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Posted Date: 13 February 2026

doi: 10.20944/preprints202602.1036.v1

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Nature-Like Fishways in Spain: A General Cost-Effectiveness Overview

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Abstract

Nature-like fishways (NLFs) are a key restoration measure for fragmented rivers at low-head barriers, yet their economic and functional performance is poorly documented. This study provides a comprehensive analysis of 134 NLF projects in Spain (2003–2025), classifying them by typology, energy dissipation elements, and construction method. We quantified construction costs using standardized indicators and assessed available hydraulic and biological efficiency data. Results show a predominance of public funding schemes and a strong geographical concentration of NLFs in the northern half of the country, with ramps (76.1%) being more frequent than bypass channels. Construction costs varied markedly among designs, with concrete boulder ramps consistently representing the most cost-intensive NLF configurations, while also being strongly influenced by local site conditions and construction constraints. Only a small fraction of projects (13.4%) underwent post-construction efficiency assessment, but those evaluated generally showed favorable performance for multiple fish species. Our findings provide a state-of-the-art overview of NLFs in Spain, together with a practical classification framework and standardized cost indicators to support the planning and prioritization of river connectivity restoration projects.

Keywords: fish passage; river connectivity; ecological restoration; cost-effectiveness; construction

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1. Introduction

Transversal barriers such as weirs, dams, culverts, and gauging stations are among the primary causes of river habitat fragmentation and disruption of fish migration routes [1,2]. These structures modify the natural hydromorphological and ecological processes of river systems, altering flow regimes and connectivity, and therefore threatening the conservation of freshwater fish biodiversity [3]. When barrier removal is not feasible, fishways represent the most effective mitigation measure to restore longitudinal connectivity and allow the upstream and downstream movements of aquatic fauna [4,5].

Among the available typologies, **nature-like fishways (NLFs)** —including rock ramps and bypass channels— are increasingly used for low-head barriers (typically < 4 m) due to their hydraulic simplicity, ecological compatibility, and landscape integration [6,7]. These fishways mimic the physical and hydraulic conditions of natural rivers, using gentle slopes and coarse substrates (rocks, boulders, gravels, logs) to create a heterogeneous flow field that provides multiple migration pathways and resting areas for fish [8]. As a result, they tend to be less selective for species and body sizes than conventional technical fishways, and usually require less maintenance once built [9,10].

In recent years, several studies have analyzed the **biological efficiency** and hydraulic performance of nature-like fishways across different regions [11–15]. More recently, comprehensive assessments have addressed some cost-effectiveness and engineering aspects [16,17]. Despite these advances, the **economic dimension** of such systems remains underrepresented in scientific literature [18]. Construction costs are highly variable, influenced by local geology, material availability, site accessibility, and design typology, but few studies have attempted to quantify these relationships systematically. This information is critical for managers and planners, as financial feasibility is often a decisive factor when prioritizing restoration projects and allocating limited conservation budgets.

While cost databases and standard indicators are available for technical fishways—such as pool-weir, or vertical-slot designs [19]—equivalent references for nature-like structures are lacking. Consequently, project planners often rely on rough empirical estimates or case-specific budgets, which can hinder the optimization of fish passage solutions. Developing robust economic indicators that relate construction cost to easily measurable variables (e.g., dam height, total length, or constructed area) would improve the transparency and comparability of future projects.

In Spain, the construction of NLFs has grown considerably in the last two decades, driven by the implementation of the Water Framework Directive (2000/60/EC) [20] and associated river restoration programs. However, there has been limited discussion regarding their technical and biological performance or their true cost-effectiveness. Current design practices vary widely between regions, and post-construction fish efficiency assessments remain scarce. Moreover, there is little quantitative information on their geographical distribution, typological variability, and economic trends.

Therefore, the objectives of this study are: (1) to develop and apply a systematic descriptive framework for nature-like fishways implemented in Spain, encompassing their geographical distribution as well as their main typological, spatial, and geometric characteristics; (2) to quantify their construction costs through standardized and comparable indicators; and (3) to analyze available data on their biological and hydraulic efficiency for fish. Together, these results will contribute to a better understanding of the cost-effectiveness of NLFs and provide a practical tool for decision-making in river connectivity planning and management.

2. Materials and Methods

2.1. Data Acquisition

Technical information on construction costs and geometric characteristics of NLFs was obtained from official inquiries to public administrations (the National Ministry of Environment, the Spanish Water Authorities, and regional fish management services), as well as through contacts with consulting companies and universities. In addition, all available information on hydraulic and/or biological performance evaluations of the fishways analyzed in this study was requested and compiled.

This dataset was complemented with targeted web searches using Google, employing both Spanish and English keywords such as *"presupuesto" (budget)*, *"proyecto constructivo" (construction project)*, *"paso naturalizado" (nature-like fishway)*, *"rampa para peces" (rock/y ramp)*, *"río artificial" (bypass channel)*, *"hydraulic/biological assessment"*, and *"continuidad fluvial" (river continuity)*.

A database was then developed in which each project was assigned a unique code according to the nature-like fishway typology (see Section 2.2 and Supplementary Material). For each project, the following information was compiled: (i) Location (province, municipality, river, river basin authority, and coordinates); (ii) Year of project development; (iii) Geometric characteristics, including dam height —understood as hydraulic head—, and fishway width, length, area, and slope; (iv) Design characteristics (see Section 2.2), including partial or full-width implementation and upstream or downstream positioning relative to the dam; (v) Direct Building Cost (DBC), updated to 2024 prices and excluding overheads (6–16%), contractor profit (6%), and taxes (e.g., VAT, 16–21% between 2003 and 2024); (vi) Data suitability for analysis (Yes/No; see Section 2.3); (vii) Construction status (Yes/No); (viii) Type of project funding (public/private); and (ix) Efficiency assessment, including the

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presence and type of post-construction evaluation, applied monitoring methods, key outcomes, and data sources.

2.2. Classification of Nature-Like Fishways

Nature-like fishways were classified according to three hierarchical levels. The first level is based on the fishway position relative to the dam, distinguishing between ramps and bypass channels [21] (Figure 1).

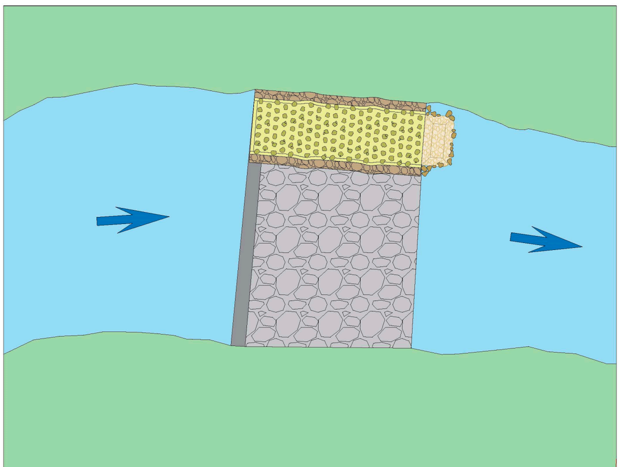
- Ramps (R) are channels with slopes up to 10% that are placed within the main river channel, typically attached to the weir. They can be constructed downstream of the obstacle (most common), upstream (less frequent), or embedded within the structure. Moreover, they may span the entire dam or only a portion of it.
- Bypass channels (BC), or artificial rivers, are side channels built outside the main riverbed that circumvent the barrier, providing an alternative low-slope (usually <5%) route for fish migration.

The second classification criterion focuses on the roughness or energy dissipation elements used within the fishway [21] (Figure 1, Figure 2 and Figure 3):

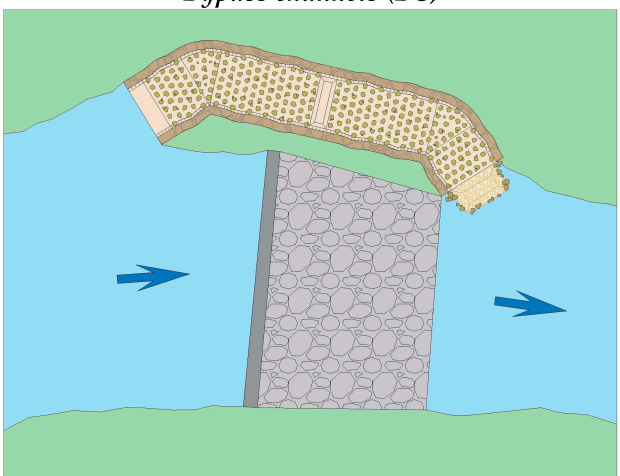
- The bottom type (bt) uses the natural bed material —gravel, rocks and even boulders— to construct a uniform rough channel bottom that slows down flow velocity and provides refuge areas for fish within the interstitial spaces.
- The boulder type (bl) adds large —staggered/random/row-aligned/grouped— perturbation rocks (boulders) on the rough channel bed to further increase energy dissipation and allow fish passage for steeper slopes; these boulders create shadow zones and hydraulic shelters behind them. The distinction between bottom (bt) and boulder (bl) types is sometimes ambiguous due to overlapping material sizes and grain composition.
- Additionally, the pool-and-weir system (pw) replicates a conventional technical fishway, using rock weirs of different sizes to form a sequence of pools where fish can rest during their ascent.

Level 1: fishway position

Ramp (R)



Bypass channels (BC)



Level 2: roughness or energy dissipation elements

Bottom type (bt) ***Boulder type (bl)*** ***Pool-and-weir system (pw)***

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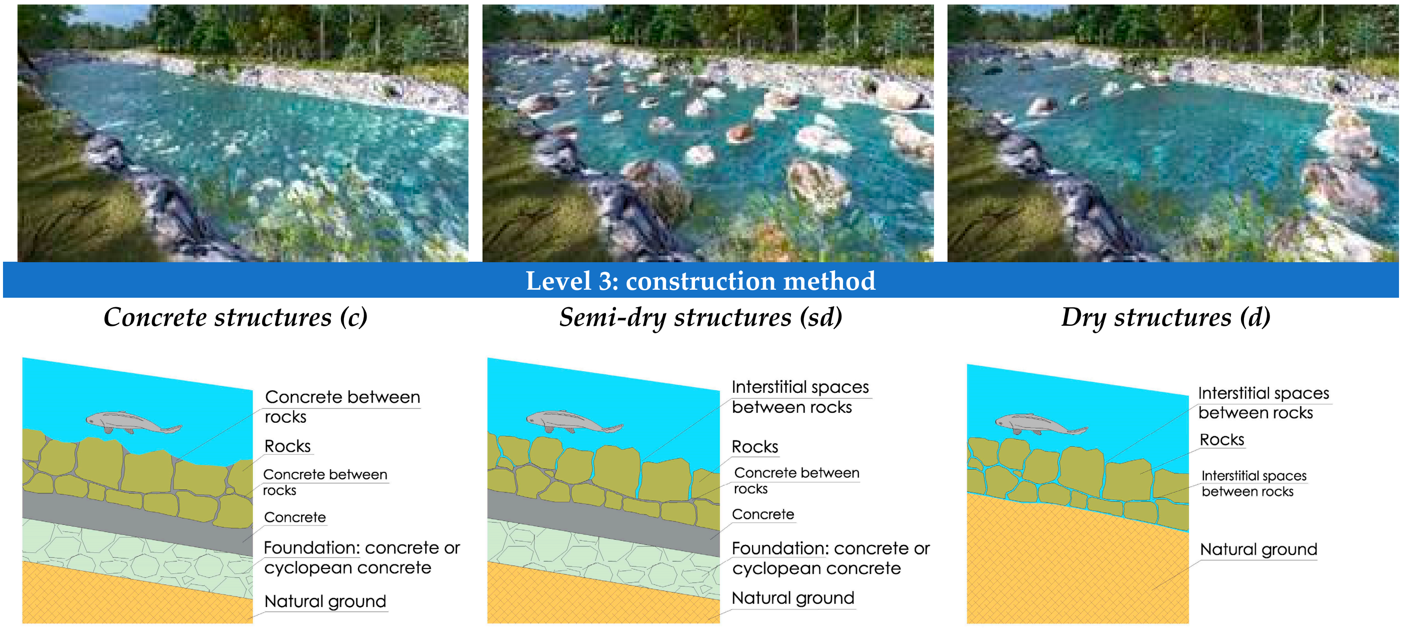

Figure 1. Classification of nature-like fishways according to the three hierarchical levels considered in this study.

Figure 2. Left: bottom semi-dry ramp in Azkoitia (Gipuzkoa). Center: boulder ramp [R-bl-c] in the Najerilla River, La Rioja). Right: concrete pool-and-weir ramp [R-pw-c] in the Pisuerga River, northern Palencia.

The third level of classification is based on the **construction method.** This study considers three categories (Figure 1 and Figure 3):

- Concrete structures (c) consist of placing rocks and boulders on a gravel or concrete foundation and grouting the cavities between them with concrete mortar to stabilize materials. This approach, normally used in boulder ramps and pool-and-weir systems, ensures structural stability under high flows or steeper gradients.
- Semi-dry structures (sd) use concrete only at the base of the main boulders, leaving the upper joints ungrouted. The remaining cavities serve as cover and resting areas for ascending fish, and are

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often partially filled by gravel after floods. This assembly is more related to large boulder bottom ramps.

- Dry structures (d) are built entirely without concrete, using large rocks and blocks to stabilize the fishway channel. They are typically applied to low-slope ramps or small bypasses, either bottom or boulder type, at remote or difficult-to-access sites (e.g., road crossings or culverts with bed scouring that hinders fish passage).

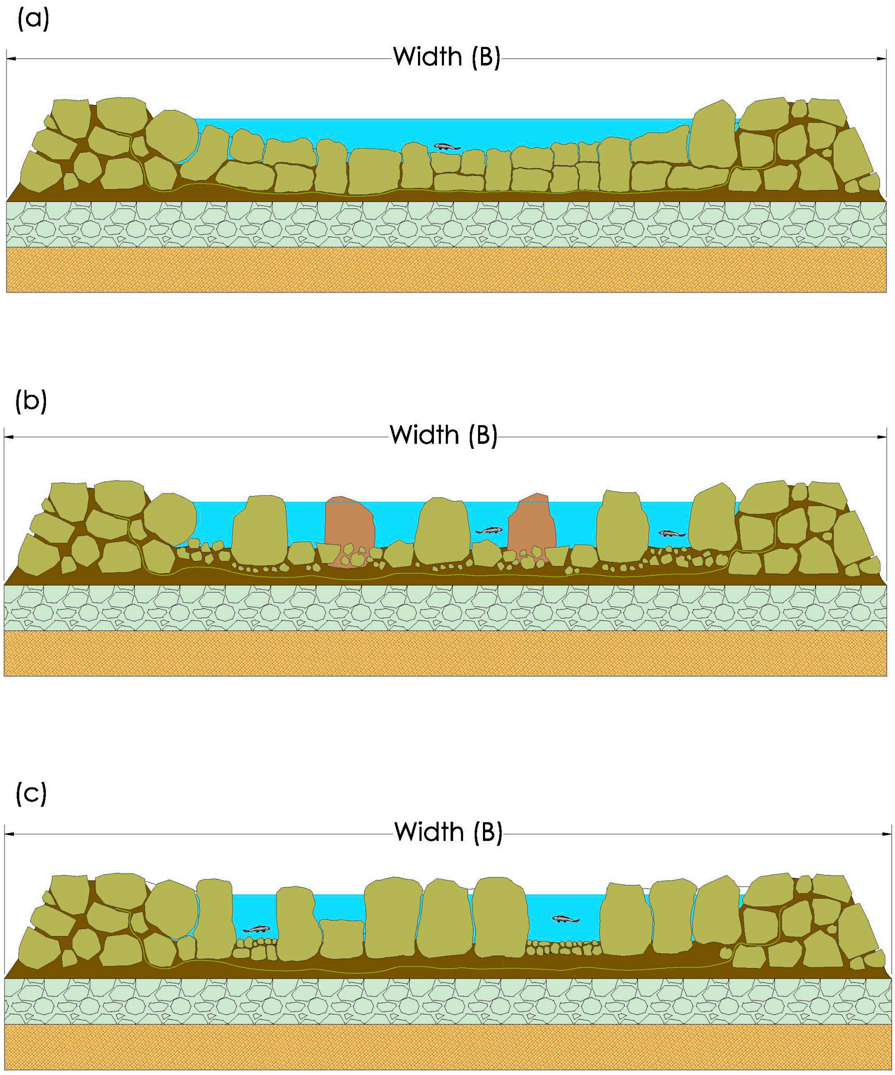

Figure 3. (a) Cross-section of a semi-dry roughness ramp [R-r-sd]; (b) Cross-section of a boulder ramp with concrete slab and sidewalls [R-bl-c]; (c) Cross-section of a pool and weir system with concrete [R-pw-c].

2.3. Data Curation

The fishway projects analyzed were designed and built between 2003 and 2025. To ensure comparability of construction costs, all monetary values were updated using the last published version of the "Construction Cost Index for the Civil Engineering Sector" published by the Spanish Ministry of Transport, Mobility and Urban Agenda [22]. This index reflects the annual evolution of construction costs in Spain, based on a 2021 baseline, and accounts for both material and labor costs. Each project's budget was normalized to 2024 by multiplying its original DBC by the cost updating

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index —ratio between the 2024 index value and that of its year of drafting— (Table 1). 2025 index was not available at the time of the study and was considered the same as 2024.

Table 1. Cost updating indices used to convert project budgets to 2024 values.

Year	Cost updating index	Year	Cost updating index
2003	1.522	2014	1.264
2004	1.480	2015	1.277
2005	1.429	2016	1.288
2006	1.380	2017	1.261
2007	1.332	2018	1.238
2008	1.280	2019	1.238
2009	1.312	2020	1.249
2010	1.301	2021	1.172
2011	1.262	2022	1.034
2012	1.255	2023	1.009
2013	1.261	2024/25	1.000

Projects: that did not meet the functional and design criteria established in fishway design manuals [4,21,23]—such as high cost due to undefined complementary works or the inclusion of other works (i.e. dam rehabilitation, pipelines, or urban development), excessive slope, insufficient depth, or inadequate width— were excluded from the analysis.

2.4. Data Analysis

Economic indicators were designed to allow for a rapid and reliable estimation of construction costs, as well as comparison among similar projects. Based on the main geometric fishway variables:

- Height (*H* in m), i.e., the hydraulic head across the obstacle (water level difference) to be overcome by fish.
- Width (*B* in m), understood as the whole fishway width, from side to side of lateral walls (Figure 3).
- Horizontal length (*L* in m), which depends on the overall slope of the structure.
- Slope (*S* in %), assumed as the ratio *H*/*L*.
- Area (*A* in m^2), considered as *BxL*.

Each of these dimensions is directly related to DBC. Nevertheless, a unique standardized indicator of DBC was selected: €/m^2 of constructed area (*A*), because of its independence from fishway size (*H*, *B*, *L*-*S*), which makes it easy and reliable to extrapolate across all types of devices. All geometric variables were used to describe the typological and spatial characteristics of nature-like fishways.

On the other hand, for comparison with other fishway cost data [19], DBC in € per m of head difference (€/m) is proposed. As fishway width and slope strongly affect total cost, results were normalized to a standard width of 5 m, with this width corresponding to design discharges of approximately 1–1.5 m^3/s for bottom and boulder ramps, and 0.4–0.8 m^3/s for pool-and-weir artificial rivers (BC-pw).

Comparisons among different fishway typologies were performed using the Kruskal–Wallis (KW) test to evaluate median differences, as cost data (€/m^2) did not follow a normal distribution. In addition, boxplots together with the KW test were used to find the differences in cost data (€/m^2) by type, roughness and construction method. When the KW test was significant, post hoc Dunn's multiple comparison test with Holm correction was performed. All data processing and statistical analyses were performed using R version 2025.05.1+513 [24], and the significance level was established at *alpha* = 0.05 for all the analyses.

3. Results

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3.1. Descriptive Framework

Information was obtained for a total of 134 NLFs, including 102 ramps and 32 bypass channels. The complete dataset is presented in the Supplementary Material. The projects are distributed heterogeneously across different regions and river basins in Spain, with the highest concentration (88.8%) located in the northern part of the country—particularly within the Duero, Gipuzkoa, Catalonian, Ebro, Miño-Sil and Cantabrian basins (Figure 4). Most of the projects (around 84%) were constructed after 2010 and are related to public investment (128/134; 95.5% of all projects studied).

Figure 4. Location map of the projects used in the study: in blue "ramps" (R) and in brown "bypass channels" (BC).

Ramps were by far the most common solution (76.1%, 102 of 134 cases) across all geographical areas, compared to 23.9% for bypass channels (Figure 4).

A total of 39 projects (29.1%) were excluded from the technical and economic analyses (see Supplementary Material) because (1) they did not meet the design and construction requirements necessary to ensure fish passage functionality (6/39); (2) corresponded to highly site-specific, excessively costly, small-scale interventions with neither comparable geometric nor cost data, such as non-concrete boulder and bottom type roughness ramps (R-bl-d and R-bt-d; $n = 12/39$), or (3) there was insufficient economic data available to assess the cost of the projects (21/39).

Consequently, 95 projects were selected for the core analysis: 67 ramps and 28 bypass channels, representing a total DBC of 12.6 M€, updated to 2024 values.

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Within ramps (level 2 typology), the three design types showed a relatively balanced occurrence: boulder ramps (R-bl; n = 18; 26.9%), pool-and-weir ramps (R-pw; n = 20; 29.8%), and roughness bottom-type ramps (R-bt; n = 29; 43.3%).

Most of the selected ramps were built downstream of the weir and directly attached to the structure (n = 64 downstream vs. n = 3 upstream). 37 of them were partial-width ramps (median B = 6.5 m), while total-width ramps (n = 30) showed a median width of 8 m (no significant differences in median width were found between partial- and total-width ramps, KW test p = 0.29). In general, the ramp width ranged from 2.7 to 36 m, with a median of 8 m, with no differences at level 2 (p = 0.96).

The dam height to be overcome by ramps varied from 0.3 m to 5.5 m, with a median of 1.5 m; only two projects exceeded 4 m. Ramp slopes ranged between 2.0% and 10.3%, with a median of 4.9%. No significant differences were detected at level 2 (neither for H (p = 0.11) nor for S (p = 0.61) (Figure 5).

From a construction standpoint, concrete designs (c) predominated in boulder (18/18) and pool-and-weir ramps (20/20), whereas semi-dry structures (sd) were more common among roughness ramps (28/29).

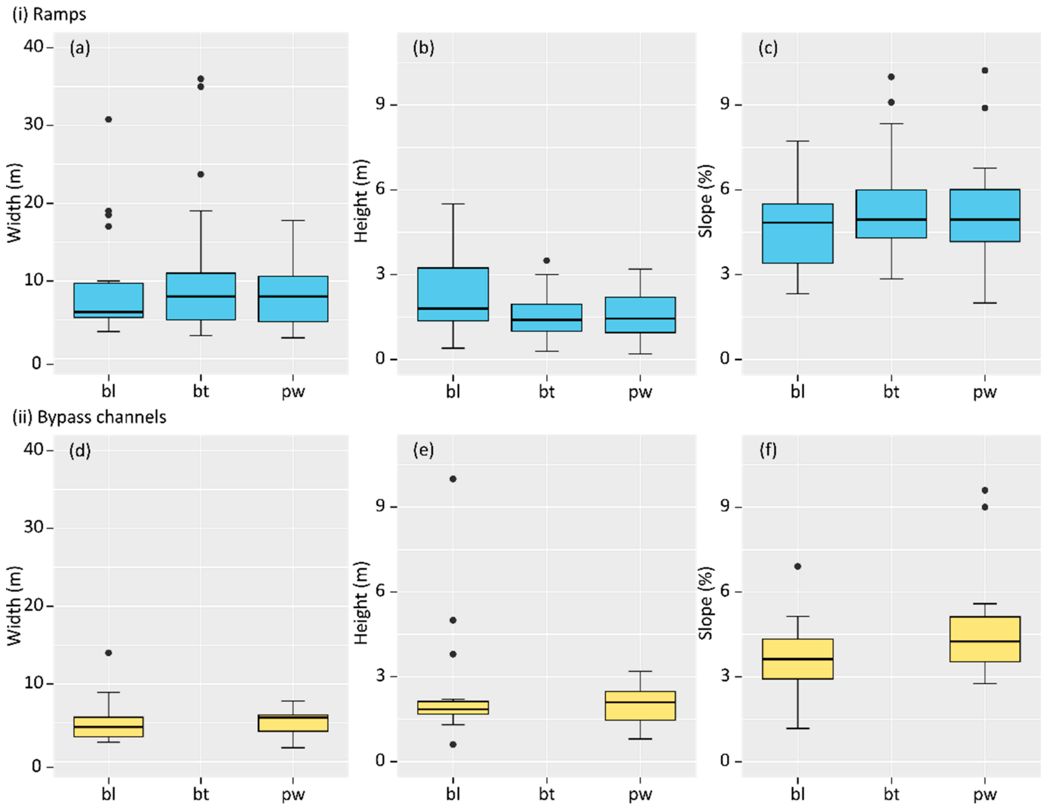

Figure 5. Box-plot for width, height, and slope by construction type: bl (boulder), bt (roughness bottom), and pw (pool-and-weir) for ramps (a-c) and bypass channels (d-f).

For bypass channels (n = 28), the most frequent configurations were boulder channels (BC-bl; n = 16; 57.1%) and pool-and-weir channels (BC-pw; n = 12; 42.9%), with no available data for bottom-type roughness-based systems (BC-bt).

Bypass channel width was more homogeneous than ramps, with a median value of 4.6 m and a range of 1.8 –14 m. By construction type, the median ranges from 4.5 m for boulder channels to 5.7 m for pool-and-weir channels.

Dam height for BC was similar at level 2 (p = 0.96) ranged from 0.6 m to 10.0 m, with a median of 1.95 m, slightly higher than ramps (p = 0.01). Only two projects exceeded 4 m height (5 and 5.5 m, respectively).

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Their slopes ranged between 1.2% and 9.6%, with a median of 3.9%—slightly lower ($p = 0.14$) in boulder types (3.6%) compared to pool-and-weir types (4.3%) (Figure 5).

No significant differences were found in *B*, *H*, or *S* at level 2 for bypass channels (p-values: 0.61, 0.96, and 0.14, respectively).

Nearly all artificial rivers were concrete structures (BC-bl-c and RA-bt-c), while only two projects were constructed without concrete (BC-bt-d), both associated with low slopes (<3%) and small-scale applications.

3.2. Construction Costs and Economic Indicators

Construction costs are summarized in Table 2 and the Supplementary Material. No statistically significant differences were observed in the median DBC per square meter (€/m²) between the two main typologies considered (level 1): ramps (308 €/m²) and bypass channels (338 €/m²) ($p = 0.86$; Figure 6).

In contrast, significant cost differences were detected among the energy dissipation systems (level 2; $p = 0.03$). Fishways incorporating large boulders (bl) exhibited significantly higher construction costs than pool-and-weir (pw) and bottom-type roughness (bt) systems (Figure 6).

Significant differences were also found among construction methods, highlighting the influence of concrete use on total cost (concrete > semi-dry > dry; $p = 0.02$; Figure 6).

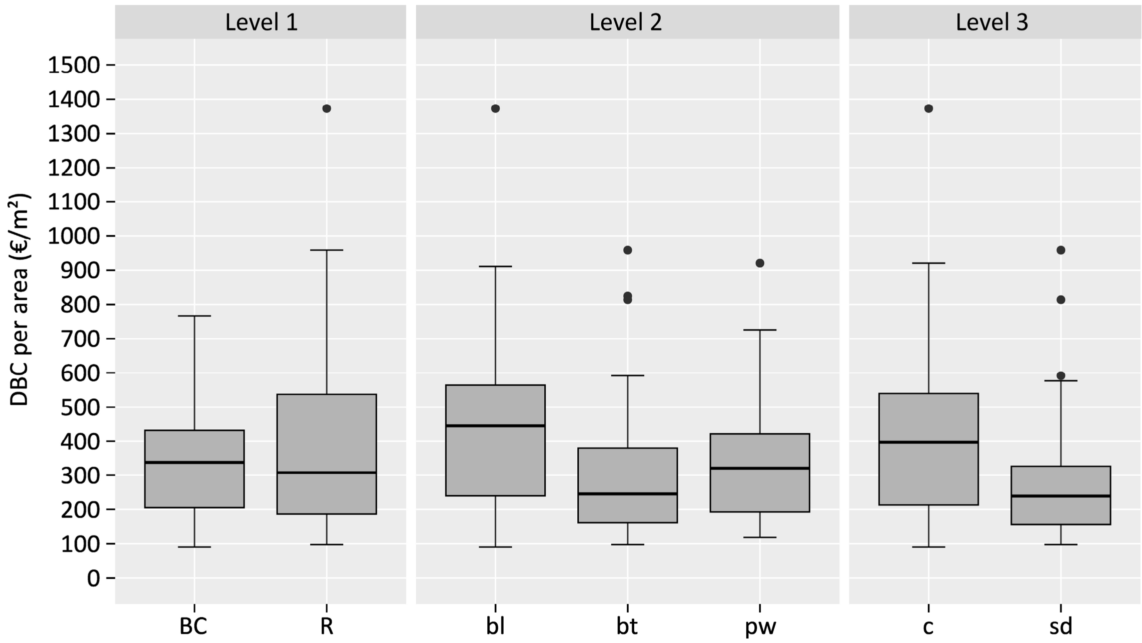

Figure 6. Box-plot for construction costs per area (€/m²) by level 1: ramp (R), bypass channel (BC); 2: boulder type (bl), bottom type (bt), pool-and-weir system (pw); 3: concrete structures (c), semi-dry structures (sd). Categories "dry structures" (d) and "no construction type data" (n/d)) are not included because they contain only a single data point.

Table 2. Median values and interquartile ranges of construction costs (DBC) per area (€/m²) for combinations of fishway typology (level 1), energy dissipation system (level 2), and construction method (level 3).

Level	n	Category	Min	Q1	Median (Q2)	Q3	Max	Mean	SD
Level 1	67	R	97.52	186.69	307.73	537.66	1372.42	388.14	262.45
	28	BC	90.37	204.91	337.97	432.65	765.87	350.83	186.77
Level 1+2	18	R-bl	148.47	404.02	482.32	564.51	1372.42	529.06	296.69
	20	R-pw	119.40	178.37	299.84	472.96	920.48	363.69	229.43
	29	R-bt	97.52	161.66	245.95	379.90	957.84	317.54	234.18

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	16	BC-bl	90.37	202.95	373.74	504.30	765.87	379.01	218.37
	12	BC-pw	129.33	209.68	321.01	364.13	619.84	313.25	133.80
Level 1+2+3	18	R-bl-c	148.47	404.02	482.32	564.51	1372.42	529.06	296.69
	20	R-pw-c	119.40	178.37	299.84	472.96	920.48	363.69	229.43
	1	R-bt-c	824.40	824.40	824.40	824.40	824.40	824.40	NA
	28	R-bt-sd	97.52	156.49	239.78	326.73	957.84	299.44	216.83
	15	BC-bl-c	90.37	224.61	382.48	525.97	765.87	398.02	211.88
	1	BC-bl-d	93.80	93.80	93.80	93.80	93.80	93.80	NA
	11	BC-pw-c	129.33	241.85	325.89	375.13	619.84	323.04	135.74
	1	BC-pw-n/d	205.52	205.52	205.52	205.52	205.52	205.52	NA

Within ramps, the most expensive solutions corresponded to boulder ramps (R-bl) characterized by a high density of large blocks arranged in structured patterns (e.g., staggered, random, rowed, or grouped) and relatively gentle slopes (around 5%) (Figure 7). These configurations almost doubled the construction cost compared to other ramp typologies.

Conversely, bypass channels showed similar costs among BC-pw, BC-bl, and BC-bt typologies (Figure 7). Likewise, when comparing ramps and bypass channels within the same classification level, no differences were detected (e.g., R-pw vs. BC-pw and R-bl vs. BC-bl).

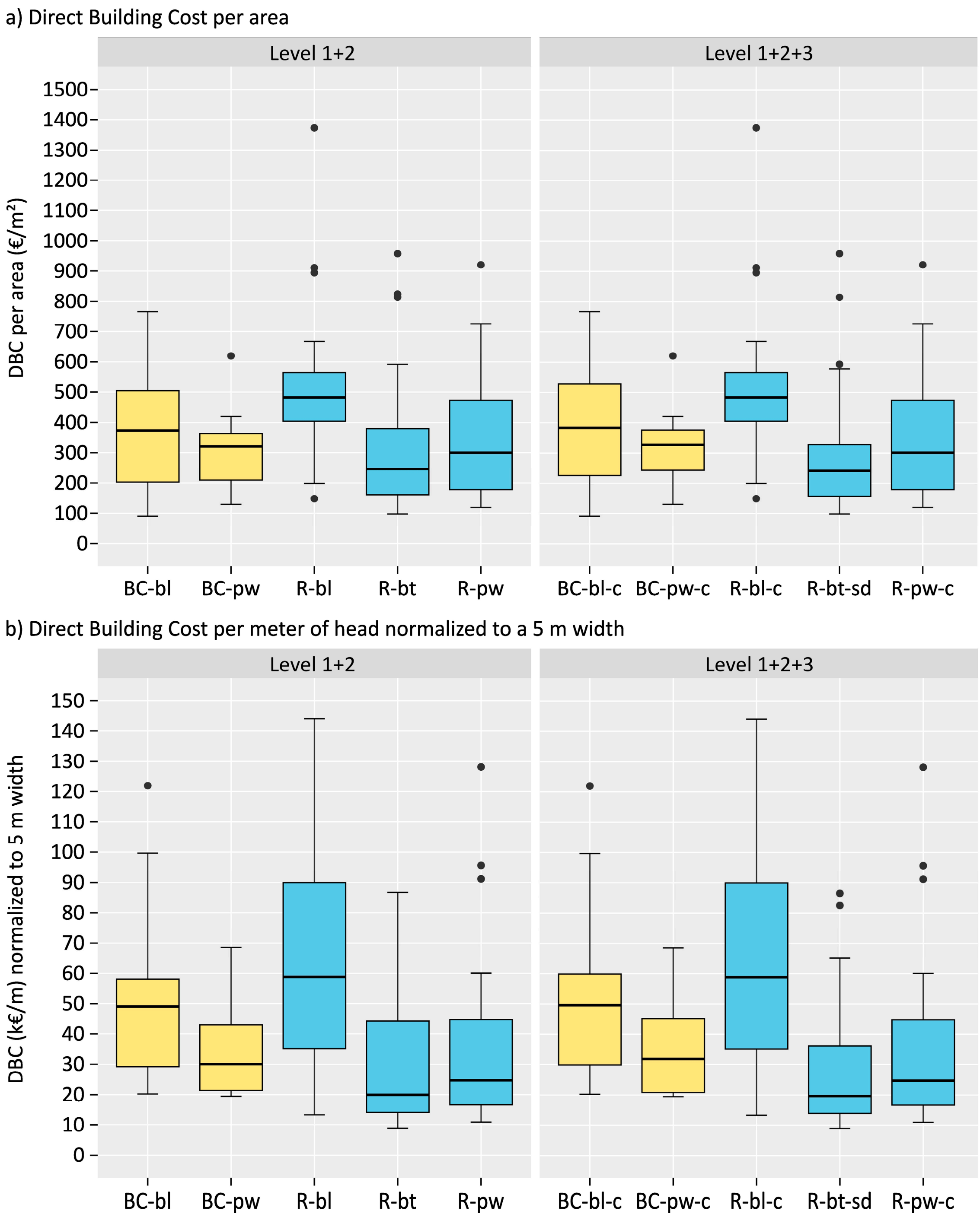

Figure 7. Box-plot for construction costs per area (€/m²) and costs per height for a width of 5 m (€/m) for each type of solution (Level 1+2 and Level 1+2+3). Categories “BC-bl-d”, “BC-pw-n/d” and “R-bt-c” are not included because they contain only a single data point.

Construction cost data can also be expressed as €/m of head difference, normalized to a standard fishway width of 5 m (see Supplementary Material). Cost differences among typologies remain consistent with those described above; however, this metric is particularly useful for practitioners and river managers, as it provides a rapid and intuitive cost estimate and facilitates direct comparison with previously published fishway cost studies.

3.3. Nature-Like Fishways’ Efficiency Assessment

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Only a limited number of all nature-like fishways—18 out of 134 projects (13.4%; see Supplementary Material)—had any form of post-construction efficiency assessment. Within the peer-reviewed literature, only one paper was identified that qualitatively assessed fish passage in two studied NLFs using mark–recapture techniques [25], along with three conference proceedings: one based on fish capture data [26] and the other two based on PIT tagging [27,28]. In addition, several fishways included in the present study (*n* = 11) were evaluated using the AEPS rapid hydraulic coarse assessment methodology [23]. A smaller subset (*n* = 7, of which four were also hydraulic assessed), were subject to more detailed biological monitoring, including mark-recapture techniques, PIT-tag tracking, and/or radiotelemetry. Most of these evaluations belong to grey literature, typically contained in internal reports from national or regional agencies, and are therefore difficult to access.

Overall, the majority of assessed fishways obtained favorable performance evaluations (16/18). Nevertheless, several recurring issues were identified, including insufficient water depth in specific sections (particularly in ramps near the junction with the weir crest), and in some cases: excessive flow velocities (>3 m/s), poor entrance location, and local scouring (perching) at the downstream junction between the fishway and the riverbed.

Despite these shortcomings, most evaluated structures showed a high degree of naturalization, supported the passage of multiple fish species, and facilitated a wide range of movements throughout the year, including both upstream and downstream movements.

4. Discussion

4.1. Descriptive Framework

Nature-like fishways represent an effective technical solution to mitigate the ecological impacts of transverse river barriers, particularly at low-head structures (<4 m) [15,21]. In the Iberian Peninsula, their implementation has increased markedly since 2010, largely driven by public funding and the requirements of the Water Framework Directive (2000/60/EC) [20]. At present, NLFs account for a substantial proportion —estimated in 15 to 25%— of the total number of inventoried fish passes in Spain (*n* = 612 [29]). At the river basin scale, available data are limited, but, for example, in the Spanish Duero basin NLFs represent 53 out of 184 fishways (28.8%) [30]. A similar increasing trend has also been reported in Portugal (18% NLFs; 18/100) [31].

Despite this growing relevance, their construction techniques, economic performance, and functional efficiency have received comparatively limited attention in the national literature [23,25,32]. The hierarchical classification proposed in this study provides a structured framework to systematize the diversity of NLFs designed in Spain, distinguishing position, energy dissipation system, and construction method. This approach has proven useful to organize heterogeneous designs and to relate them consistently to cost and performance indicators. Overall, 134 NLFs have been collected for this study. In the case of the Duero basin, the largest river basin in the Iberian Peninsula, where well documented inventories are accessible, it means that 50.9% of NLFs were incorporated into our work.

The compiled dataset indicates that NLFs in Spain are mostly publicly funded and unevenly distributed, with a strong concentration in northern river basins. Both patterns likely reflect higher institutional awareness and proactive river basin management. The predominance of low to moderate slopes (median $S < 5\%$) and relatively small hydraulic heads of the obstacles (median $H < 2$ m) confirms that these solutions are primarily applied to low-head barriers, in line with international design recommendations [21].

Ramps are the predominant solution (approximately 76.1%), typically built downstream and attached to the weir, often as either partial- or total-width structures. Boulder, pool-and-weir, and bottom-type ramps show a relatively balanced distribution, although bottom-type ramps are mainly concentrated in specific regions (e.g., Gipuzkoa). Bypass channels represent around 23.9% of the cases —either pw (42.9%) or bl (57.1%)— and are mostly implemented where lateral space allows for longer, lower-slope alignments than ramps.

Construction practices commonly combine boulders and coarse gravels with extensive concrete stabilization. An emerging trend consists of shaping the channel structure in concrete and using precast baffle units to provide hydraulic roughness, also observed in Australia and Portugal [17,31]. This increasing reliance on concrete challenges the conceptual boundary between nature-like and technical fishways.

4.2. Construction Costs and Economic Indicators

The economic aspects of NLFs are still poorly covered in research [18,19]. While construction costs vary widely based on local geology, materials, accessibility, and design, few studies have systematically analyzed these cost drivers. This gap is critical for decision-makers, as financial viability often determines which restoration projects are prioritized within constrained conservation budgets.

Construction costs of nature-like fishways are highly variable across regions and design contexts. Published international estimates range from 5–20 k€ per meter of head difference in Europe [33], to 28–42.5 k€/m in the Lower Mekong River [34]. Substantially higher values have been reported for large-bodied fish passage projects, such as 190 k€/m for bypass channels and up to 280 k€/m for ramps in low-gradient U.S. rivers designed for sturgeon passage [35]. In Australia, mean construction costs are on the order of 100 k€/m, with exceptionally wide ranges spanning 4–275 k€/m, reflecting strong site- and design-specific effects [17]. In Spain, the cost ranges identified in this study are approximately 9–145 k€/m for ramps and 20–122 k€/m for bypass channels, values that fall within the lower to intermediate ranges reported internationally.

Nevertheless, direct comparisons among studies remain limited, as published cost figures often lack standardized reporting of fishway dimensions and cost components, particularly with respect to the inclusion or exclusion of overheads, taxes, and other indirect costs. Thus, by focusing on Direct Building Cost (DBC) and introducing standardized indicators expressed as €/m² and €/m normalized to 5 m width, this study provides more robust and transferable cost metrics. These indicators reduce the influence of fishway dimensions and allow meaningful comparisons among different typologies and construction methods.

Our results show that ramps and bypass channels exhibit similar relative construction costs once normalized, suggesting that neither solution is intrinsically more economical. Geometric characteristics differ between the two solutions, but these differences tend to be balanced in terms of construction effort. Ramps usually require steeper slopes and more complex in-channel works, whereas bypass channels demand longer alignments and greater excavation volumes.

Among typologies, boulder ramps constructed with concrete (R-bl-c) are consistently the most expensive solutions, reflecting the high material volume, block size, and construction complexity involved. In contrast, bottom-type and pool-and-weir systems generally show lower median costs.

The construction of NLFs is generally simpler than other fishways; however, this does not necessarily imply lower construction costs. When NLFs are compared with stepped technical fishways—specifically vertical slot (VS) and submerged notch and bottom orifice (SNBO) designs—the latter tend to exhibit intermediate values between ramp and bypass channel solutions. For example, translating the values reported by [19] in Spain into the economic indicators used in the present study, the DBC for a vs. fishway is approximately 0.93 k€/m² (design discharge 0.5 m³/s; slope 7%) and 1.02 k€/m² for the SNBO configuration at a 10% slope and the same discharge. Although these relative costs per unit area are higher than those observed for nature-like fishways, technical fishways generally require a much smaller construction footprint. Thus, a NLF designed to overcome a 2 m head difference with a 5 m width requires approximately 200 m² of ramp or bypass channel at a 5% slope (1.0 m³/s for ramps; 0.5 m³/s for bypass channels), compared to only 72.2 m² for an SNBO fishway operating at a 10% slope and 0.5 m³/s, or 91.6 m² for a 7% slope vs. fishway. This translates into estimated DBC of approximately 74 k€ for the SNBO solution and 85 k€ for a vs. fishway, compared with 96 k€ for a 5 m width concrete boulder ramp (R-bl-c) or 66 k€ for a concrete pool-and-weir bypass channel (BC-pw-c).

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Therefore, beyond purely economic considerations, the selection of a fish passage solution should also be guided by space availability, site accessibility, and constructability constraints, which often play a decisive role in the feasibility of nature-like designs.

4.3. Hydraulic and Biological Efficiency

Despite their increasing implementation, post-construction efficiency assessments of nature-like fishways remain scarce. Only a small fraction of the inventoried projects included any form of hydraulic or biological evaluation, and most of these assessments belong to grey literature. Nevertheless, the available evidence suggests generally favorable performance, with approximately 90% of evaluated structures considered effective for fish passage. Importantly, according to an expert judgement–based assessment, the Duero River Basin Authority estimates a mean functional efficiency of around 60% across their NLF projects [30].

Overall, when properly designed, NLFs in Spain appear to achieve efficiency levels comparable to those of conventional stepped fishways constructed after 2010 [36]. This finding is consistent with broader syntheses indicating that nature-like and technical fishways generally show similar passage efficiencies, while nature-like designs often provide improved attraction and entrance conditions due to their larger width, higher discharge, and better integration with the main river flow [12].

Recurring deficiencies—such as insufficient water depth, excessive local velocities, poor entrance positioning, or downstream perching—are consistent with those reported for general fishway types [12,31] and highlight the importance of rigorous design and construction control.

4.4. Implications for Planning and Management

The cost indicators and typological patterns presented in this study are intended as decision-support tools for the early planning stages of river connectivity projects, rather than as substitutes for detailed design and budgeting. They allow rapid, transparent, and comparable cost estimates, helping managers prioritize interventions and allocate limited resources more efficiently.

While NLFs may offer ecological and landscape integration advantages —particularly improved attraction and entrance conditions due to their larger width and discharge—their economic and functional performance ultimately depends on site-specific constraints. Therefore, future efforts should focus on expanding standardized monitoring programs and integrating economic, hydraulic, and biological evaluations to improve adaptive management and evidence-based decision-making in river restoration.

5. Conclusions

This study provides a standardized assessment of NLFs implemented in Spain, focusing on their typological characteristics, construction costs, and available performance evidence.

First, the hierarchical descriptive framework developed in this study enabled a systematic characterization of nature-like fishways, integrating geographical, typological, spatial, and geometric features. Most projects are located in the northern half of the country and have been implemented under public funding schemes. Ramps were the predominant solution, although bypass channels were also widely applied where site conditions allowed. Construction practices frequently relied on concrete stabilization.

Second, construction costs showed high variability and were mainly driven by typology and construction method. Boulder ramps built with concrete were consistently the most expensive solutions, whereas bottom-type and pool-and-weir configurations showed lower median costs. The standardized cost indicators proposed (€/m^2 and €/m of head difference, normalized to a 5 m width) provide transferable metrics for comparing projects and supporting early-stage planning.

Third, although post-construction monitoring remains limited, available evidence indicates that properly designed NLFs achieve efficiencies comparable to those of technical fishways. Recurring

 doi:10.20944/preprints202602.1036.v1

deficiencies related to entrance conditions and local hydraulics highlight the need for rigorous design, construction control, and systematic evaluation.

Overall, NLFs are an effective option for restoring connectivity at low-head barriers, but their selection should jointly consider ecological suitability, space availability, construction feasibility, and standardized cost-effectiveness criteria. Expanding post-implementation monitoring and integrating economic and efficiency assessments will be essential to optimize future restoration strategies.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Table of data and information used in the research work; S2: Table and box plot of median values and interquartile ranges of construction costs per height for a width of 5 m (€/m).

Author Contributions: Conceptualization, A.S.-R. and F.J.S.-R.; methodology, A.S.-R. and F.J.S.-R.; investigation, A.S.-R.; data acquisition A.S.-R. and F.J.S.-R.; data curation, A.S.-R., A.G.-V., F.J.B.-C. and F.J.S.-R; writing—original draft preparation, A.S.-R., A.G.-V., F.J.B.-C. and F.J.S.-R; writing—review and editing, A.S.-R., A.G.-V., F.J.B.-C. and F.J.S.-R; project administration, A.S.-R. and F.J.S.-R. All authors have read and agreed to the published version of the manuscript.

Funding: The work has been partially funded by the IV Agreement between the Duero River Basin Authority, Itagra Technological Center and the University of Valladolid.

Data Availability Statement: The original contributions presented in this study are included in the supplementary material. Further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors would like to thank the technicians and public and private entities that provided us with the information necessary for carrying out this study, such as: Pedro Castillo and Ismael Pérez in Orekan company (Navarra); Pedro Boné in Typsa (Zaragoza); Arturo Prieto, Ignacio Rodriguez and Henar de Meer of the Duero River Basin Authority (CHD); Felipe Álvarez and Arantza Unzurrunzaga of the Gipuzkoa Hydraulic Works Service; Víctor Manuel Pérez Goya of the Tajo River Basin Authority (CHT); Pablo Fernández (Zamora), Rosa Olivo (Murcia), José Alberto Alcaraz, Eugenio Cano and José Ángel Gómez (Granada) in Tragsa company; Gonzalo Magdaleno in the Ministry for Ecological Transition and the Demographic Challenge, Jesús Carasa of the Cantabrian Basin Authority (CHC); Agustín Sevilla of the Miño-Sil Water Authority (CHMS); Eduardo Lafuente of the Segura River Basin (CHS); Rosa Olivo Juan José Villegas, Mónica Bardina and Emilio Sánchez of the Catalonian Water Agency (ACA). During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language editing and the rephrasing of text. All scientific content, data analysis, and interpretation were performed by the authors. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. They have no known financial conflicts of interest or personal relationships that could have influenced the work presented in this article.

Abbreviations

The following abbreviations are used in this manuscript:

NLFs	Nature-like fishways
R	Ramp
BC	Bypass channel
bl	Boulder type
pw	Pool and weir system
bt	Bottom type
c	Concrete structures
sd	Semi dry structures
d	Dry structures
DBC	Direct Building Cost
VS	Vertical slot fishway
SNBO	Submerged notch and bottom orifice fishway

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