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Review

Fishways in Portugal: Status, Main Findings and Research Needs

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Abstract

Anthropogenic barriers fragment Portuguese rivers, threatening endemic freshwater fish communities. This study compiled national inventories and peer-reviewed research (2002–2024) to quantify fishway implementation, evolution and typology, while evaluating fish performance from published research. One hundred fishways built between 1950 and 2024 were recorded, half of which were constructed after the implementation of the Water Framework Directive in Portugal (29 Dec 2005), tripling the annual construction rate. Fishways were found to be associated mainly with weirs (46%) and small hydropower plants (44%), with typology being dominated by the pool-type design (67%), nature-like facilities (18%), fish locks and combined systems (6% each), fish lifts (2%) and a single eel pass. Forty scientific contributions addressed fishway effectiveness; three-quarters dealt with pool-type facilities, while 12.5% and 10% focused on nature-like fishways and lifts, respectively. Experimental and field studies highlighted species-specific hydraulic preferences, the benefits of vertical slot and multislot configurations, and the potential of retrofitting fishways with macro-rugosities (i.e., fixed structural elements placed on the bottom) to improve non-salmonid fish passage. However, low attraction efficiency, limited multi-season monitoring and risks of aiding invasive species remain a concern. Research needs are proposed, including the refinement of species-specific hydrodynamic criteria, and the development of standardized efficiency metrics and of selective passage solutions, to advance fishway performance under Mediterranean hydrological constraints.

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1. Introduction

The negative impacts of anthropogenic barriers—most notably river fragmentation and regulation caused by instream structures such as dams and weirs—have recently been identified as major factors affecting the sustainability of aquatic biota, with particular concern for fish populations [1–4]. This is quite unfortunate, as fish need to move across varying distances within rivers to satisfy essential needs for reproduction, feeding, and sheltering, and such barriers can disrupt these critical migrations [5,6].

Mitigating the impacts of river fragmentation on fish movements has become a key issue of rehabilitation efforts during the past few decades [4,7]. Although the ideal way to solve the problem of river fragmentation by instream barriers is their removal, particularly when they become obsolete or structurally unsafe [8,9], this often turns out to be unfeasible, as such removal may cause a loss of ecosystem services (e.g., water supply or irrigation, hydroelectricity, tourism) or ecological impacts on the environment [10]. Therefore, the implementation of engineered solutions, namely, fishways, stands as one of the most common tools to improve connectivity for migratory fish [11–14].

Fishways are available in different typologies, ranging from technical engineering structures, made of concrete, to nature-like designs that aesthetically blend into the landscape, resembling natural streams [15]. The widest recognized nomenclature, from FAO [16], identifies three different fishway typologies: (i) technical fishways, i.e., pool-type fishways, such as pool-and-weir (PaW) or vertical slot fishways (VSF), and Denil fishways, generally concrete- or steel-made and built under pre-defined design criteria; (ii) nature-like fishways, usually site-specific, such as rock ramps and nature-like bypass channels, resembling as much as possible natural river sections and employing local materials, and (iii) special fishways, which are specific for certain species (e.g., European eel passes, hereafter eel passes) or conditions (e.g., very high heads, for which fish locks or fish lifts stand up as the most feasible solutions). It is thus important to establish a comprehensive inventory of fishways (e.g., their location, distribution, type of barrier where they are located, typology, year of construction) to better understand their current status, to correct possible malfunctioning and structural deviations, and to ensure the effective protection and management of fish populations to inform policymaking [17,18].

Fishway research has historically focused on the upstream migration of adult anadromous fish, particularly salmonids and clupeids [11,19]. This emphasis led to the development of water velocity and turbulence criteria shaped to these species, based on their physiological swimming capabilities [20]. However, the study of non-salmonid fish, including potamodromous cyprinids and leuciscids, many of which hold lower commercial value, was largely overlooked for decades. Nonetheless, significant progress on fishway research for these species, particularly on design and monitoring, has been made in the last decade with several successful fish passage studies documenting considerable fish passage efficiencies (often > 60%) for cyprinids, clupeids, catfishes and other non-salmonid taxa [21–24]. Similarly, downstream migration, critical for multiple life stages, received comparatively little attention despite its ecological relevance [25,26].

Globally, fishways remain a widely implemented but often ineffective solution, with considerable variability in their performance [22], despite improvements in fish passage efficacy having been noted in the past decade, particularly for non-salmonids [27,28]. While countries with strong salmonid populations, such as those in Northern Europe and North America, historically developed passage systems tailored to these species, the early

adoption of such designs in other regions often resulted in suboptimal performance for diverse local fauna mainly dominated by cyprinids, leuciscids and other small-bodied fish [22,29]. Nonetheless, over the past decade, there has been significant advancement in the design and implementation of multispecies fishways throughout Southern Europe and beyond. Improved fish passage solutions, increasingly informed by local species requirements and regional hydrological conditions, have improved passage success for many non-salmonid fishes [30,31], though knowledge gaps still exist due to their diversity of body shapes and migratory ecologies. As a result, there is a growing recognition of the need for more inclusive and regionally adapted fishway designs to encompass the diverse biological and ecological characteristics of fish assemblages worldwide [11,29].

Water policy instruments, such as the Water Framework Directive (WFD), the EU Biodiversity Strategy and the Nature Restoration Regulation, require fishways to be tailored to the swimming abilities, behavioral traits and physiological limits of multiple fish species and life stages. Research therefore increasingly targets hydraulics—fish interactions and the design or retrofit of passage devices that guarantee year-round passage for representative ecological guilds [4,13,32]. Yet limited knowledge of non-salmonid performance under varied hydraulic conditions has left many facilities—especially fish locks, lifts and Denil designs, and even some pool-type and nature-like fishways used by cyprinids, leuciscids and other taxa—operating below their goals [4,33,34]; despite recent field and laboratory advances, most fishways still require significant improvement to fully counteract habitat fragmentation for entire fish communities.

This study provides an overview of the fishways installed in Portugal, as well as the main findings from field and laboratory fishway research conducted therein over the last 22 years (2002–2024). The country supports a freshwater fish fauna with a high degree of endemicity, with nearly three-quarters of the species being endemic, often exhibiting highly restricted distribution ranges [35,36]. As a result, these species are generally more vulnerable to threats than those with wider distributions [37]. The prime goals of this study were as follows: (i) to catalogue the number, type, year of construction (i.e., before or after the implementation of the WFD) and fishway location (e.g., at small barriers, small hydropower plants and dams), therefore providing a regional view of fishway requirements, and (ii) to systematize the main findings achieved from studies conducted over the different fishway types, highlighting future needs for operative actions and research. This study constitutes a preliminary assessment, aiming to provide a foundation for subsequent in-depth investigations, while sharing fishway technical information and contribute to improved fishway design and construction, and contribute to fish conservation.

2. Materials and Methods

2.1. Fishway Mapping

The number of fishways, the river basin to which they belong, the barrier type upon which they were built, as well as their type and year of construction, were compiled from the databases provided by the Portuguese Environmental Agency (APA) and the Institute for Nature Conservation and Forests (ICNF). Barriers were regarded as anthropogenic structures that could interrupt the ecological processes described by the River Continuum Concept [38], and their types, upon which fishways were constructed, were categorized as (i) weirs (i.e., small barriers that allow the water to flow over the crest of the structure [10]), (ii) small hydropower plants (SHP, i.e., plants with installed capacity < 10 MW, [39]), and (iii) dams. As for the type of fishways considered, the following major categories were used according to the nomenclature from FAO [16]: pool-type fishways (e.g., pool-and-weir (PaW), single (VSF) or multiple vertical slots (MSF)), nature-like fishways, fish lifts, fish locks and eel passes (Figure 1).

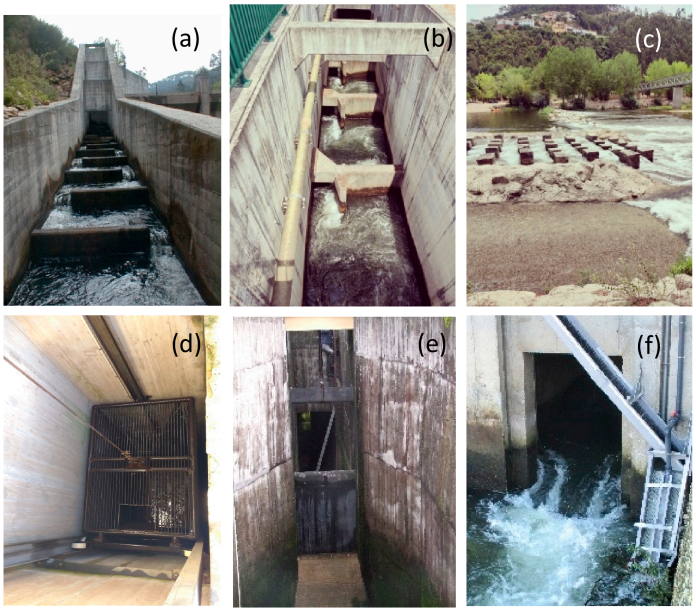


Figure 1. Most common types of fishways addressed in the present study: (**a**) PaW at São Pedro do Sul (#53); (**b**) VSF at Ponte de Coimbra I (#78); (**c**) nature-like (fish ramp) at Palheiros (#76); (**d**) fish lift at Touvedo (#8); (**e**) fish lock at Crestuma-Lever (#37) and (**f**) eel pass at Ponte de Coimbra II (#77). Combined systems (e.g., PaW with fish lift) are also present (fishways codes are provided in Table S1).

2.2. Literature Search

The literature reviewed spanned a 23-year period from 2002 to 2024 to capture the infancy of fishway science in Portugal up to the most recent published research, encompassing the implementation of the WFD (2006). The search was performed using the Institute for Scientific Information (ISI), Web of Science (WoS) and Google Scholar. The search in ISI WoS used the WoS Core Collection database and the query for each type of fishway was TOPIC = (fish passage) AND (fishway type), where fishway type here followed the nomenclature defined by FAO [16]—(a) pool and weir OR vertical slot, representing the technical fishways; (b) nature-like, representing the close-to-nature fishways; (c) fish lift, and (d) fish lock, with both these latter representing special fishways. Conference proceedings were also included in the study, but only if their content, or part of it, was not published as an article in a WoS journal. Selected sources were then refined by COUNTRIES/REGIONS = (Portugal).

2.3. Data Analysis

Chi-square tests of proportions [40] were employed to test for significant differences in (i) the fishways built before and after the implementation of the WFD in Portugal (2006); (ii) the spatial distribution of fishways between the temperate and Mediterranean river watersheds; (iii) the types of barriers upon which fishways were constructed, and (iv) the most common types of fishways. Tests were performed on the MedCalc® Statistical Software version 22.021 (MedCalc Software Ltd., Ostend, Belgium; https://www.medcalc.org; 2025). Due to their specificity, the analyses of the key results of the existing studies on pool-type fishways were performed separately for pool-and-weir and for vertical single- or multiple-slot fishways.

3. Results and Discussion

3.1. Fishways Inventory, Typology and Effectiveness

A total of 100 fishways built from 1950 until December 2024 were identified (Table S1), representing a density of 0.0011 fishways/km^2, which is almost identical to the correspond-

ing Spanish value (0.0012 fishways/km^2), where 612 fishways are catalogued (Sanz-Ronda, pers. comm.).

Half of the fishways (49%) were built before the implementation of the WFD in 2006, whereas the other half (51%) were built thereafter, with no significance between proportions ($\chi 2 = 0.019$, $p > 0.05$). However, the construction rate of such devices tripled from the pre-WFD period (0.88 fishways/year) to the post-WFD (2.68 fishways/year).

The distribution of fishways among the territory is not uniform—80% are located within the northern and central watersheds; the remaining 20% are located in the Mediterranean southern part of the country, in the Tejo, Sado and Guadiana basins, where temporary rivers prevail ($\chi 2 = 25.57$, $p < 0.001$) (Figure 2) and fish recolonization after seasonal droughts [41] is more dependent on the existence of flow connectivity.

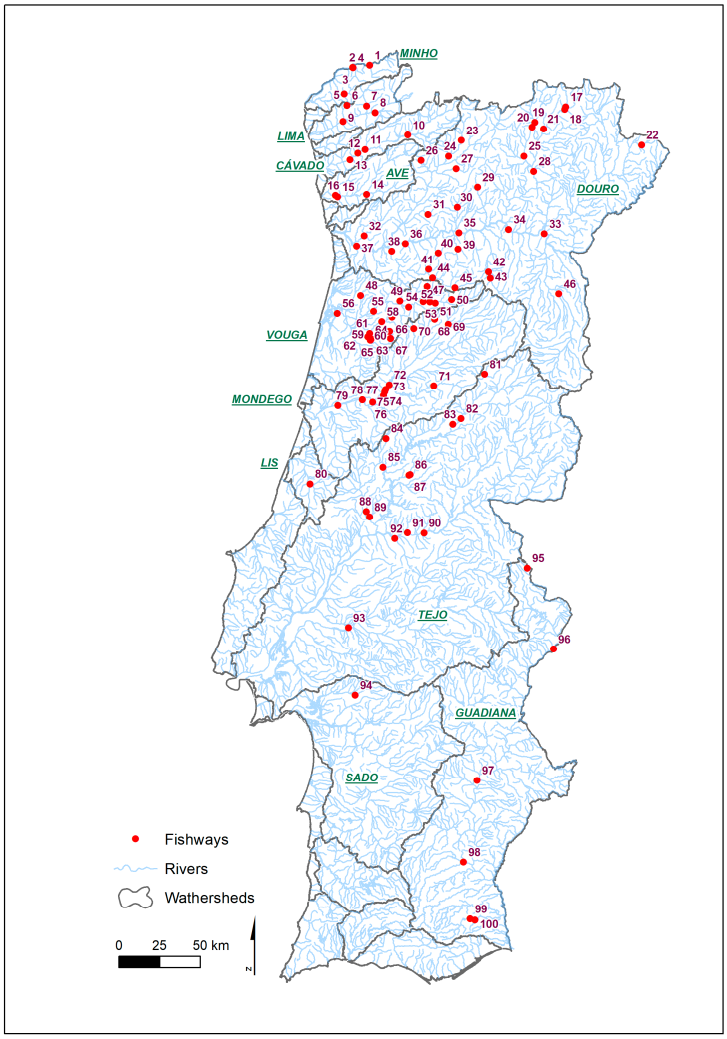


Figure 2. Map of the 100 fishways located in Portugal. See Table S1 for fishway name, type and year of construction (some points overlap due to fishway proximity).

Fishways were built at different types of instream obstacles, namely, weirs (46%) SHP (44%) and dams (10%), with significant differences in the proportions between the former and the latter (weirs vs. dams; $\chi 2 = 30.75$, $p < 0.001$; SHP vs. dams; $\chi 2 = 29.23$, $p < 0.001$). Regarding fishway design, the pool-type fishway (encompassing PaW, VSF and MSF) was found to be the most commonly used (67%), followed by nature-like facilities (18%), fish locks and combined systems, each accounting for 6%, fish lifts (2%) and eel passes (only one device, 1%). Significant differences between these proportions were found for pool-type fishways when compared to the other designs ($\chi 2$ tests, $p < 0.05$) (no test was conducted for

lifts and eel passes, due to the respective very low sample sizes). All fish locks and lifts (100%) were found to have been built before the implementation of the WFD. In contrast, almost all nature-like facilities (n = 17, 94.4%) were built after the implementation of the WFD ($\chi 2 = 21.19$, $p < 0.001$).

Of the 100 fishways, only 37—all pool-type fishways built at SHP—have been previously evaluated for hydraulic effectiveness, taking into account connectivity parameters, such as the suitability of the dimensions of openings for target species, fish entrance attraction and the presence of obstructions in notches and orifices, as well as present hydraulic conditions measured on site [13]. The results reveal that more than half of these facilities (51%) were hydraulically unsuitable for their target potamodromous fish species, mainly due to non-adequate design criteria primarily adapted from northern European contexts that poorly matched the requirements of local fish assemblages and site hydrology. The main reasons for this low overall fishway effectiveness included insufficient entrance attraction, orifices and notches blocked by debris, overly high turbulence, and inadequate pool sizes and head drops, possibly leading to the disorientation or exclusion of smaller-bodied fish.

3.2. Scientific Finding of Fishway Research in Portugal

We searched the literature in the ISI WoS and Google Scholar on the existing studies on fishways in Portugal between 2002 and 2024, resulting in a total of 40 contributions (Table 1), of which 30 (75.0%) were from pool-type fishways (i.e., PaW and VSF designs), 5 (12.5%) from nature-like fishways, 4 (10.0%) from fish lifts and 1 (2.5%) from fish locks.

Table 1. Key results of the existing studies on fishways in Portugal conducted between 2002 and 2024, outlining the fishway type, the environment (Env.) where the study was conducted (field or lab), the target species and the key results. PaW—pool and weir; VSF—vertical slot fishway; MSF—multiple-slot fishway; NA—not applicable.

Fishway Type	Ref.	Env.	Species	Key Results
Pool-type (PaW)	[42]	Field	I. nase	Continuous fish passage info collected by the infrared counter. Counter not accurate for monitoring small fish, <15 cm total length (TL). Peak movements in spring and associated with water temperature.
Pool-type (PaW)	[43]	Lab	I. barbel	Orifices were the clear choice by which to negotiate the fishway. Orifices and notches were equally used during streaming flow. Orifices used much more than notches during plunging flow.
Pool-type (PaW)	[44]	Lab	I. barbel	Electromyogram telemetry (EMG) useful to study fish behavior in fishways allowing us to estimate muscle activity and energetics.
Pool-type (PaW)	[45]	Lab	I. barbel	Fish passage success was size-related (higher for larger fish). Fishway transit time was size-related (lower for larger fish). Reynolds shear stress (RSS) was the most important variable.
Pool-type (PaW)	[46]	Lab	I. barbel	Orifice arrangement influenced fish passage success. Offset orifices with higher passage success than straight ones. RSS was the most influential hydrodynamic variable.
Pool-type (PaW)	[47]	Lab	I. barbel	Fish response to turbulence was size-related. Fish transit time across orifices was highly influenced by RSS. Large fish behavior strongly affected by the eddies.
Pool-type (PaW)	[48]	Lab	I. barbel	EMG-tagged fish exhibited high passage success. Fish used burst swimming to move through the orifices. Horizontal RSS most related to fish swimming speed.

Table 1. *Cont.*

Fishway Type	Ref.	Env.	Species	Key Results
Pool-type (PaW)	[49]	Lab	I. barbel I. chub	Fish use of notches higher during streaming flow. Fish passage success higher in streaming flow. Streaming flow better suited in the presence of multiple species.
Pool-type (PaW)	[50]	Lab	I. chub	Higher passage success under streaming flow regime. Plunging flow prevents access to surface notches. Streaming flow stands as a sound option for small species.
Pool-type (PaW)	[51]	Lab	I. barbel	Boulder placement facilitated fishway negotiation. Boulder placement can be a useful tool in river restoration. Boulder placement optimization design is species/size-specific.
Pool-type (PaW)	[52]	Lab	I. barbel	No difference in passage success between flow regimes (d/h [1]). Fish transit time was lower in flow regime with lower d/h. Lower relative depth of flow more beneficial to fish passage.
Pool-type (PaW)	[53]	Lab	I. barbel	No difference in passage success between boulder spacings. Fish passage success was found to be discharge-related. Higher boulder density and discharge (Q) lowered transit time.
Pool-type (PaW)	[54]	Lab	I. barbel	Fish passage success was flow-related when using boulders. Fish passage success was independent of boulder density. Fish passage success was higher at lower Q when using grass.
Pool-type (PaW)	[55]	Lab	NA	PIV [2] and ADV [3] showed good agreement on key hydraulic variables. PIV showed a higher resolution in turbulence characterization. Despite lower resolution, ADV can accurately estimate turbulence.
Pool-type (PaW)	[56]	Lab	NA	3D numerical model able to reproduce the fishway flow field. Importance of model validation is highlighted. CFD [4] models may reduce and complement physical model testing.
Pool-type (VSF)	[57]	Field	Sea lamprey	1/3 of marked individuals passed the fishway in less than 24 h. Overall fishway efficiency was 31%; time to ascension was 3 h. Fish passage occurred mainly at night, with $Q < 50\ m^3s^{-1}$.
Pool-type (VSF)	[58]	Lab	I. barbel I. chub	Passage performance differed according to slot configuration (SC). SC2 (lateral baffle only) yielded the highest number of movements. SC2 is more cost-effective as it requires less water to operate.
Pool-type (VSF)	[59]	Lab	I. barbel	Fish made broader use of pools with lower head drops. Fishway walls were determinant for spatial usage. Need to consider hydrodynamic scenarios for fishway assessments.
Pool-type (MSF)	[60]	Lab	NA	MSF needed lower discharge to operate than VSF. Velocity and turbulence were found to be much lower in MSF. MSF can be less selective for small-sized species.
Pool-type (VSF)	[32]	Lab	I. barbel	No difference in fish performance metrics between seasons. Muscular fatigue was higher in autumn than in spring. Fish passage assessment can be further extended to autumn.
Pool-type (VSF/MSF)	[61]	Lab	I. barbel	Higher number of movements in MSF than in VSF. Fish passage performance was similar between MSF and VSF. MSF revealed to be a more discharge-efficient configuration.
Pool-type (VSF)	[62]	Field	Sea lamprey	Upstream migration mainly in spring and during the night. Environmental triggers were flow and temperature. In dry years, temperature is key for upstream migration.
Pool-type (MSF)	[63]	Lab	I. barbel I. chub	No difference in fish passage success between seasons. Chub: higher entry efficiency and lower transit time in spring. MSF stands as a promising cost-effective design for non-salmonids.

Table 1. *Cont.*

Fishway Type	Ref.	Env.	Species	Key Results
Pool-type (All)	[14]	Lab Field	I. barbel	Review paper (2009–2019) of pool-type fishways for I. barbel.
Pool-type (VSF/MSF)	[64]	Lab	I. barbel I. chub	Entry efficiency was higher in MSF than VSF. Entrance and transit time were lower in MSF. Velocity and turbulence were 30–70% lower in MSF.
Pool-type (VSF)	[65]	Field	A. shad T. shad	Almost all (95.6%) shads migrated in April and June. Environmental triggers were flow and temperature. Fishway use was variable between years.
Pool-type (VSF)	[66]	Field	Grey mullet	Annually c. 500 k fish migrate upstream to freshwaters. Movements are diurnal; migrants are mainly young adults. Upstream movements increased with temperatures > 15 °C.
Pool-type (VSF/MSF)	[67]	Lab	I. barbel I. chub	Meta-analysis on VSF to identify the best solution. Fish size is the main predictor of fish passage. MSF with orifice as the best-performing configuration.
Pool-type (VSF)	[68]	Lab	I. barbel	Higher-than-recommended turbulence did not impair fish passage. Spatial turbulence distribution was more important for fish passage. General design guidelines for cyprinids may be overly conservative.
Pool-type (VSF)	[69]	Field	I. barbel I. nase	Both species exhibited autumnal upstream migration movements. Both species showed a clear preference for diurnal movements. Flow and water temperature were the most influential variables.
Nature-like	[70]	Field	All	Nature-like bypass was used by different species and size-classes. Bypass was effective for almost all species and sizes. These facilities should be encouraged in river restoration.
Nature-like	[71]	Lab	I. barbel	Fish passage success decreased with increasing ramp length. Successes and passage efficiency peaked at intermediate slope. Higher but not excessive slopes can be more cost-effective.
Nature-like	[72]	Lab	I. barbel	Passability of ramped weirs was affected by retrofitting design (RD). The “Nature” RD was the most successful configuration. Natural substrate may increase the permeability of ramped weirs.
Nature-like	[73]	Lab	I. barbel	“Nature” RD enhanced fish passage performance. Increasing discharge reduced upstream fish movements. Fish physiological parameters were affected by discharge.
Nature-like	[74]	Field	All	Minimum flow (3 m^3s^{-1}) required for all species to pass the ramp. Modeled ramp passability was species-specific. Ramp passability will reduce under climate change scenarios.
Fish lift	[75]	Field	All	Cyprinids and leuciscids were the dominant fish that used the lift. Movements peaked in the spring and were related to reproduction. Water temperature was the most important trigger.
Fish lift	[76]	Field	E. eel	Reducing fish-lift gap width may decrease yellow eel escape. Eel movements occurred mainly in summer and early fall. Rainfall and moon illumination were the main migration triggers.
Fish lift	[77]	Field	All	Most potamodromous fish used the lift in summer and early fall. Temperature (cyprinids) and flow (trout) as migration triggers. Movements differed according to peak-flow magnitude.
Fish lift	[78]	Field	All	First record of the red swamp crayfish passing through a fish lift. Use occurred in summer and at periods of turbine shutdown. Crayfish passage should be considered when planning fishways.

Table 1. *Cont.*

Fishway Type	Ref.	Env.	Species	Key Results
Fish lock	[79]	Field	All	Diadromous eels and mullets were the most abundant species. Movements were evident all year round, especially in summer. Moon, discharge and tide were the main migration triggers.

Notes: [1] d—water depth; h—height of artificial bottom substrata; [2] PIV—Particle Image Velocimetry; [3] ADV—Acoustic Doppler Velocimetry; [4] CFD—computational fluid dynamics.

3.2.1. Pool-Type Fishways (Pool-and-Weir)

Of the 30 papers on pool-type fishways, 15 (50%) specifically concerned the PaW design. Of these, 11 (73.3%) took place with a smooth bottom, whereas the other 4 (26.7%) were developed under different bottom roughness configurations.

Smooth Bottom

From the 11 papers on PaW fishways with smooth bottoms, only 1 (9.1%) took place in the field, whereas the remaining ones (n = 10, 90.9%) were developed in the laboratory under experimental conditions (Table 1).

The field study examined the movements of potamodromous fish—Iberian straight-mouth nase *Pseudochondrostoma polylepis* (hereafter nase)—migrating through a PaW fishway in Zêzere River (Tejo basin) to collect information on seasonal and daily patterns of passage and identify the main triggers of migration. Monitoring was performed by infrared beaming technology [42], and the results show that peak migration occurred mainly in spring, independent of time of day, with water temperature being the main trigger of fish migration.

From the 10 experimental studies on the PaW design with a smooth bottom, 6 (60%) focused solely on the Iberian barbel (*Luciobarbus bocagei*), a large potamodromous cyprinid (hereafter barbel); 1 (10%) focused on the small-sized Southern Iberian chub (*Squalius pyrenaicus*), a leuciscid (hereafter chub); 1 (10%) focused on both species, and 2 (20%) focused on hydrodynamics and numerical modeling without live fish. All studies were conducted in the full-scale (1:1) pool-type fishway model at the National Laboratory of Civil Engineering (LNEC), Lisbon [46,53,58]. The facility, measuring 10 m long × 1 m wide × 1.2 m high, features glass sidewalls for behavioral observation, and was set at an 8.5% slope, within typical fishway ranges [80]. It consisted of six pools divided by five steel, polypropylene or plywood cross-walls, incorporating submerged orifices, surface notches, or vertical slots (single or multi-slots), with adjustable dimensions, depending on the study objectives. Experimental studies on hydrodynamics and numerical modeling, conducted without live fish, also used a 1:2.5 scaled pool-type fishway model at LNEC's facility, installed in the Hydraulics and Environment Laboratory of Instituto Superior Técnico (IST). Early studies analyzed the effects of hydraulic conditions on barbel upstream passage in the pool-type fishway using different-sized fish. Monitoring methods included visual observation, video analysis, and electromyogram telemetry to study swimming behavior. Overall, the fishway was deemed effective, with key findings indicating the following: (i) submerged orifices were preferred, especially under plunging flow, though small fish struggled to pass [43]; (ii) turbulence metrics (TKE and RSS) significantly affected smaller fish [45,48]; (iii) offset orifices improved passage over straight ones [46]; and (iv) turbulence responses were size-related and highly influenced by RSS [47].

Orifices were predominantly used (>75%) over notches, consistent with findings for other species [81]. Ref. [43] suggested that, despite similar velocities, flow from submerged orifices provided a stronger cue. Ref. [49] found that under plunging flow, most upstream movements (>75%) occurred through orifices, whereas in streaming flow, both openings

were used in similar proportions. The limited use of surface notches in plunging conditions was likely due to the barbel's weak leaping ability (but see [82]). Passage efficiency was size-related, with larger barbel performing better (higher success and lower time), a trend also reported in other Iberian studies [83,84].

Among the hydraulic variables affecting barbel behavior [45–48], RSS was the most influential, particularly for smaller individuals, where it significantly correlated with passage time [46]. Passage success was higher for larger fish (80%) than for smaller ones (<60%) in an offset orifice arrangement [45,46]. In contrast, performance was lower and not size-related in a straight orifice setup [46,47]. The higher RSS and greater velocity variations in straight arrangements likely disoriented fish, thus decreasing overall passage performance.

Refs. [49,50] demonstrated that flow regime (plunging vs. streaming) affects fishway negotiation, particularly for barbel and the surface-oriented chub. The results show that (i) both species preferred surface notches during streaming flow, (ii) chub used notches more frequently in streaming flow, and (iii) upstream passage success was higher for both species in streaming than in plunging flow. The authors concluded that streaming flow improves passage by creating a continuous surface current, reducing energy expenditures by allowing fish to swim rather than leap over notches.

Bottom Roughness

Studies concerning the use of bottom roughness in PaW fishways (n = 4, 26.7%) were all experimental and used the barbel as the target species.

Building on previous findings, research has explored retrofitting fishways with bottom roughness to enhance passage efficiency. Studies tested embedded boulders at varying densities [53] and heights [52], as well as artificial grass [54], in a pool-type fishway. Flow remained uniform (ranging from 38.5 to 77.0 Ls^{-1}) with a constant head drop (Δh = 0.16 m). Key findings include the following: (i) passage success increased with flow, from 25% at lower flows to 50% at higher flows [53]; (ii) success was independent of boulder density [53]; (iii) higher boulder density combined with reduced transit time [53]; (iv) lower relative flow depth ($1.3 < d/h < 4$) improved passage efficiency compared to higher ones ($d/h > 4$) [52]; and (v) artificial grass enhanced passage success at lower flows [54].

The increase in fish passage success at higher flows likely resulted from more pronounced velocity gradients in the vertical and lateral directions near the fishway entrance and orifices. These gradients, especially those found along the shoreline and near the bottom, provide key cues for upstream migrants who use these regions—not because they experience flow acceleration, but because the presence of vertical or lateral changes in velocity helps them navigate and orient in the fishway environment [85]. Contrarily, transit time was influenced by boulder density at the highest discharge, with fish negotiating the fishway faster under higher densities. This may be due to reduced delays caused by high-velocity areas near orifices in lower-density scenarios, aligning with findings that denser boulder spacing enhances hydraulic heterogeneity and facilitates passage [86].

Experiments on flow regimes—based on the relative depth (d/h) of flow (i.e., regime 1 = $d/h > 4$; regime 2 = $1.3 < d/h < 4$)—on barbel revealed similar passage success but significantly shorter transit times under regime 2. This was likely due to the higher spatial hydraulic heterogeneity and small recirculation zones, which aid upstream movements [87]. In contrast, the larger recirculation in regime 1 may have led fish to become disoriented and delayed passage [88].

3.2.2. Pool-Type Fishways (Vertical Single- or Multiple-Slot)

Of the 30 papers on pool-type fishways, 14 (46.7%) specifically concerned the vertical single- (VSF) and/or multiple-slot (MSF) design. Of these, 5 (35.7%) were field studies,

8 (57.1%) were experimental and 1 (7.1%) was a meta-analysis paper aiming to identify the best configuration [67].

All five field studies took place in the Ponte de Coimbra I VSF (see Table 1). The VSF is a 125 m-long channel with an average water depth of 2 m. The channel is divided into 23 rectangular pools (4.5 m long × 3.0 m wide), which are interconnected by vertical slots, each 0.5 m wide, with an average velocity of 1.5 m s^{-1} and volumetric dissipation power of 222 Wm^{-3}, creating a uniform head drop of 0.25 m between successive pools [57,69].

Most of the field studies (n = 4, 80%) focused on diadromous species, including sea lamprey *Petromyzon marinus* (n = 2) [57,62], allis shads *Alosa alosa* (n = 1) [65] and thinlip grey mullet *Chelon ramada* (n = 1) [66], over an average four-year period. These studies analyzed seasonal and daily up-and-downstream movement patterns, quantifying annual fish stocks and correlating movements with environmental variables, like river flow and water temperature [62,65,66], highlighting their importance for species life cycles and the food web, particularly in the case of the mullet [66]. Fish pass efficiency was assessed to address fine-scale movements for sea lamprey using radio and PIT telemetry, revealing a 31% success rate, with one-third of the individuals passing in less than 24 h [57]. A more recent study targeting the same objectives on potamodromous species, barbel and nase, found that both species primarily migrated in spring during day-time, with a second peak of migration occurring in autumn, with river flow and water temperature being the main environmental triggers of migration [69].

Experimental studies (n = 8) conducted using the pool-type fishway model at LNEC focused on vertical single- (VSF) or multiple-slot (MSF) fishways, with the following parameters:

- Three (43%) used both the barbel and the chub, aiming to compare species performance upon negotiating (i) a VSF with distinct slot configurations [58], (ii) an MSF across distinct seasons (i.e., spring and autumn) [63], and (iii) both a VSF and an MSF, with focus on entrance performance (i.e., entrance time and entry efficiency) and transit time [64];
- Four (50%) used solely the barbel as the target species, and assessed (i) fish performance in a VSF under different seasons (spring, the reproductive season vs. autumn) [32], (ii) the effect of non-uniformity of flow on fish behavior under different hydrodynamic scenarios (uniform, non-uniform backwater and non-uniform drawdown) [59], (iii) fish passage performance when negotiating two different types of VSF, i.e., a standard VSF and an MSF [61], and (iv) the hydraulic thresholds for VSF in a tentative attempt to develop more efficient and less costly VSF [68];
- One (14%) did not use fish, but employed a modeling approach to compare hydrodynamics between VSF and MSF [60].

Overall, results show that (i) modifying VSF slot configurations reduced operational costs without compromising effectiveness for endemic cyprinids and leuciscids with different ecological traits [58]; (ii) VSFs effectively facilitate potamodromous cyprinid passage year-round, though fish may exhibit higher effort (elevated lactate levels) in early autumn [32]; (iii) computational fluid dynamics (CFD) accurately models fishway hydrodynamics, reducing reliance on physical models [60]; (iv) MSF operated with 26–50% less water than a standard VSF while maintaining equivalent effectiveness for a potamodromous cyprinid [61]; (v) MSF is an effective multi-species fishway [63], and (vi) higher-than-recommended turbulence levels in VSF did not impair cyprinid fish passage success [68].

The first study comparing two slot configurations (C1—central and a lateral baffle; C2—lateral baffle only) derived from [89] found no significant differences in passage performance [58]. Nonetheless, configuration C2 required less flow (81 Ls^{-1} vs. 110 Ls^{-1} for C1), making it a more cost-effective design, particularly in water-scarce regions like

southern Portugal. Further testing C2 for barbel in the spring reproductive season [90] and early autumn showed no seasonal differences in passage performance, except for higher entry efficiency in early autumn [32]. These findings suggest that fish motivation to enter VSF extends reproductive migration, supporting seasonal flow adjustments differences as reinforced by recent meta-analysis [67].

Ref. [60] used CFD modeling (FLOW-3D) to compare hydrodynamics between VSFs and MSFs, the latter being a recently developed fishway design. The study assessed two VSF configurations [58] and three MSF configurations differing in the inner wall of the pool entrance to evaluate their suitability for cyprinid and leuciscids. The results show that (i) the MSFs required less discharge and exhibited lower velocity, TKE, and RSS, suggesting a less challenging environment for non-salmonids. MSFs also provided larger low-velocity, low-turbulent areas, favoring smaller fish, though live-fish testing was required to confirm these findings.

Ref. [61] then tested wild Iberian barbel in the most effective VSF (C2; [58]) and an MSF (MSF1; [60]). The VSF exhibited higher velocities and turbulence (TKE and RSS), particularly near the slots, creating more challenging conditions. While no differences were found in entry time and efficiency or passage success, fish showed a significantly larger number of movements in MSF. All this notwithstanding, the MSF required 30% less water to operate at the same pool depth, highlighting its discharge efficiency. Ref. [63] extended MSF experiments to South Iberian chub and different seasons to evaluate multi-species passage efficiency in and outside the reproductive migratory period. Fishway settings remained consistent with those in previous studies [32,58,61] to ensure valid comparisons. FLOW-3D modeling characterized fishway hydrodynamics. The results show seasonal and species differences—in spring, chub had higher entry efficiency and shorter transit time, while barbel showed no seasonal variation, aligning with [32] on VSFs. Frequent bidirectional movements through the first slot indicated suboptimal hydraulic conditions at the fishway entrance. Nonetheless, the MSF proved effective for cyprinids and leuciscids with varied morphologies and swimming abilities, offering a discharge-efficient solution for fishways in water-scarce Mediterranean regions.

Ref. [64] compared the entrance and transit time performances between two VSFs and two MSFs configurations, maintaining an identical design but operating at different discharges to achieve hydraulic equilibrium under uniform flow conditions [16,91]. MSFs showed higher entry efficiency and lower entrance and transit times. Numerical modelling revealed 30% lower velocities in MSFs, with turbulence reductions of around 70% in RSS and 50% in TKE. These findings confirm MSFs as a cost-effective alternative, balancing water use trade-offs and offering a viable solution where water scarcity or site constraints prevent the installation of other types of fishway facilities, such as nature-like ones [92].

More recently, Ref. [68] assessed established hydraulic guidelines for VSF designed for cyprinid passage, focusing on whether current turbulence thresholds are overly conservative. For that, and motivated by the need to develop species-specific guidelines, the authors conducted experiments at the full-scale fishway with a steep 15.2% slope, testing four configurations—two standard VSF and two with deep notch modifications—at different water depths and flows. Barbel passage performance was assessed by PIT telemetry, analyzing motivation, ascent success, and transit time, while hydrodynamics was characterized by CFD. The results show that (i) the standard VSF with the highest turbulence (volumetric dissipation power, Pv = 222 Wm^{-3}) had the best passage performance, challenging the prevailing Pv < 150 Wm^{-3} guideline for cyprinids, and that (ii) the spatial distribution of turbulence and velocity, rather than their average magnitudes, was found to be more important for fish passage. These results highlight the need for context- and species-specific

guidelines, and advocate for integrating detailed hydrodynamic modeling into fishway design to better support fish connectivity.

Although none of the papers on pool-type fishways tested the placement of bottom roughness in VSF, recent work on these devices confirms that adding macroroughness elements to the fishways bottom can broaden the hydraulic envelope and benefit species with weaker swimming abilities. For example, flume experiments and ADV mapping in French prototypes showed that a uniformly distributed bottom roughness can make VSF more biologically suitable—particularly for benthic or small fish—while only moderately affecting hydraulic performance [93]. In China, other authors [94] demonstrated that adding coarse stones to the bed of a VSF significantly improved the benthic cyprinid *Schizothorax wangchiachii*'s ability to ascend by raising its critical and burst swimming speeds by about 13% and 15%, respectively. In their study of multispecies fish passage behavior in a VSF, other authors [95] acknowledged that a smooth bottom contributed to the poor passage of small fish, and inferred that incorporating boulders or artificial roughness would likely improve performance for those size classes without harming larger fish. Taken together, these results match our Portuguese PaW results in that adding bottom roughness to VSF can improve fishway effectiveness, likely representing a transferable, low-cost strategy to expand pool-type fishways to smaller and weaker swimming species.

3.2.3. Nature-like Fishways

Five of all published studies were on nature-like fishways (12.5%); two were carried out in the field, whereas the other three were developed in the laboratory (Table 1).

Ref. [70] conducted the first field study on this type of fishway in Portugal, aiming to assess species' seasonal and daily passage patterns and fishway efficacy while documenting its role as habitat. The study took place in a 26 m × 6 m nature-like bypass channel on the Lima River (NW Portugal) over 120 days across all seasons. Fish passage was continuously monitored via an automatic video system, complemented by monthly electrofishing downstream (to estimate efficacy as the ratio of observed to captured fish) and within the facility (to assess colonization and residence). The results reveal that the bypass was used by various fish species, encompassing all migratory guilds (i.e., diadromous, potamodromous and resident). Over 70% of fish used the facility in spring and early summer, with most species—except mullet—migrating nocturnally. Migration was mainly triggered by temperature (mostly for diadromous species) and bypass flow (for cyprinids and leuciscids). The study confirmed the bypass's effectiveness as both a migratory corridor and habitat, supporting its role in river restoration actions.

Laboratory research at LNEC's ecohydraulics flume (see description in Section 3) tested experimental ramps to assess the influence of ramp length (L) and slope (S) on Iberian barbel passage performance [71]. Four configurations (L—1.5, 3.0 m; S—10%, 20%, 30%) were tested under a constant discharge of 110 Ls^{-1}. Behavioral metrics included the number of fish approaches, attempts and successful negotiations. Overall, attraction efficiency increased with L and S, while passage efficiency declined with L. Passage efficiency peaked at 20% rather than 10% S, likely due to more attractive velocities. The findings suggest that steeper but not excessive slopes enhance attraction while optimizing space and cost-effectiveness.

Building on previous results, the second study tested retrofitting scenarios to improve passage performance in the least effective configuration (L—3.0 m; S—10%) under different discharges [72]. Substrate placement at the bottom of the ramp, with varying size and arrangement [53,96–99], aimed to create low-velocity and low-turbulence areas [100–102] to enhance fish passage. A smooth-bottom control was also tested. The results show that both retrofitting and discharge affected passage success, with the "nature-like" design

yielding the highest attraction and passage efficiency. Randomly placed cobbles improved fish permeability by providing suitable hydraulic conditions. These findings were later confirmed using individual fish instead of schools [73].

Another field study addressed how river flows from a large hydropower plant in the Tejo River impact native fish passability over a 250 m-long low-head ramped weir, equipped with a nature-like fish ramp [74]. Due to the scarcity of empirical data on large rivers, an expert judgment approach [103] and a literature review were used to develop habitat suitability curves (HSC) for key environmental variables (water depth and velocity). Multi-species passability was modeled under historical (1991–2005) and future flow scenarios (RCP 4.5, conservative; RCP 8.5, extreme). The results indicate a lower passability in future scenarios, especially RCP 8.5, compared to historical records, with species-specific differences. The study highlights the potential decline in fish passage over rock ramps and weirs due to global warming, emphasizing the need for adaptive fishway designs to improve entry efficiency under low flows.

3.2.4. Fish Lifts

Over the past two decades, four studies (10%) have examined fish lift performance, primarily in the last seven years. All were conducted at the Touvedo hydropower plant, which has fragmented the Lima River 47 km upstream since the early 1990s. The 2.1 m × 1.3 m × 2.9 m fish lift, located on the left bank, features three entrances—two upstream of the turbine gates (rear entrances) and one 20 m downstream (wing entrance) utilizing turbine flow. Designed to enhance connectivity for diadromous species, the lift operates under three dam conditions, as follows: (i) turbine shutdown (0 m^3s^{-1}), compensated by a 5.5 m^3s^{-1} environmental flow release; (ii) half-load operation (50 m^3s^{-1}); and (iii) full-load operation (100 m^3s^{-1}).

The performance of the fish lift was first assessed continuously from March 1998 to February 1999 using an automated video system to document fish use, passage patterns, and environmental migration triggers [75]. The results show that endemic cyprinids and leuciscids (c. 80%, mainly barbel and nase), salmonids (10%, primarily brown trout *Salmo trutta*, with minimal Atlantic salmon *Salmo salar*) and European eel *Anguilla anguilla* (c. 10%) used the lift. Cyprinids and leuciscids migrated mainly at night in spring, while yellow eels peaked in summer, responding to warmer temperatures. Overall, the lift was deemed effective even for weaker swimmers like eels [104]. However, its selectivity and efficiency remained unquantified.

Subsequent studies focused on improving performance for specific groups—European eels, more specifically yellow eels [76], and potamodromous species [77]. Both spanned all seasons, using an automatic video system and monthly electrofishing downstream to assess migration patterns, lift selectivity, and efficacy. For eels, the study focused on the cage retention screens' gap width, as wider gaps often allow smaller individuals to escape, limiting effectiveness [15,16]. Two annual periods were compared: a pre-treatment period (width of the cage retention screens was 23 mm) and a post-treatment period (5 mm gap width). The narrower gap resulted in a threefold increase in eel numbers, particularly smaller individuals (<20 cm TL), while downstream captures and seasonal movement patterns (summer to early-autumn) remained unchanged. These findings suggest that reducing screen gaps enhance fish lift efficiency for yellow eels, minimizing size selectivity at high obstructions. However, success also depends on the attraction circuit water velocities remaining within their critical swimming speed range [104].

Potamodromous fish exhibited similar seasonal movement patterns to eels, with 80% of movements occurring from summer to early fall, driven by warmer temperatures (cyprinids and leuciscids) and increased river discharge (trout), consistent with previous findings on

"out of season" migrations for refuge-seeking [105]. Passage correlated with peak-flow magnitudes; most nase (68%) used the lift when turbines were off, while barbel (45%) and trout (44%)—the two largest species—prevailed at half load (50 m^3s^{-1}) and full-load (100 m^3s^{-1}), respectively, due to their greater tolerance to short-term high velocities [106,107]. The lift exhibited size-selectivity for barbel and trout, likely because smaller individuals lack a strong migratory drive [105] and struggle with entrance velocities [44]. The standardized passage-to-catch ratio indicated higher efficiency than reported for similar facilities [34]. While effective for target species, future studies should refine attraction and entry efficiency assessments [22] and investigate passage delays using biotelemetry techniques in challenging conditions.

Recent video observations documented the red swamp crayfish (*Procambarus clarkii*) using the fish lift, making the first recorded passage of this invasive species through a high-head obstacle [78]. Though only two individuals were observed, both during summer turbine shutdown, this finding highlights the potential for fish lifts to facilitate crayfish dispersal. In river segments where non-native invasive species are a concern, fishway designs should incorporate trait-based approaches [108] to enable native fish passage while restricting non-native species.

3.2.5. Fish Locks

Despite fish locks being built in Portugal since the 1970s and 1980s, only one study has examined their use [79]. This recent study monitored a Borland fish lock at the Crestuma-Lever dam (26 m high, inundated area at pool level of 13 km^2; installed capacity of 117 MW) on the lower Douro River over nine months (November 2016–July 2017). Using video recording and active fishing techniques (creel surveys, gill nets, trammel nets, longlines, as well as other small-scale traditional techniques), the results show predominant use by eels (75.7%) and mugilids (21.3%), with minor passages of barbel (2.1%) and non-native species (<1%). Eel movements were year-round, peaking in summer, full moons, low discharges, and high tides, while mugilids mainly migrated from May to July, preferring similar conditions but during daylight. The lock was highly selective, as anadromous sea lamprey and allis shad, though abundant downstream, did not use it. While the fish lock enables migration for European eels and mullets, continuous monitoring is needed to optimize fish passage and balance competing water uses, such as navigation and hydropower.

4. Conclusions

The construction of fishways has tripled since the implementation of the WFD, with pool-type fishways being the dominant fishway type, accounting for almost 70% of the total number of fishways, which is in accordance with what is reported from Spain [109] and worldwide [33,110]. Most fishways occur in the central and northern parts of the country, where available runoff and permanent flow enable HP structures and related fishways.

Of all the WoS literature that addressed fishways in Portugal, three-quarters (75%) focused on pool-type fishways, which were revealed to be the most common (67%) at river obstacles. This pattern is consistent globally [80,111,112], as pool-type fishways remain the predominant passage solution. Despite well-established design guidelines [15,16], their performance remained poorly known until the late 1990s, often leading to suboptimal fish passage [33,34].

Over the past two decades, research has advanced knowledge on pool-type fishways using diverse methods such as video monitoring, PIT, radio and EMG telemetry, infrared beaming, and 3D numerical modeling. These approaches provided critical insights into migratory behavior under field conditions, and, at a finer scale under laboratory conditions, have allowed us to understand fish interactions with key hydrodynamic variables

(e.g., velocity, turbulence, RSS) under multiple configurations, varying in notch/orifice area, vertical slot width, flow regime type, and the presence of macro-rugosities. Key findings include the following: (i) fish prefer offset orifices over notches in PaW fishways; (ii) streaming flow improves passage success compared to plunging flow; (iii) the RSS stood as the most influential hydrodynamic parameter; (iv) macro-rugosities (e.g., boulders) at the bottoms of fishways, coupled with increased discharge, may reduce turbulence and create micro-channels that facilitate fish passage; (v) in VSFs, a single lateral baffle is more efficient than configurations with a central and a lateral baffle, and when built at steeper slopes and with higher Pv than standard guidelines, they still enabled a high passage performance, and (vi) MSFs are more discharge-efficient and less selective for small species than single VSFs designs, making them preferable in water-scarce regions.

Some of these measures, such as placing boulders at the bottom of pool-type fishways, are now being applied in new constructions. Additionally, there has been a shift from PaW to VSFs, which better accommodate species movements and are less sensitive to upstream water level fluctuations, reflecting a direct application of experimental research.

Nature-like fishways were the second most common type in Portugal, representing 18% of all fishways, closely matching the proportion of ISI-published studies on them (5 out of 40; 12.5%). Only one study focused on the field monitoring of a nature-like bypass channel, highlighting its dual role as a migration corridor and habitat for local fish communities. These facilities, typically built at low slopes (<5%), improve passage by small or weak-swimming species, but can reduce attraction because lower slopes generate weaker entrance velocities [113,114]. Experimental studies by [72,73] tested short experimental ramps (1.5–3 m) in a flume, and found peak passage success at an intermediate 20% slope. However, it should be noted that these results derive from controlled laboratory conditions; full-scale nature-like fishways are typically much longer (>30–50 m), and applying such steep slopes in the field could increase fish fatigue and lower efficiency, especially for non-salmonids. Further field research—accounting for discharge variability, hydraulic complexity (e.g., substrate placement) and climate-change-driven low-flow scenarios—is required before steep designs are recommended.

However, neither pool-type fishways nor nature-like facilities are adequate solutions for high obstacles, such as large dams (>15 m). In such cases, fish lifts and locks are the most cost-effective solutions [115], though they are less common, with only two lifts identified in this review (2%), aligning with global trends [34]. Despite their low representativeness, four papers (10%) focused on the Touvedo fish lift, monitored through video recordings and electrofishing. The findings revealed seasonal and daily migration patterns, with eels, cyprinids, and leuciscids migrating from summer to early autumn, influenced by flow discharge, moon phase, and water temperature. Fish passage varied with peak-flow magnitudes, reflecting species' swimming capabilities. Notably, reducing the fish-lift gap width of the retention screens decreased eel escape, improving suitability for small-sized species [76].

Overall, the body of work produced in the last 20 years has gathered very relevant insights into the optimization of the effectiveness of fishways for Iberian fish species. These insights have been applied to in situ, recently build fishways, and can benefit future facility construction or improve existing facilities. This knowledge contributed to the management of river basins and fish communities, allowing connectivity enhancement actions to be effective and thus contributing to the fulfilment of European Directives, such as the Habitats and the WFD.

5. Future Research and Management Needs

The alignment of research, management and policy is a good practice that should be observed, particularly when public funding is available. This is not only recommended but also advocated by the European Commission (e.g., Knowledge4Policy). This alignment results in translational science for the benefit of nature and society. Based on the above results, which incorporate a range of different field and experimental conditions, and considering not only the existing knowledge gaps on pool-type fishways [14] but also extending the scope to other fishway types and species, along with the latest findings in fishway science, the following lines of research, management actions, policies and regulations are recommended to assist in the design, evaluation, construction, and monitoring of the efficacy of fishways for Iberian species.

(1) Improving the knowledge of species- and size-specific hydraulic criteria for fishway construction and retrofitting. As demanded by the WFD, fishways should accommodate the smallest and weakest fish from local fish assemblages. To this end, the first step would be to identify its composition, size and structure. Targeted swimming performance studies should then quantify the capacities and energetic costs of any possible vulnerable species size classes under hydraulics that mimic intended fishway conditions. If funds are available, priority should be given to open-channel flume experiments that allow voluntary, free-schooling movements and capture burst-and-coast strategies, while quantifying both velocity- and turbulence-based metrics such as volumetric dissipation power [71,116]. These focused data will help designers set velocity–turbulence envelopes that are simultaneously biologically realistic and cost effective for new fishway instalments or retrofits.

(2) Provision of supplemental attraction flow—through auxiliary water supplies or adaptive environmental flow releases, whenever possible—to improve the attraction efficiency of fishways. Attraction efficiency, the proportion of fish successfully locating the fishway entrance, is a key factor in fish passage success, and requires further investigation [24]. The fishway entrance must effectively guide fish using the outflow as an extension of the passage itself. As the entrance outflow must act as a hydraulic "extension" of the passage itself, it should be positioned at the upstream limit of migration, where fish naturally stall against the barrier or turbulence field across the full operating range of river discharges [117–119]. However, pool-type fishways, fish lifts and fish locks often have low attraction efficiency due to insufficient discharge, which can be overshadowed by competing flows from turbines, spillways, or environmental flows [120]. To address this, supplemental attraction flow can be added near the fishway entrance via auxiliary water systems or environmental flow adjustments [121], enhancing hydraulic signals without disrupting internal fishway conditions [122]. Optimizing attraction flow requires research on flow quantity, pattern, direction, and entry point, with physical habitat modeling offering valuable insights based on species-specific preferences for velocity, depth, cover, and substrate [74,123].

(3) Developing indicators of fishway performance and its obligatory monitoring. Though standardized methods for assessing fish passage efficiency using telemetry have been developed [124], a lack of uniform monitoring approaches persists [22,33,125]. Efficacy refers to whether a fishway allows target species to pass, while efficiency quantifies performance as the proportion of marked fish downstream that successfully pass [80]. Although fishways are generally effective, success rates vary widely (0–100%), raising questions about acceptable performance [4,126]. Establishing biological and hydraulic performance standards is essential for setting evaluation targets [127]. Fishways should be designed to allow the passage of the weakest swimming size classes of migratory species that need to

migrate upstream the barrier, and, where relevant, should maintain the downstream drift of early life stages (eggs and larvae).

(4) Encouraging the use of vertical-slot fishways (VSF) in detriment to pool-and-weir ones. VSFs are among the most effective designs, operating across various discharges and headwater levels, allowing fish to swim at their preferred depths, and requiring less maintenance due to reduced clogging [58]. Further, increasing their slope beyond standard guidelines still revealed a high passage performance. MSF uses about one-third less water than a VSF for the same pool water depth [63], but may hinder large shoaling species like Atlantic salmon, allis shad or sea lamprey, though further field studies are needed. The addition of submerged structures, such as embedded cobbles, while beneficial for PaW fishways [53], should be avoided in MSF to prevent clogging and reduced entry efficiency.

(5) Whenever possible, retrofit and improve PaW fishway passability. Incorporating surface notches and offset submerged orifices while maintaining streaming flow regimes enhances fish passage, increases success rates and reduces delays, particularly for smaller individuals [14,45,46]. Surface notches also provide an alternative route when orifices become clogged [49], which is crucial in remote areas with limited maintenance. Adding bottom substrates or rugosity further improves fishway performance.

(6) Increasing field studies to validate the results from experimental assessments and to diagnose in situ the causes of low fishway efficacy. While laboratory studies allow the controlled manipulation of variables, they often lack the complexity of field conditions, where multiple environmental factors interact [101]. Field studies, despite their limitation in controlling variables, can provide high-quality data on wild migrating fish when appropriate techniques are applied [128,129]. Ideally, experimental and field approaches should be combined to inform management decisions within River Basin Management Plans.

(7) Consider bidirectional fish passage when designing, building, and monitoring fishways. Most fishway studies focus on upstream reproductive movements in pool-type and nature-like fishways [130–132], while downstream migration is often overlooked [133]. This is problematic, as two-way connectivity is essential for habitat selection, spawning, feeding, sheltering [1,134] and maintaining gene flow in fragmented rivers [135]. Ideally, fish should pass downstream through the fishway itself to avoid the high mortality risk associated with spillways and turbines at hydropower plants [136]. To achieve this, physical or behavioral guidance systems (e.g., angled screens, louvers, surface bypasses) installed at the hydropower plants could deflect fish away from turbines or spillways, and direct them towards the fishway entrance across the full range of operating flows [137,138]. At non-hydropower weirs, safe downstream passage can be further enhanced by incorporating deep plunge pools and ogee-shaped crests that dissipate energy and reduce impact injuries [139].

(8) Experimental and field fishway monitoring should be extended further beyond the typical migratory season. Most fishway studies focus on the reproductive season (spring and early summer) when fish are most motivated to swim, and efficiency is highest [70,90,120]. However, recent studies show migrations can extend into autumn and winter as fish seek shelter from harsher conditions [32,69,105]. To ensure access to functional habitats year-round, fishways should remain operational in all seasons [12].

(9) Quantification of attraction and passage efficiency standardized metrics for all fishway types. Future studies should quantify attraction (fish that are guided to and enter the fishway) and passage (fish successfully ascending/descending the fishway after having entered it) efficiency across various fishway types and species, where data remain limited. A meta-analysis found global average passage efficiencies of c. 40% upstream and c. 70% downstream, with nature-like and pool-type fishways performing best [34]. Nonetheless,

recent findings suggest fishway type does not predict passage efficiency, which varies by ecological guild—highest for pelagic rheophiles and diadromous species, and lowest for limnophilids [22]. Standardized efficiency metrics are essential for the comparability and broader applicability of research findings.

(10) Develop selective fishways as a response to widespread invasions by non-native fish. A key challenge in multi-species fish passage is preventing the spread of non-native invasive species, which can colonize new river segments [140]. Selectively blocking invasive species is difficult when size and swimming abilities overlap, creating a "connectivity conundrum" [141], where restoring connectivity conflicts with controlling invasions. An integrated approach considering physical traits, body morphology, and movement phenology—potentially enhanced by sorting technology [140] and behavioral barriers like acoustic and light guidance systems [142,143]—is essential for developing ecological filters to limit invasions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w17192898/s1, Table S1: Fishways in Portugal as of December/2024 (SHP—small hydropower plant). See Figure 2 for spatial position across main river basins.

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