitat availability (Hari et al. 2006; Jonsson and Jonsson 2009). Therefore, the loss of longitudinal connectivity poses one of the most serious threats to their populations' prosperity, reinforcing the need to provide suitable pathways capable of allowing genetic flow and free movements between habitats.

Despite the significant body of research on brown trout's passage through various types of fishways, the effectiveness of brown trout ascending VSFs remains scarce (Sanz-Ronda et al. 2016; García-Vega et al. 2017; Ovidio et al. 2023; Gibouin et al. 2025).

Moreover, limited information exists on how modifications to vertical slot designs, such as incorporating deep notches, might influence brown trout passage.

Therefore, the primary objective of this study was to evaluate and compare the upstream passage performance of the potamodromous brown trout, a vulnerable species (Doadrio 2011), during its spawning migration (Doadrio 2002) across two distinct VSF designs. The designs assessed included: (i) the Revolvo VSF (design flow 0.60 m^3/s), a widely used configuration (FAO/DVWK 2002) (referred to as VS) and (ii) the El Arral VSF (design flow 0.27 m^3/s), featuring a vertical slot with a low sill (Rajaratnam et al. 1986) of 15 cm (referred to as deep notch – DN). Therefore, the following research question was outlined: What is the impact of fishway design on brown trout passage performance? It was hypothesized that a low-flow DN can be as effective for fish to ascend as a conventional VS, saving water and building costs. To pursue these objectives, passage performance trials were conducted for both designs, using motivation, ascent success and transit time as quantitative metrics. Data was analysed using a time-to-event framework, exploring associations with fish biometric parameters (e.g. body length and condition factor), environmental factors and key hydraulic characteristics to highlight factors influencing passage performance.

Materials and methods

Fishways and trials

Brown trout passage performance experiments were conducted in two distinct VSF designs (Figure 1 and Table 1): i) Revolvo – VS and ii) El Arral – DN (Figure 2), both located at the Miera River in Cantabria, northern Spain. Its catchment area is 297 km^2 and produces an average annual discharge of 5.24 m^3/s, ranging from a minimum of 2.64 m^3/s during summer low flows to a maximum of 7.75 m^3/s during peak flows in autumn and winter (average annual precipitation of 1200 mm). Originating in U-shaped glacial valleys characterized by steep topography, the river presents an average longitudinal slope of approximately 3.5% in its upper reaches, which progressively decreases to approximately 0.7% in the lowland sections. The mainstem downstream of the village of Liérganes corresponds to a third-order stream, according to Strahler's classification (Strahler 1957). The riverbed is predominantly composed of limestone bedrock, with coarse karstic sediments in the headwaters transitioning to more finely sorted alluvial deposits downstream. Historical deforestation in the upper catchment has led to widespread land cover change, primarily to pastures and shrublands, while the lower reaches are dominated by agricultural floodplains.

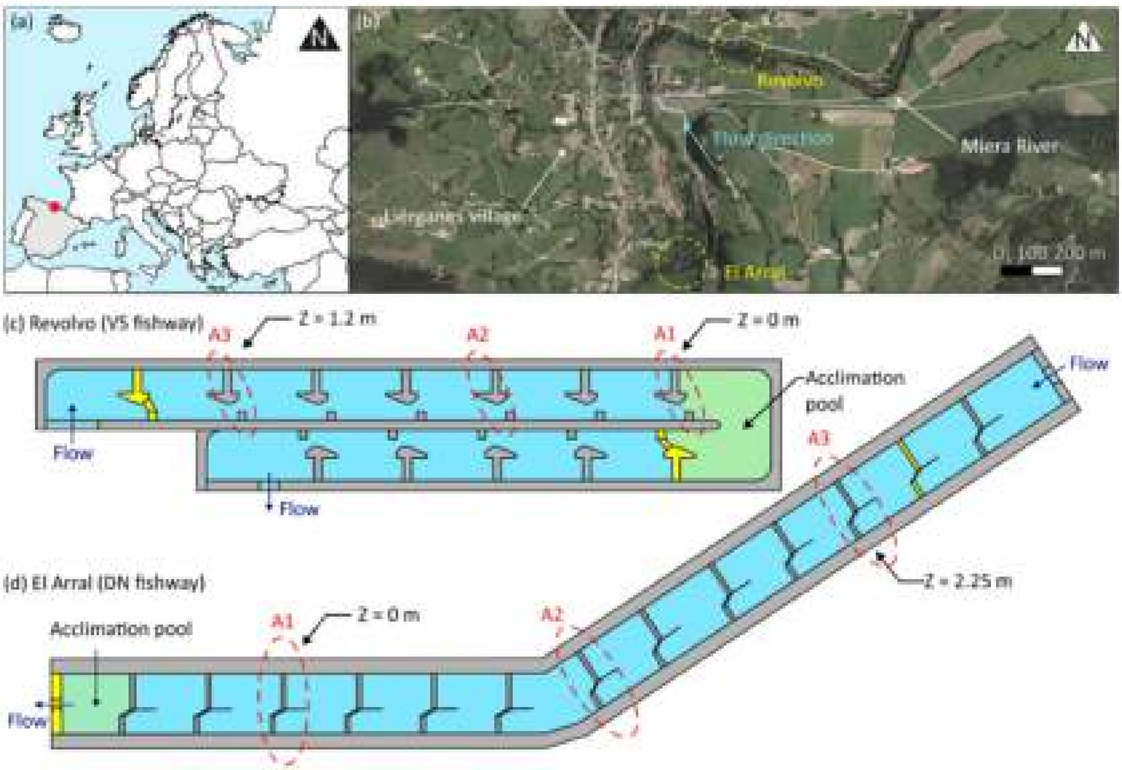

Figure 1. a) And b) study site: Miera river, Cantabria region, in North Spain; c) top view scheme of the Revolvo vertical slot (VS); and d) top view scheme of the El Arral Deep Notch (DN); yellow cross walls: confined studied section; red dotted ellipses: PIT antenna location and position (A1, A2 and A3); green striped Pool: acclimation area; arrows indicate flow direction; Z: relative height (dimensions in meters).

Table 1. Mean geometric and hydraulic variables for the studied vertical slot (VS) and deep Notch (DN) fishways.

Variables	VS	DN
Pool dimension (length × width)	3.00 m × 2.00 m	2.10 m × 1.80 m
Slope	8.00%	7.31%
Total height	3.20 m	3.60 m
Height between antennas	1.20 m	1.20 m
Width of the slot[a]	0.30 m (0.29–0.31)	0.28 m (0.26–0.30)
Height of the notch/sill[a]	NA	0.15 m (0.15–0.20)
Drop between pools[a]	0.20 m (0.19–0.22)	0.23 m (0.20–0.25)
Mean water depth[a]	1.25 m	0.80 m
Flow discharge[b]	0.60 m^3/s	0.27 m^3/s
Volumetric energy dissipation	190 W/m^3 (180–195)	200 W/m^3 (190–220)
Water velocity at the slot/Notch[c]	2.01 m/s (1.95–2.10)	2.05 m/s (1.98–2.10)

Range of values in brackets.
NA: not applicable
[a]Measured with a total station (model Leica TC307) and/or measuring tape ± 0.01 m;
[b]Calculated with (Fuentes-Pérez et al. 2017);
[c]Direct measurements with a propeller flowmeter ± 0.01 m/s (model 2100, Swoffer Instruments Inc.).

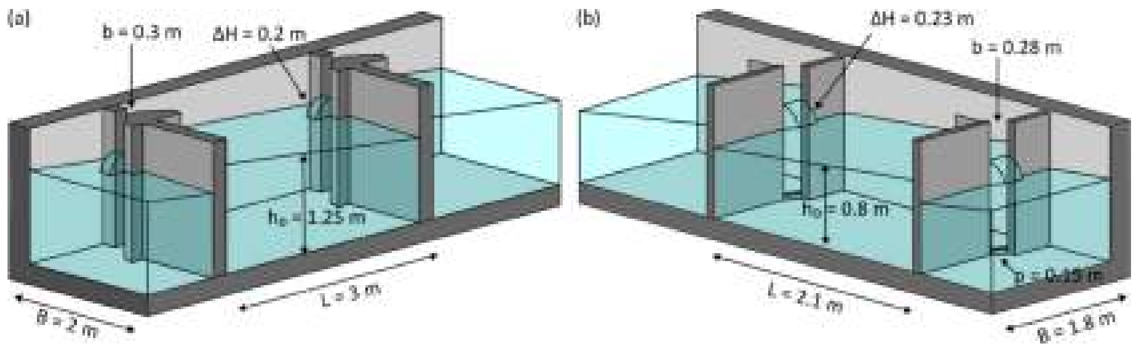

Figure 2. a) Pool and cross-wall details of the Revolvo vertical slot (VS); and b) Pool and cross-wall details of the El Arral Deep Notch (DN). Water drop between pools (ΔH); width of the slot (b); Pool length (L); Pool width (B); Pool mean water depth (h_0); height of the notch/sill (p). Dimensions in meters.

Table 2. Fish samples.

			Fork length (mm)*		Weight (g)*		K*	
Fishway type	Fish trial	*N*	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Revolvo	1	18	190 ± 36	120–245	89 ± 46	18–198	1.18 ± 0.11	0.83–1.35
VS	2	17	189 ± 34	125–250	86 ± 42	26–192	1.19 ± 0.08	0.97–1.33
El Arral	1	18	218 ± 85	112–415	170 ± 190	18–724	1.18 ± 0.13	1.01–1.56
DN	2	17	202 ± 70	122–430	134 ± 193	18–867	1.22 ± 0,10	1.00–1.38

K: Fulton's condition factor [100 × weight (g)/fork length $(cm)^3$];
SD: standard deviation
*Kruskal–Wallis test comparing tested trials on each fishway type: no significant differences (in all cases $p > 0.171$).

Experiments were carried out on 24–25th October 2018 at Revolvo fishway and on 29–30th October 2019 at El Arral fishway. During the experiments, the water temperature was continuously monitored using a data logger (model Orpheus Mini, OTT Hydromet GmbH). Recorded temperatures ranged from 11 °C to 13 °C in the VS and 12 °C to 13 °C in the DN design.

A total of 70 brown trout (Table 2) were used for the experiments. Fish were collected in the river stretch downstream of both fishway entrances one day before the start of the experiments with electrofishing (Hans Grassl ELT60II backpack equipment), following the standard electrofishing procedures (Comité Européen de Normalisation 2003). After the capture, fish were kept in an acclimation tank inside the fishway to recover from the fishing procedure for 24 h. Following the recovery period, each individual was anaesthetized using eugenol (diluted in 95% ethanol at a 1:10 ratio) for 1–2 min. Afterwards, fish were measured (fork length), weighed and marked intraperitoneal with PIT-tags (Passive Integrated Transponders – Oregon RFID®, Portland, OR, USA – tags of 12- and 23-mm length, ensuring < 2% of the fish's body weight). During the handling process, no anomalies were observed in any individual fish and none died.

Fish experiments were outlined as follows: 2 fishway types (VS and DN) × 2 fish trials per configuration, each one composed of 17–18 fish of similar size. Fish trials were performed from 09:00 h to 22:00 h, and started with a 30-min acclimation period at the downstream pool of the studied section of the fishway (Figure 1), to allow each individual to get used to the flow conditions experienced in each fishway type. The acclimation area was composed of two mesh panels placed in the upstream and downstream slots of the pool. Makaras et al. (2021) highlighted the importance of an acclimation period in moderating fish stress before behavioural observations, a well-established procedure, forming a central component of standard methodologies in fish passage assessments (Bravo-Córdoba et al. 2021; Romão et al. 2024). Subsequently, after the acclimation period, the upstream mesh panel was removed, and fish were able to move of their own volition for 12 h. Three pass-through PIT-tag antennas were alternately placed in the slots for monitoring fish movements (Figure 1) (for more details related to the tagging process and the antennas' installation, see Bravo-Córdoba et al., 2018). After the experiments, fish were released into the river in the vicinity of the fishways.

Ethical statement

All fish experiments were performed following European Union ethical guidelines (Directive 2010/63/UE) and Spanish Act RD 53/2013, with the approval of the competent authorities (Regional Government on Natural Resources and Water Management Authority). All procedures were adopted to minimize fish stress.

Data analysis

To investigate differences across fish trials in Fulton's condition factor (weight/length^3) (Nash et al. 2006; Sanz-Ronda et al. 2015), body mass and fork total length, a non-parametric statistical method was employed due to the non-normal distribution of the data. For this analysis, Kruskal–Wallis tests were applied.

The evaluation of fish passage effectiveness in the two fishway designs was based on standardized metrics: motivation, ascent success and transit time. Motivation was estimated by measuring the time from the start of the trial to the first attempt (first detection at antenna A1). Additionally, an attempt rate was calculated as the percentage of fish making at least one attempt, defined by any record at A1 (considering only one record per fish), out of the total number of fish.

Ascent success was measured by counting fish detected at both antennas A1 and A3, representing successful passage, i.e. complete traversal of the tested configuration. Movements were further analysed based on transit time, defined as the time required to travel between A1 and A3 (calculated as the difference between the last record in A1 and the first record in A3). To facilitate comparisons with other fishway assessments, transit time data were relativised by the water height difference between antennas, resulting in a metric of transit time per meter of ascended height (Bravo-Córdoba et al. 2021).

Chi-square tests of independence were used to compare the attempt rate and ascent success between fish trials within and between fishways. If the differences between trials within the same fishways were not significant, they were merged for the subsequent analysis. Cox Proportional Hazard regression was used to examine the impact of key variables (fishway type, fork length and Fulton's condition factor) on outcome measures, including transit time per meter of ascended height and the time between trial initiation and the first attempt. This survival analysis approach uses the concept of survival time (i.e. time or height until an event occurs) (Allison 1995; Castro-Santos and Haro 2003; Castro-Santos). Right censoring was applied for fish that did not make attempts (for the time between trial initiation and first attempt), with the maximum trial duration set at 12 h (720 min).

All analyses were conducted using Statgraphics Centurion version 18.1; Statgraphics Technologies, Inc., The Plains, Virginia) and SAS® (PHReg procedure, SAS Studio web version; SAS Institute Inc, Cary, NC).

Results

Fish trials in each fishway (VS trial 1 *vs*. VS trial 2, and DN trial 1 *vs*. DN trial 2; Table 2) showed no significant differences in all ascent or motivation metrics ($p > 0.05$ in all cases). Therefore, data from both trials in the same fishway design were merged and processed together.

For the motivation analysis, Chi-square tests indicate no statistical significance ($\chi^2 = 0.565$; $p = 0.452$) in attempt percentage. In VS, brown trout displayed a 91.4% (32/35) attempt percentage, while

Table 3. Estimation of the parameters of the Cox Proportional Hazard models [β: regression coefficient; HR: Hazard ratio = exp (β); SE: Standard error] for the response variables in relation to the fork length (mm), the Fulton's condition factor and the fishway type (VS: Revolvo vertical slot; DN: El Arral Deep Notch).

	$\beta \pm$ SE	*p* Value	HR
Time until the first attempt ($n = 70$)			
Fork length (mm)	0.0055 ± 0.0020	0.0050	1.006
Fulton's condition factor		0.4514	
Fishway type = VS	Reference level		
Fishway type = DN		0.2414	
Transit time per meter of ascended height ($n = 53$)			
Fork length (mm)	0.0086 ± 0.0049	0.0016	1.009
Fulton's condition factor		0.1066	
Fishway type = VS	Reference level		
Fishway type = DN		0.1474	

None of the selected Cox models violated the proportional hazard assumptions.

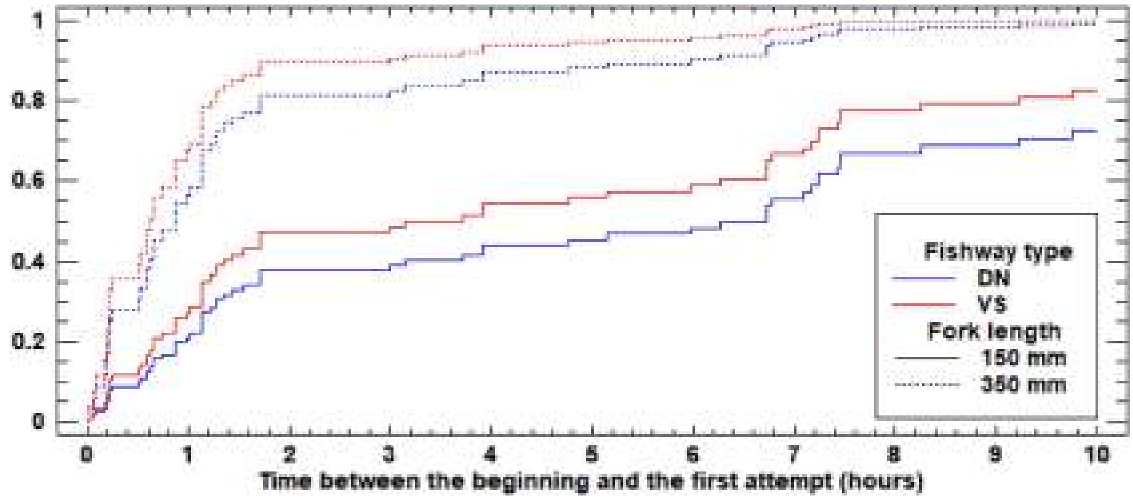

Figure 3. Cox model curves for the proportion of fish attempting to ascend over time since the trial initiation and the first attempt, by fishway type (VS = Revolvo vertical slot; DN = El Arral Deep Notch) and fork length (150 mm and 350 mm, taken as reference values for better visualization).

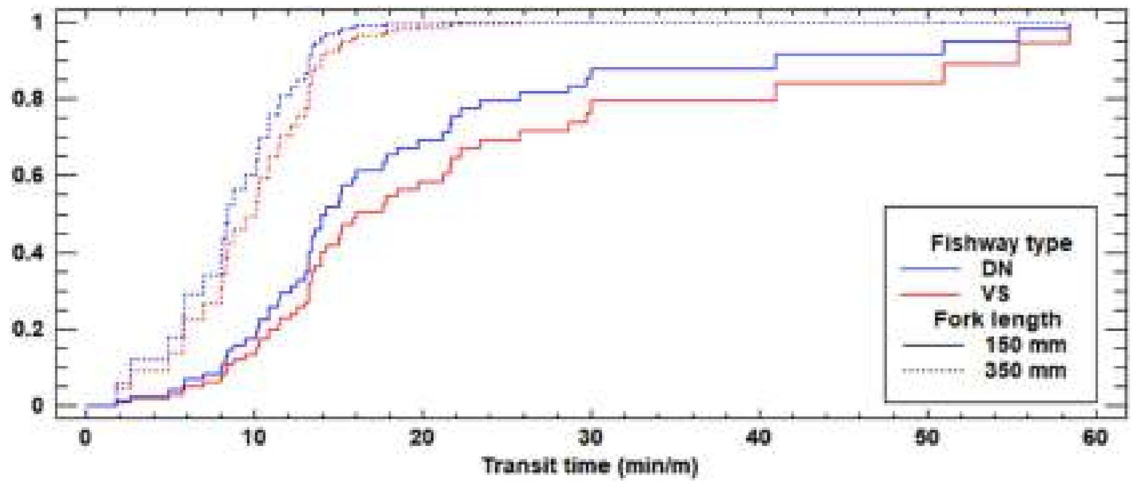

Figure 4. Cox model curves for the proportion of fish that performed passage attempts and the transit time displayed per meter of ascended height, by fishway type (VS = Revolvo vertical slot; DN = El Arral Deep Notch), and fork length (150 mm and 350 mm, taken as reference values for better visualization).

for DN 85.7% (30/35). Concerning the time between the beginning of the trial and the first attempt (median = 77 min; interquartile range: 15–287 min), only the fork length showed a significant relation with this metric (Table 3), which indicates a shorter time for larger fish in both fishway types ($p = 0.005$). Figure 3 provides the Cox model curves depicting the proportion of fish as a function of the time from trial initiation to the first attempt.

Daily movement patterns for the first passage attempts indicated that a majority of activity occurred during the early hours (09:00–11:00), with more than 60% in VS and over 50% in DN.

Considering the ascent success, no significant differences were found ($\chi^2 = 0{,}010$; $p = 0.922$) between both configurations. Brown trout presented 87.5% ascent success (28/32) in the VS, with a quite similar value, 86.7% (26/30), in the DN.

For transit time, the applied Cox Proportional Hazard regression models indicated again only significance ($p = 0.001$) in fork length (Table 3), with no significant effect for fishway type and/or condition factor. Brown trout displayed a median transit time of 15.5 min/m (range: 13.3–21.5) in the VS while in the DN, 11.5 min/m (range: 8.3–13.9). Figure 4 illustrates the Cox model curves depicting the proportion of fish as a function of transit time.

Discussion

Fishway monitoring using quantitative assessments provides researchers and managers with essential empirical evidence to evaluate fishway performance and, consequently, the health of fish populations that depend on these structures to pursue their basic life cycle movements. Despite the large number of unsuitable fishway designs operating in the field (Mallen-Cooper and Brand 2007; Ordeix et al. 2011; Noonan et al. 2012; Santos et al. 2012; Błońska et al. 2024), the importance of quantitative post-construction field monitoring is often overlooked, as well as maintenance (Valbuena-Castro et al. 2020; O'Connor et al. 2022). Therefore, to ensure long-term success, this comprehensive data-driven approach remains one of the most vital steps to pinpoint if the implemented mitigation solution complies with the expected ecological goals (O'Connor et al. 2022). Moreover, from an adaptive management prospect (Castro-Santos et al. 2009), gathering robust field monitoring data is key to enhancing fishway resilience by seasonally adjusting the operational regime, for instance, flows, water depth and shading, to cope with uncertain climate scenarios (Fenkes et al. 2016) and other stressors, such as the presence of non-native invasive species (McLaughlin et al. 2013).

This study compared the performance of two fishway designs installed in the same river, targeting the same species, the brown trout, the most representative taxon occurring in the study area. The results achieved revealed that the tested fish showed a clear motivation to ascend both fishway designs. The analysis of the metrics used as a proxy for motivation showed a high rate of attempts for both cases: 91.4% for VS and 85.7% for DN. About the metric – the time between the beginning and the first attempt – significant differences were evident when comparing fish length in both designs, where larger brown trout took a shorter period to perform their first attempt. These metrics not only indicate that brown trout were intrinsically motivated to perform their spawning migratory upstream movements but also that the hydraulic conditions experienced inside the pools did not inhibit fish from performing attempts to cross both designs. Concerning the relation between fish length and motivation observed in the VS design, a previous study (Bravo-Córdoba et al. 2022) also corroborated this pattern for the same species (temperature range: $6.5 - 8.2\,^{\circ}$C) negotiating a pool and weir fishway with plunging flows and overly high drops between pools.

Considering the ascent movement's analysis or passage success, both designs presented suitable conditions and revealed high success rates for brown trout: 87.5% for VS and 86.7% for DN during 12 h of experimentation. A much lower rate of success was observed by Bravo-Córdoba et al. (2022), where brown trout achieved 19% of ascents. However, in this particular case, the assessed pool and weir fishway exhibited water drops between pools of 0.65 m, exceeding design recommendations maximum limits of 0.20–0.30m for this target species (FAO/DVWK 2002; Larinier 2008). Comparatively, Sanz-Ronda et al. (2016) in similar experimental conditions found a lower rate of success (70%) and attempt rate (38.8%), for the brown trout (mean length ± SD: 220 ± 33 mm) ascending a VSF with a similar slope (7.7%), drops between pools (0.20 m) and Volumetric Energy Dissipation (180–190 W/m^3). Nevertheless, it is worth considering that in those experimental conditions, water temperature ranged between 2.8 and 5.6 °C, which may have inhibited brown trout movements (Ojanguren and Brañta 2000; Taugbøl et al. 2019) while in this study, the temperature ranged between 11 and 13 °C in the VS and 12–13 °C in the DN. According to Garcia-Vega et al. (2017), water temperature significantly influenced the upstream passage of brown trout, with no movement observed at temperatures $\leq$ 4.5 °C. Additionally, other environmental factors, such as river flow and photoperiod, were found to correlate with both seasonal and daily movement patterns (Slavík et al. 2012; Ordeix and Casals 2024). During the spawning season, daily movements were most frequent in the early morning (García-Vega et al. 2017), a pattern consistent with the findings of this study, where the majority of activity (>50%) was also observed during this period.

While ascent success is often regarded as a key metric for evaluating fishway performance, it alone does not offer insights into the passage negotiation process, including the time and effort required for successful passage or the potential impacts on swimming energetics and migratory delays (Caudill et al. 2007; Castro-Santos and Haro 2010; Pon et al. 2012). Therefore, the transit relativised by the distance of ascended height stands as a valuable metric, which allows deducing the potential distance covered in similar hydrodynamic conditions (Bravo-Córdoba et al. 2021). Achieved transit time results highlight that both designs assessed revealed suitable conditions for the brown trout: median transit time of 15.5 min/m in the VS, while in the DN, 11.5 min/m. When compared to Sanz-Ronda et al. (2016) study in a VSF, under similar conditions, the median transit time determined was notably longer, 30 min/m at water temperatures between 2.8 and 5.6 °C. Ovidio et al. (2023) determined a similar median transit time for the brown trout of approximately 12 min/m when ascending a VSF (total height 5.7 m; drop between pools of 0.3 m; Maximum Volumetric Energy Dissipation of 168 W/m^3). According to Bravo-Córdoba et al. (2021), the submerged notch with bottom orifice fishway design (SNBO), assessed for the same target species, also revealed comparable transit times. For instance, in a SNBO with a slope of 7.9%, drop between pools of 0.30 m, brown trout reached a median transit time of 19.4 min/m for a rate of 93% ascent success; or in a SNBO with a slope of 12.5% and same drop per pool achieved 16.0 min/m for a rate of 90% ascent success. It should be noted, though, that the experimental conditions differed in this former case; fish trials were performed by releasing marked individuals in the river section downstream of the fishway, as opposed to the present assessment, where fish were confined inside the facility (Hershey 2021).

Given the transit time values determined for VS and DN, it is possible to estimate that a proportion of the brown trout migrating population occurring in that river stretch could overcome the difference in water elevation from downstream to upstream of the barrier, with no significant migratory delay that could jeopardize population fitness. Nonetheless, although the energy cost is most likely reduced due to the transit time displayed, this assumption does not consider the cumulative effect of swimming costs, generally reflected through physiological or metabolic parameters. For this, other tools could be employed, such as Electromyogram telemetry (Alexandre et al. 2013), acceleration telemetry (Cruz-Font et al. 2016; Thiem et al. 2016) or physiological biopsy (Pon et al. 2009). On the other hand, in this particular case, both VS and DN presented water depth in the pools, drop between pools and Volumetric Energy Dissipation within design recommendations, which, in theory, should ensure resting conditions during ascent movements (FAO/DVWK 2002; Larinier 2008; Romão et al. 2024). The addition of roughness elements, if implemented, could potentially enhance passage performance by facilitating fish station-holding, navigability and contributing to supporting energy efficiency (FAO/DVWK 2002; Santos et al. 2014; Makrakis et al. 2024; Song and Xie 2024).

In the current assessment, consistent with predictions and findings from previous studies (Forty et al. 2016; Bravo-Córdoba et al. 2022), a significant relationship was observed between fish size and transit time, with larger brown trout exhibiting lower passage times in both tested fishways. This aligns with findings from confined and open-channel swimming performance tests, which demonstrated that body size is a strong predictor of enhanced swimming capacity (Beamish 1978; Hammer 1995; Plaut 2001; Castro-Santos et al. 2013). Likewise, fish length has been described as a major driver of fishway passage success across different assessments encompassing multiple species. For example, larger individuals in brown trout populations have been shown to be more successful in overcoming upstream barriers (Jones et al. 2021; Dodd et al. 2024), potentially influencing long-term population structure through phenotypic selectivity (Haugen et al. 2008; Lothian et al. 2020). Field studies carried out with other species in the Meuse River support this pattern, as reported by Ovidio et al. (2023), where larger individuals of *Barbus barbus* and *Squalius cephalus* (a cyprinid and leuciscid species, respectively) were more frequently detected ascending VSF compared to smaller conspecifics. Conversely, Maynard et al., (2017) observed a contrasting pattern reporting a selective pressure against larger-bodied individuals of anadromous Atlantic salmon (*Salmo salar*) in specific fishways in the Penobscot River, illustrating that fishway design and hydrodynamic characteristics can result in size-dependent passage biases that vary by species and context.

As highlighted in several comprehensive review studies (Bracewell et al. 2004; Roscoe and Hinch 2010; Bunt et al. 2012; Noonan et al. 2012; Silva et al. 2018; Hershey 2021; Błońska et al. 2024), biological comparisons among different fishways remain challenging due to a variety of factors. These include inconsistencies in methodologies and evaluation criteria, the absence of detailed hydraulic and hydrodynamic characterizations of fishways, hydrological variability and other environmental conditions that can trigger complex, intrinsic fish behaviours. Such behaviours influence motivational cues for fish migrations, partial migrations and overall population dynamics, often reflecting a gap in foundational knowledge and underscoring the need to gather baseline data (Cooke and Hinch 2013; van Leeuwen et al. 2016; Lothian and Lucas 2021; O'Connor et al. 2022; Fuentes-Pérez et al. 2024). To address these challenges, collecting and analysing quantitative data from both field and laboratory fish passage assessments offers a tailored approach to improving best practices. This strategy supports the design of more efficient, cost-effective and resilient fish passage systems, bridging the gap between fishway design and passage success (Castro-Santos and Haro 2010; Lothian et al. 2020; Romão et al. 2024) and incorporating an adaptive management framework by discharge regulation and/or operating hours (Fuentes-Pérez et al. 2022; Quaranta et al. 2023; Fuentes-Pérez et al. 2024). Our work enhances these efforts because it demonstrates similar performance for brown trout in a low-flow DN (0.27 m^3/s) as in a conventional VS (0.60 m^3/s). Moreover, the study indicates how fish movements concentrate mostly during the morning, corroborating previous findings (García-Vega et al. 2017). Furthermore, incorporating advanced technologies, such as sensor networks (Fuentes-Pérez et al. 2022), computer vision (Rodríguez et al. 2015) and environmental DNA within an adaptive management framework (Quaranta et al. 2023; Nakai et al. 2024) will enhance these efforts. Such an approach should account for ecosystem dynamics, future climate scenarios, invasive species spread and other emerging pressures, providing customised solutions for sustainable fish passage management (Radinger and García-Berthou 2020; Franklin et al. 2024).

This study primarily focused on evaluating the passage performance of brown trout in two fishway designs, both of which adhered to recommended design guidelines for the target species (FAO/DVWK 2002; Larinier 2008). However, fish experiments were carried out under confined circumstances and additional critical factors to the overall success of fish passage, such as attraction, entrance location and exit functionality, should not be overlooked to ensure the study's depth and thoroughness (FAO/DVWK 2002; Williams et al. 2012; Cooke and Hinch 2013; Valbuena-Castro et al. 2020; O'Connor et al. 2022). The quantitative assessment revealed that differences in performance metrics are negligible between the two designs. Overall, it was demonstrated that both designs facilitated adequate passage performance, with no significant delays to migration anticipated. DN may offer additional advantages relative to VS, particularly in rivers with limited discharge, ensuring a suitable water depth during low-flow conditions (Larinier 2002). Given the anticipated intensification of low-flow events due to climate change (Ayllón et al. 2019), this type of operational flexibility may become increasingly critical for maintaining fishway functionality. Moreover, the use of sills in VSFs may also improve their functionality, especially where, due to construction issues or wide variation of up-and-downstream boundary conditions, non-uniform profiles may emerge and compromise the facility operation (Fuentes-Pérez et al. 2019; Zheng et al. 2025). For instance, as a retrofitting option, these structures can be inserted at the base of the slot to restore the pool water depth balance (Ballu et al. 2019; Fuentes-Pérez et al. 2024). Nonetheless, while no significant differences in brown trout performance were observed between VS and DN, the addition of sills affects the flow topology and turbulence inside the pools (Wang et al. 2010; Romão et al. 2024). As Pena et al. (2018) noted, sills improve low-flow functionality by ensuring sufficient water depth but also generate complex, three-dimensional flow patterns with high turbulence, potentially limiting their suitability for a diverse range of species. Hence, further studies are needed to validate and reinforce their broader application.

In conclusion, the findings of this study highlight the effectiveness of both VS and DN fishway designs in facilitating brown trout passage, underscoring their suitability for use in a river system with the characteristics of the study site. The successful passage rates and the clear motivation observed in both fishway types provide valuable insights about design and performance. However, it is important to recognize that the success of fishways is influenced by multiple factors, including fish behaviour (Castro-Santos and Haro 2010; Cooke and Hinch 2013), hydraulic conditions (Wu et al. 1999; Clay 2017), extrinsic environmental cues, such as temperature (Crawford et al. 2024; Xu et al. 2024), moon phase (Bizzotto et al. 2009), photoperiod (Ordeix and Casals 2024), hydrological variability (Fuentes-Pérez et al. 2024) and maintenance, a key factor that can cause functional fishways to fail (Valbuena-Castro et al. 2020). As such, ongoing field testing and refinement of fishway designs will be crucial to ensure their effectiveness in diverse river systems, particularly in light of the increasing pressures of climate change and habitat degradation. By integrating comprehensive monitoring, adaptive management and technological advances (Fuentes-Pérez et al. 2022), fish passage systems can be optimized to better support migratory fish populations and contribute to the restoration of freshwater ecosystems.

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Author contributions

Conceptualization: Francisco J. Bravo-Córdoba, Ana García-Vega, Juan F. Fuentez-Pérez; Ana L. Quaresma, Filipe Romão; Methodology: Francisco J. Bravo-Córdoba, Ana García-Vega, Juan F. Fuentez-Pérez; Validation: Francisco J. Bravo-Córdoba, Filipe Romão; Formal analysis: Francisco J. Bravo-Córdoba, Ana García-Vega, Juan F. Fuentez-Pérez; Ana L. Quaresma, Filipe Romão; Investigation: Francisco J. Bravo-Córdoba, Ana García-Vega, Juan F. Fuentez-Pérez; Data curation: Francisco J. Bravo-Córdoba, Filipe Romão; Writing-original draft preparation: Filipe Romão; Writing-review and editing:

Francisco J. Bravo-Córdoba, Ana García-Vega, Juan F. Fuentez-Pérez; Ana L. Quaresma, Filipe Romão, Francisco J. Sanz-Ronda; Visualization: Filipe Romão, Francisco J. Bravo-Córdoba; Supervision: Francisco J. Bravo-Córdoba, Francisco J. Sanz-Ronda; Project Administration: Francisco J. Bravo-Córdoba, Francisco J. Sanz-Ronda; Funding acquisition: Francisco J. Sanz-Ronda. All authors read and approved the final manuscript.

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ORCID

Filipe Romão http://orcid.org/0000-0003-3811-775X
Francisco J. Bravo-Córdoba http://orcid.org/0000-0003-3687-9902
Ana L. Quaresma http://orcid.org/0000-0002-7854-6850
Ana García-Vega http://orcid.org/0000-0002-3765-9007
Juan F. Fuentez-Pérez http://orcid.org/0000-0003-2384-9085
Francisco J. Sanz-Ronda http://orcid.org/0000-0003-4566-9499

Data availability statement

Data will be available on request.

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