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Research article

A step forward in fishway engineering: Validation and implementation of advanced algorithms for effective stepped fishway design, modeling, and retrofitting

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A R T I C L E I N F O

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A B S T R A C T

Stepped fishways are the main alternative to allow fish migration in river obstacles. Their design is a multidisciplinary process, where civil engineering meets biology. This can bias the fishway design towards one discipline, which may cause low efficiencies or inadequate solutions. Likewise, it is often challenging to incorporate new discoveries into well-established design principles. To solve these problems, we have developed a novel tool named "*Escalas*". *Escalas* is a multipurpose platform for the assisted design, 1D simulation, assessment, and correction of stepped fishways. *Escalas* architecture allows fishway assessment during different hydraulic scenarios in the river (i.e., different water levels and discharges in the river), automatic dimensioning considering fish's physical needs, the study of any type of stepped fishway, to test solutions for malfunctioning or to assess fishway retrofitting. This is achieved by a modular variable definition during fishway design or definition, which allows multiple combinations of connections within and/or between cross-walls and independent discharge equation definition. This work aims to introduce *Escalas* to the research and engineering community, describe its algorithms, and show and validate its performance by its use in real and practical cases. Among others, results demonstrate how the tool can reproduce uniform and non-uniform performances on stepped fishways and allows fishway retrofitting to make hydraulic conditions compatible with fish usage during different river scenarios. Therefore, this work represents a step forward in the fishway engineering discipline by applying methods of engineering informatics and providing a technical and scientific base to make engineering decision-making more reliable and accessible as well as to incorporate new advances in fishway research into the engineering design process.

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1. Introduction

Stepped fishways have become the most common alternative to facilitate fish migration across transversal obstacles in rivers. Their installation has proliferated and accelerated due to the decline of freshwater fish stocks in many rivers worldwide [1] and owing to temporal limits established by different regional environmental regulations to address this issue [2]. However, despite their widespread acceptance for facilitating fish migration, their performance remains inadequately understood, leading in some cases to suboptimal efficiencies [3,4].

Based on their general configuration, stepped fishways can be classified into several types: pool and weir fishway (PWF) [5,6], vertical slot fishway (VSF) [7,8], or step-pool nature-like fishway (SPNF) [9]. All of them, however, have a similar working principle [10]. Stepped fishways consist of a succession of cross-walls, with different kinds and numbers of connections (slots, notches, and/or orifices) in a sloping channel. The cross-walls divide the total height of the obstacle (H) into smaller water drops (ΔH), ensuring hydraulic conditions within the range of the physical capacities of fish, enabling their passage.

At present, there are well-established guidelines and handbooks for designing these structures [11–14]. Similarly, the design community has defined simplified variables or criteria to assess fishways' performance (e.g., maximum velocity in the cross-walls (V_{max}) or volumetric dissipated power (VDP) in the pools). These variables, although oversimplify the ongoing physics, have shown relevance according to fish preferences [15,16] and correlation with more complex variables (e.g., turbulent kinetic energy vs. VPD in Ref. [17]). These methods combined with technical experience, equip engineers with the necessary tools to design fishways.

However, it is often challenging to incorporate new findings into design principles, both (a) because the classical design criteria are rarely challenged and (b) because researchers fail in the information transmission to engineers [18]. For less experienced engineers, it is difficult to account for all the design considerations and constraints. A specific example is the non-uniform water-level profiles in fishways [19]. These profiles are the hydraulic response of fishways to river variability, they modify hydraulics inside them and, thus, fish passability. Despite this phenomenon started to become well-known since the first VSF serial studies of Rajaratnam et al. [7], some technical solutions were proposed by Larinier [12], and has been widely studied in recent years [6,19–21], it is still rarely considered by the design and the research community (e.g., Refs. [22,23]).

The design and research of fishways are multidisciplinary disciplines, where hydraulic and civil engineering meet biology. This borderline nature of fishways has the potential of biasing the fishway design and research towards one discipline over another, which may cause inadequate designs and solutions or weak research results. On the other hand, formalizing complex engineering knowledge through advanced computational tools is crucial for engineers to effectively solve practical problems within the constraints and financial restrictions they face [24,25].

To solve this problem, to have a joint point for all the advances in stepped fishway design, and to facilitate the fishway design and evaluation, we have developed a free toolbox named *Escalas* ([26]; *Software S1*). First *Escalas* release was born as a proprietary simulator of water levels and as a tool to evaluate discharge equations [27]. Through the years and its use in the design and evaluation of different fishways (>150), it has become a multipurpose platform for assisted design, 1D simulation, evaluation, and correction of stepped fishways. Therefore, *Escalas* supposes a step forward in the fishway engineering discipline by applying methods of engineering informatics (e.g. simulation, assisted design, information systems, system optimization, or data analysis).

Escalas has evolved from our earlier research on non-uniformity in fishways [6,8,10], which has enabled us to validate the proposed equations and simulation procedures. However, it expands on this by facilitating the integration of biological and hydraulic data to generate optimized designs for fishways and providing a simulation algorithm capable of managing various combinations of connections in fishway cross-walls, obstacles, and river discharges. Furthermore, it offers a user-friendly and configurable platform for the design, testing, simulation, and retrofitting of stepped fishways.

In contrast to other available software (e.g., FishPath [28,29] or Cassiopée [30,31]), *Escalas'* equations and performance have been tested and validated in real case field studies. In addition, it offers 1) the assisted design of any type of stepped fishways (and equation combination) and 2) automatically takes into account biological constraints during the design process. Moreover, *Escalas'* architecture allows 3) the evaluation of different hydraulic scenarios in the river (i.e., different boundary conditions), 4) testing solutions for possible malfunctioning, and 5) assessing retrofitting scenarios to improve fishway performance. This is achieved by a modular variable definition which allows any type of possible combination of connections within a cross-wall and, if necessary, different ones between cross-walls, as well as independent discharge equation definition for each connection. This provides a technical and scientific base to make engineering decision-making more reliable and accessible as well as to incorporate new advances in fishway research to the design process in environmental engineering.

Furthermore, differing from computational fluid dynamics (CFD) tools, which can accurately simulate the 3D performance of fishways with an adequate investment of time and a high level of expertise [20,32–34], *Escalas* does not require highly demanding computations or advanced-level users. In addition, 1D models can provide enough information for the design and evaluation of fishways and can also synergize with 3D models, to establish boundary conditions and predefine the fishway, reducing overall computational costs [34].

Therefore, given the considerations above, the main objectives of this paper are to i) share *Escalas* toolbox with the academic, research, and engineering community, while allowing its use and evolution; ii) describe its architecture and algorithms; and iii) validate and show its performance by study cases.

2. Material and methods

The following sections describe the discretization of the problem (i.e., design and modeling of stepped fishways) to be solved

(Subsection 2.1) and the algorithms used in *Escalas* (Subsections 2.2 and 2.3). Subsection 2.4 introduces the study cases to validate and illustrate the results of the toolbox.

2.1. Fishway and variable definition

As mentioned in the introduction, stepped fishways can be described as a succession of cross-walls over a sloping channel (Fig. 1). The number and type of connections in the cross-walls may change according to their spatial distribution within the same fishway (e.g., fish exit, regular cross-walls, or fish entrance) (Fig. 1a) and also according to the fishway type (Fig. 1b).

To take into consideration the possible diversity of configurations, *Escalas* defines and decomposes a fishway in modules (n), where each module consists of a single cross-wall and the pool below it (Fig. 1c). In the same way, each cross-wall can have any number (m) and types of connections. For instance, the first sketch of Fig. 1b shows a cross-wall with $m = 2$ connections: an orifice and a notch. Therefore, by defining each fishway as a succession of these modules, it is possible to describe any type of stepped fishway and, in the same way, to consider any peculiarity of the structure (e.g., special adaptations in the entrance or exit).

On the other hand, associated structures such as dams or weirs can be defined if necessary. This allows us to consider fishway performance during the different hydrodynamic scenarios in the river. They are defined similarly to a single cross-wall associated with the fishway and their geometrical definition is referred to the last cross-wall of the fishway (i.e., fish entrance) (Fig. 2).

For more information, the reader is referred to the first supplementary video associated with this publication (Video S1).

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2024.e25996.

2.2. Fishway design workflow

Fig. 1a shows a classical sketch of a stepped fishway. A stepped fishway can be discretized into a set of regular cross-walls which may include some modifications, for instance, in the fish exit (most upstream cross-wall) and/or in the fish entrance (most downstream cross-wall) due to technical reasons (e.g., a gate to allow maintenance, variable sill to adapt to high variations in water levels, etc.). Considering the described modular definition, the fish entrance has null pool variables (i.e., length of the pool (L) = 0 m and the topographic difference between cross-walls (ΔZ) = 0 m), while its cross-wall in most cases will be equal to the regular cross-walls.

Considering this discretization of the structure, it is possible to simplify the fishway design in two main steps, i) the selection of the fishway type or the regular cross-wall design and ii) the fish exit definition, in both cases considering the biological constraints (i.e., values of hydraulic variables and fishway geometry must be inside the fish preferences).

Fig. 3 shows *Escalas* algorithm for assisted fishway design. It is based on the classical guidelines [11–13] with practical modifications to optimize and automatize the design process and to include different possible design typologies and biological constraints.

First, it is necessary to define the biological constraints that the fishway must fulfill (Fig. 3a), select the type of fishway (Fig. 3b), choose a preliminary ΔH, and decide on the method to adjust it (Fig. 3c). There are different methods to adjust ΔH if it is not a multiple of H. If an adjustment using the exit cross-wall is selected, then ΔH at regular cross-walls will be equal to the pre-defined one and the adjustment of ΔH will be made by a smaller ΔH at the fish exit. The other two possible choices, which both consider ΔH at the fish exit to be equal to that at regular cross-walls, either reduce or increase ΔH to align the design with the proposed or calculated H.

Afterwards, the desired fishway discharge ($Q_{fishway}$) and the total discharge through the river (Q_{river}) have to be defined (Fig. 3d). These are the flow discharges during the design conditions, which are usually related to the migration period of the target fish species. The performance of the fishway during other periods can be later simulated with *Escalas*. When the defined Q_{river} is higher than $Q_{fishway}$ the algorithm assumes that an associated structure exists and, therefore, it will be necessary to define it (Fig. 3e). Once the obstacle or associated structure is dimensioned, H is calculated taking into account the defined variables (i.e., discharge equation and discharge

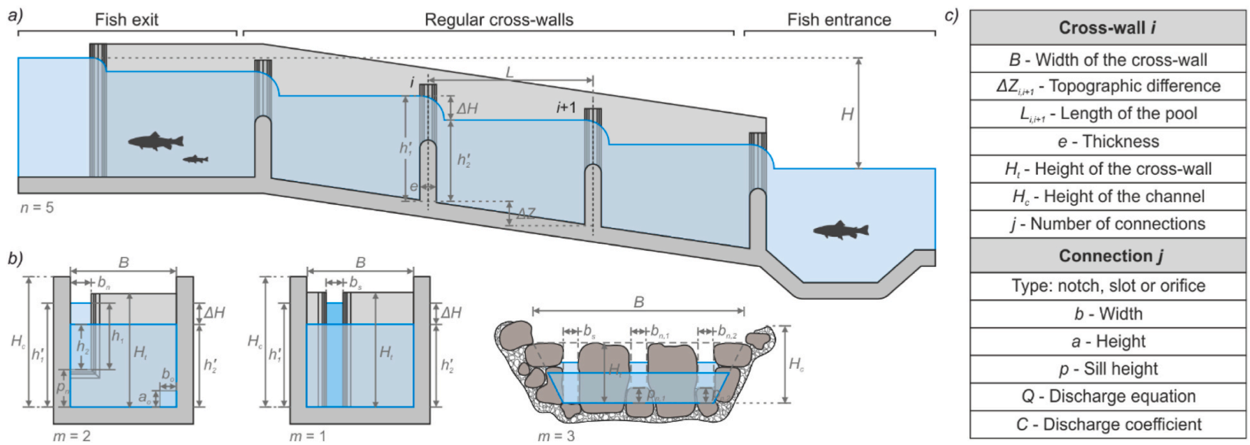

Fig. 1. Definition of fishway and variables in terms of the software architecture (see notation section for abbreviation description). a) Fishway definition. b) Example of cross-walls with different connections. c) Data structure.

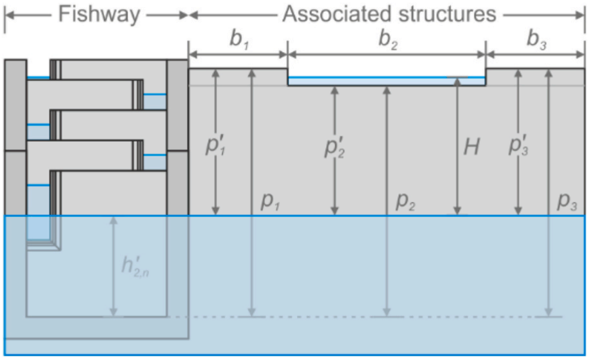

Fig. 2. Front view of a possible associated structure and its variable definitions. During the design process, the user is required to define p' (sill height, measured from the downstream water level) and b (width of the associated structure).

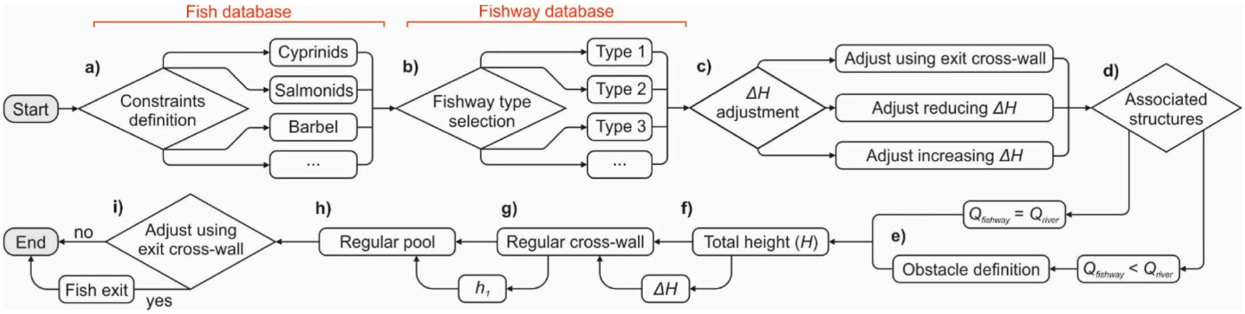

Fig. 3. Workflow for the assisted design of stepped fishways.

through the associated structure). Nevertheless, if Q_{river} is equal to $Q_{fishway}$, it will be necessary to insert H manually (Fig. 3f), indicating that all the discharge will flow through the fishway.

The next step is the definition of the regular cross-wall connections (Fig. 3g). While governing equations are pre-defined according to the selected fishway type [10,12,35] (Table 1), users can modify both discharge equations and dimensions as needed. Althought pools are auto-sized to fulfill biological constraints, the final decision always remains with the user (Fig. 3h). Finally, if the adjustment by the exit cross-wall has been chosen, the exit is automatically dimensioned taking into account the defined variables in previous steps (Fig. 3i).

Table 1
Example of fishway definitions in the database [10,12,35].

Fishway		VSF1	PWF	VSF2	SPNF
References		[10,12]	[10,12]	[10,35]	[10,12]
Slots	Discharge equation	$2/3\ C\ b \cdot h_1 \cdot (2\ g \cdot h_1)^{0.5}$	–	$2/3\ C\ b \cdot h_1 \cdot (2\ g \cdot h_1)^{0.5}$	$2/3\ C\ b \cdot h_1 \cdot (2\ g \cdot h_1)^{0.5}$
	Discharge coefficient (C)	$0.705 \cdot (1-(h_2/h_1)^{1.5})^{0.317}$	–	$0.705 \cdot (1-(h_2/h_1)^{1.5})^{0.317}$	$0.812 \cdot (1-(h_2/h_1)^{1.5})^{0.335}$
	Number	1	–	1	1
Notches	Discharge equation	–	$2/3\ C\ b \cdot h_1 \cdot (2\ g \cdot h_1)^{0.5}$	–	$2/3\ C\ b \cdot h_1 \cdot (2\ g \cdot h_1)^{0.5}$
	Discharge coefficient (C)	–	$0.644 \cdot (1-(h_2/h_1)^{1.5})^{0.275}$	–	$0.812 \cdot (1-(h_2/h_1)^{1.5})^{0.335}$
	Sill height	–	0.6	–	0.2
	Number	0	1	0	2
Orifices	Discharge equation	–	$C \cdot A \cdot (2\ g \cdot h_1)^{0.5}$	–	–
	Discharge coefficient (C)	–	0.876	–	–
	Sill height	–	0	–	–
	Type	–	Rectangle	–	–
	Number	0	1	0	0
L		9·b	9·b	10·b	9·b
B		7·b	5·b	8·b	5·b
Tolerance		b	b	0	b
e		0.20	0.20	0.05	0.60

Table 2
Example of defined constraints for cyprinids and salmonids according to specialized references.

Variables[a]	Cyprinids	Salmonids
VDP_{max} (W/m^3)	150	200
VDP_{rec} (W/m^3)	150	200
ΔH_{max} (m)	0.20	0.25
ΔH_{rec} (m)	0.15	0.20
$b_{n,min}$ (m)	0.15	0.20
$b_{n,rec}$ (m)	0.20	0.20
$h_{n,min}$ (m)	$2{\cdot}\Delta H$	$2{\cdot}\Delta H$
$h_{n,rec}$ (m)	Calculated	Calculated
$a_{o,min}$ (m)	0.15	0.20
$a_{o,rec}$ (m)	0.20	0.20
$b_{o,min}$ (m)	0.15	0.20
$b_{o,rec}$ (m)	0.20	0.20
$b_{s,min}$ (m)	0.15	0.20
$b_{s,rec}$ (m)	0.20	0.20

[a] *max*: maximum values; *rec:* recommended values; *min:* minimum values.

In *Escalas* design constraints are applied throughout the workflow, ensuring that the user satisfies them explicitly (advising) or implicitly (automatically dimensioning the structure). In the current form, the tool has standard constraints, such as V_{max} or *VDP* (both limits definable by the user) [11,36] or pool and cross-wall dimensioning [12,35] (Table 2). The constraints can be modified during the design process or by adding specific ones in the database for new species or fish groups.

Regarding fishway types, four typologies have been defined for now: 1) single slot VSFs according to Larinier [12] and Fuentes-Pérez et al. [10], 2) single slot VSFs according to Rajaratnam et al. [35] and Fuentes-Pérez et al. [10], 3) bottom orifice and weir PWFs according to Larinier [12] and Fuentes-Pérez et al. [10], and 4) single slot and double weir SPNF according to Fuentes-Pérez et al. [10] (Table 1). However, it is possible to extend the workflow to other fishway types, such as double slot VSFs, Ice Harbor type PWFs, or other SPNFs configurations, by adding their definition to the database or defining specific connections in the cross-walls during the design process. Moreover, any desired type can be defined manually starting from scratch by adding different modules (i.e., cross-wall and consecutive pool).

For more information about the fishway generator and database modifications, the reader is referenced to the second and third supplementary videos: Video S2, showing the use of the fishway generator, and Video S3, which shows database modification (in this video new fishway and new biological constraints definition are added).

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2024.e25996.

2.3. Simulation algorithm

The simulation algorithm is able to calculate water level distribution for different hydrodynamic scenarios. This, in turn, allows the assessment of their potential impact on fish fauna. For this purpose, boundary conditions of the hydrodynamic scenario have to be defined: Q_{river} (or $Q_{fishway}$ if $Q_{river} = Q_{fishway}$) and $h'_{2,n}$ (water level downstream the last cross-wall (n) from the channel bed, Figs. 1 and 2).

Q_{river} flows through the different structures of the obstacle, i.e., amongst the fishway ($Q_{fishway}$) and other associated structures (dam, diversion channels, etc.) ($Q_{associated}$), if they exist ($Q_{river} = Q_{fishway} + Q_{associated}$).

$Q_{fishway}$ is the variable that is modified during the iteration process until convergence (Fig. 4). For each $Q_{fishway}$, known $h'_{2,n}$ and considering the defined geometry (slot/notch/orifice dimensions and ΔZ_i) and the discharge equations for each connection, ΔH_i can be calculated consecutively from bottom-up, for each n cross-walls (Fig. 4). Finally, for the selected $Q_{fishway}$ value, the upstream water level of the fishway ($h'_{1,1}$) is computed.

If there are other associated structures, their flow can be calculated using $h'_{1,1}$, and lastly obtaining Q_{river} for the specific $Q_{fishway}$. A greater Q_{river} than the desired one involves a new calculation with a smaller $Q_{fishway}$ whilst a lower Q_{river} implies the selection of a greater $Q_{fishway}$ (Fig. 4).

In extreme working cases, the equations defined for the connections in regular cross-walls may be out of their range of performance (e.g., overflow in the cross-wall, orifice working as a slot, or others). In those cases, *Escalas* makes use of default equations to provide an estimation of the performance. This default equation can be also modified by the user.

For more information about the simulation, the reader is referred to Video S4 associated with this publication showing the simulation procedure.

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2024.e25996.

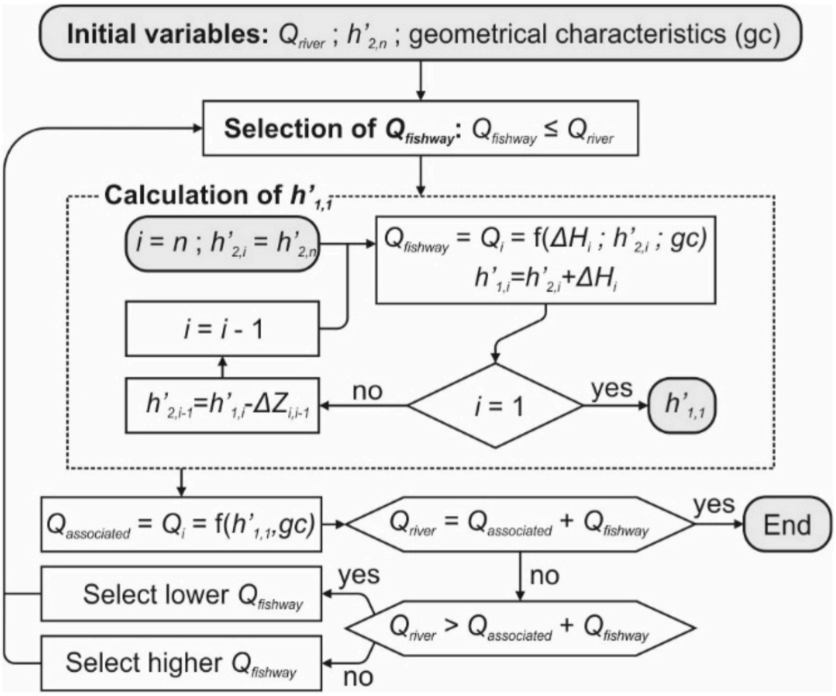

Fig. 4. Flowchart of the steps of the simulation algorithm.

2.4. Validation

The algorithm has been validated through its use in real cases, both for the design of new fishway projects as well as the evaluation of fishways after their construction (validation of discharge equations and simulation algorithm can be found in Fuentes-Pérez et al. [6,8,10]). To show its performance, Subsection 3.1 displays the expected results using a design example of a PWF and the defined constraints for cyprinids.

Subsection 3.2 shows the outcome of the simulation algorithm for the designed PWF during different hydrodynamic scenarios in the river. Additionally, due to the importance of the simulation algorithm, this paper also tests its reliability by comparing simulated results with an on-field fishway's hydrodynamic performance under different scenarios. For this purpose, a fishway located in the Duero River, near Guma village in the northwest part of Spain (41°38′13.9 N - 3°32′36.9″ W) was studied. The fishway is composed of 36 cross-walls with submerged notches and bottom orifices (notch width (b_n) = 0.3 m; sill height (p) = 0.8 m; orifice size = 0.175 m (b_o) x 0.175 m (a_o)) and 35 pools (L = 2.6 m; B = 1.6 m; slope (S) = 8.6 %), with mean water drops (ΔH) of 0.25 m, mean water depth in the pools (h_0) of 1.2 m and *VDP* of 121 ± 10 W/m^3. The geometrical parameters of the fishway were acquired through topographic surveying with a Leica TC307 total station, to a precision of 0.001 m. Smaller details, such as orifice and notch dimensions were measured using metal rulers to the same precision level. For testing and evaluation purposes, only the uppermost section of the fishway was considered, i.e., five pools. The water levels in the studied pools were measured in real-time by a sensor network of ultrasound water levels (*MS Ultra,* [37]). The tests consisted of monitoring the water level evolution under different section reductions of connections (notches and orifices) in the cross-wall during constant discharge ($Q_{fishway}$ = 0.251 m^3/s) and then comparing the results with those obtained with *Escalas* toolbox. In each cross-wall (from i = 1 to i = 5), two connection reductions were tested: 1) suppression of the orifice using a wooden board, and 2) a small reduction of the lower part of the notch (20 cm) with a wooden board avoiding the water to spill over the cross-wall. Only the section of one connection was reduced in each test (total number of scenarios = 10 connection reduction tests + 2 scenarios without obstructions (start and end of experiments)). All simulated data were obtained with *Escalas* and after they were post-processed for graphical and numerical validation with Matlab 2019b. The comparative study of the simulations and the experimental data was carried out by plotting together water level profiles and calculating the mean absolute error, as well as, plotting simulation results against experimental data and calculating the distance of the scattered points to a 1:1 line, using squared Pearson correlation (coefficient of determination, R^2) as an index.

Finally, Subsection 3.3, deals with the undesirable conditions for fish in fishways during extreme scenarios, showing the use of *Escalas* to design small adjustments or retrofits to facilitate the fish passage during extreme scenarios and extend fishways' correct performance in time.

Readers are encouraged to consult supplementary Appendix S6 for a comprehensive, step-by-step numerical resolution guide for all the examples and calculations provided in this article.

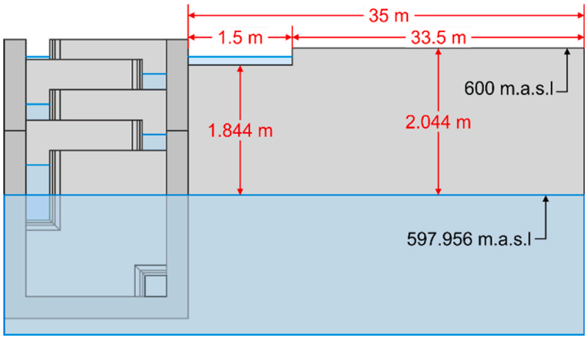

Fig. 5. Definition of the obstacle and attraction notch (front view).

3. Results and discussion

3.1. Fishway design

Escalas provides an assisted interface to design fishways, drawing from constraints defined by well-established guides [11–13,38] and incorporates not only the recent advances in the field [10,39,40] but also, the experience in the design of more than 150 fishways by the Group of Applied Ecohidraulics of University of Valladolid (Spain).

In the following section, a design example of a PWF for cyprinids (e.g., Iberian barbel, *Luciobarbus bocagei*) (Fig. 3a and b) is presented and discussed using *Escalas* (the reader is referred to Video S5). The selected PWF consists of a succession of cross-walls with submerged notches and orifices [12]. Notches will operate under a streaming regime, which has been shown to enhance the upstream movements of cyprinids [5,41]. Bottom orifices will be installed alternating side to side, as this configuration has shown higher rates of passages than other configurations for some species such as Iberian barbel [42]. The difference in level between pools (ΔZ) will be 0.2 m as recommended in the cyprinid database (Table 2) (Fig. 3c). This ensures lower velocities than 2 m/s in the notch, making it suitable for the target cyprinids [39]. In addition, to adapt the structure to the total water difference, a ΔH adjustment using the most upstream cross-wall will be selected (Fig. 3c). This means that while the regular cross-wall will have a water drop between pools of 0.2 m, the fish exit will have a smaller one.

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2024.e25996.

The mean discharge through the river during migration season, Q_{river}, is 3.1 m^3/s (diverted water has been already deducted) and a design discharge through the fishway ($Q_{fishway}$) of 0.3 m^3/s will be selected (≈10 % of the river discharge [43]). Following this, the geometrical characteristics of the obstacle must be defined (Fig. 5). In the obstacle, a notch will be incorporated to concentrate additional attraction flow. Considering this, the associated structure to the fishway will consist of a weir of 33.5 m in width and a height from the downstream water level (p') of 2.044 m, and an attraction notch of 1.5 m in width and 1.844 m in height. Selection of the correct downstream water level is always a difficult task. For this example, the mean water level during the migration season of the target species was chosen. However, it is a common practice to select the downstream water level of the scenario with the highest difference between headwater and tailwater levels [44], which usually happens with the lowest discharge in the river (dry season). Regardless of the chosen water level, after the fishway is designed, its performance will be checked under different scenarios in section 3.2.

The defined variables will give a result of 2.154 m total height to overcome (H) and a fishway of 10 pools and 11 cross-walls ($\Delta H_{\text{fish exit}} = 0.154$ m).

Escalas automatically sets the dimensions of connections in the cross-walls ($b_n = 0.2$ m, $p = 0.6$ m, $a_o = 0.2$ m and $b_o = 0.2$ m) according to the defined constraints (Table 2). With the default values, in this example, the maximum water level in the pool (h'_1) is 1.483 m. To avoid human drowns is a good practice to assign to h'_1 values lower than the mean human breast height (1.3 m), therefore a wider width for the notch will be selected ($b_n = 0.3$ m), obtaining a final h'_1 of 1.238 m. The pool dimensions are automatically set (B

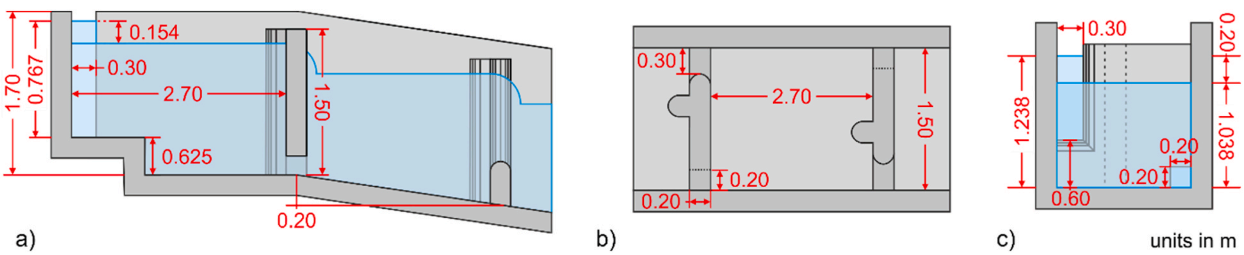

Fig. 6. Final dimensions (units in meters) of the designed fishway. a) Longitudinal view of the fish exit and consecutive pool. b) Plant of the pools and regular cross wall. c) Cross section of the regular cross-wall with its two connections: notch and orifice.

Table 3
Water level distribution for the design scenario (Q_{river} = 3.1 m^3/s and $h'_{2,n}$ = 1.038 m). Q_s – Discharge through slots; Q_{sn} - Discharge through notches in streaming conditions; Q_{fn} - Discharge through notches in plugging conditions; Q_o - Discharge through orifices; Q_T - Total discharge.

Name	ΔH (m)	h'_1 (m)	h'_2 (m)	Q_s (m^3/s)	Q_{sn} (m^3/s)	Q_{fn} (m^3/s)	Q_o (m^3/s)	Q_T (m^3/s)	VDP (W/m^3)	V_{max} (m/s)
Cross-wall 1 (fish exit/gate)	0.154	0.767	0.612	0.300	0	0	0	0.300	120.971	1.739
Cross-walls 2–10	0.200	1.237–1.238	1.037–1.038	0	0.230	0	0.069	0.300	127.709–127.585	1.981
Cross-wall 11 (fish entrance)	0.200	1.238	1.038	0	0.230	0	0.069	0.300	–	1.980
Associated 1 (weir)	2.154	3.192	1.038	0	0	2.309	0	2.309	–	–
Associated 2 (attraction notch)	2.154	3.192	1.038	0	0	0.491	0	0.491	–	–

= 1.5 m and L = 2.7 m) considering the fishway characteristics in the database (Table 1) and fish constraints (e.g., *VDP*, Table 2). The height of the cross-walls and channel walls are also dimensioned considering h'_1 values (H_t = 1.44 m and H_c = 1.64 m). These are indicative values and they will only influence the performance in extreme events. Therefore, to make the construction easier, round values will be selected for these variables (H_t = 1.5 m and H_c = 1.7 m).

The design will finish with the dimensioning of the most upstream cross-wall (slot/gate). Considering its water drop (ΔH = 0.154 m) and a width of 0.2 m a step of ΔZ = 0.242 m will be required to compensate its discharge with the discharge through the regular cross-wall. Ideally, a ΔZ = 0 m is preferable; however, the resulting slot would be narrower (0.165 m). Wider connections will allow better regulation of levels for higher discharges, easier exit for the fish and it would be less susceptible to obstructions. Therefore, a gate with equal width to the regular cross-walls (b = 0.3 m) is selected, with a step of ΔZ = 0.625 m between the exit and downstream cross-wall that will be automatically dimensioned. Fig. 6 shows the final design details and dimensions of the structure. Table 3 shows the water level distribution as well as the discharges through the different components of the structures under the design scenario (Q_{river} = 3.1 m^3/s and $h'_{2,11}$ = 1.038 m).

3.2. Scenario modeling

After the fishway design, *Escalas* enables users to simulate different water level scenarios, as well as biologically relevant variables (*VDP* and V_{max}). Simulating new scenarios involves specifying new values of the discharge through the river and the downstream water level in the *simulation* sheet (Video S5). Conducting such simulations is a good practice to ensure that the designed fishway will work in the most adverse scenarios where it is required to work. According to the fishway guides and experts, the fishway should be functional for fish on at least 300 days/year [44,45]. This observation can be used to select the maximum (Q_{330}, 330-days-non-exceedance discharge) and minimum discharge (Q_{30}, 30-days-non-exceedance discharge) to assess the fishway performance.

For the designed fishway, the maximum river discharge is Q_{river} = 12.4 m^3/s, which causes an increase in water level downstream of the obstacle of 0.6 m compared to the design situation ($h'_{2,n}$ = 1.638 m). Conversely, the minimum river discharge is Q_{river} = 0.775 m^3/s, leading to a 0.5 m decreases in the downstream level relative to the design scenario ($h'_{2,n}$ = 0.538 m). The new boundary conditions will generate different discharge rates in the fishway and associated structures and non-uniform profiles in the fishway [6,10]. Fig. 7 shows the distribution of ΔH in the pools obtained with *Escalas* during both scenarios in comparison with the performance during the design one.

In general, high discharges are associated with an increase in the downstream water level and consequently with a non-uniform water level distribution in the pools of the fishway which generates a backwater profile ($\Delta H < \Delta Z$) (Fig. 7a). These performances cause a decrease of the most downstream water drop (ΔH = 0.031 m, V_{max} = 0.767 m/s in this example) [6], resulting in a reduction of the velocity and turbulence at the fish entrance. This leads to less attraction and, thus, makes it more difficult for fish to find the fishway entrance or the migration path [3]. A velocity at the entrance equal to the design velocity in the fishway has shown good results in the fishway attraction [46], with a minimum recommended velocity of 1 m/s [43] to generate a sufficient flow field for

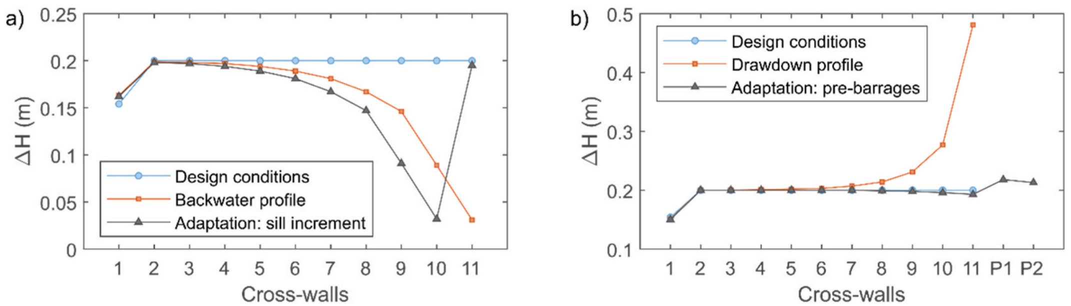

Fig. 7. Profiles of the difference in water drops (ΔH) between pools under (a) an increase of downstream water level and river discharge and (b) a decrease of downstream water level and river discharge. P in the right x tick labels refer to additional pre-barrages to overcome problems of the drawdown scenario (for more information on the ΔH distribution after the implementation of adaptation check section 3.3).

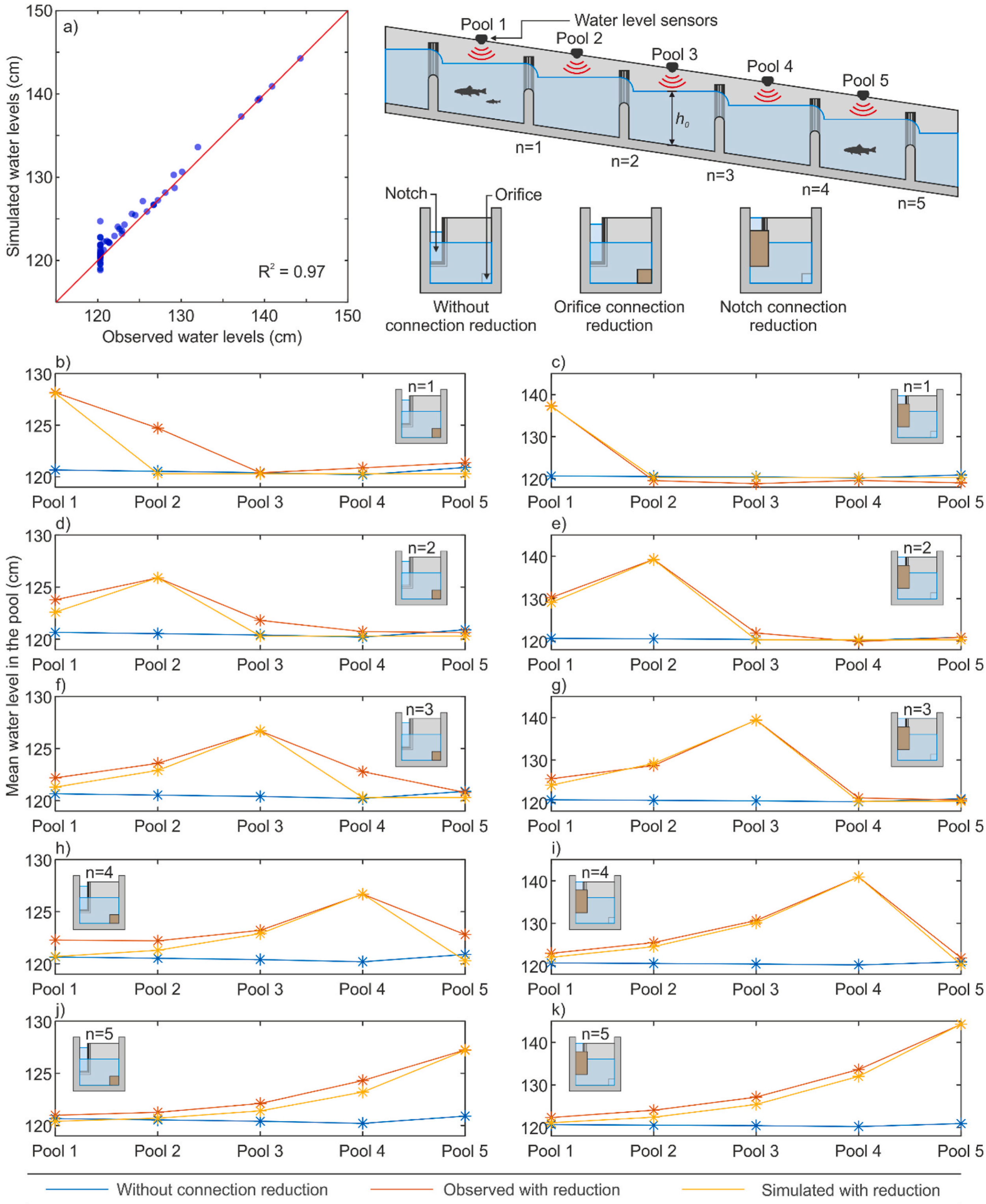

Fig. 8. Connection reductions tested in the field against 1D simulations. a) Scatter plot of all measured and simulated mean water levels in pools. b,d,f,h,j) Suppression of different orifices. c,e,g,i,k) Reduction of notch connections.

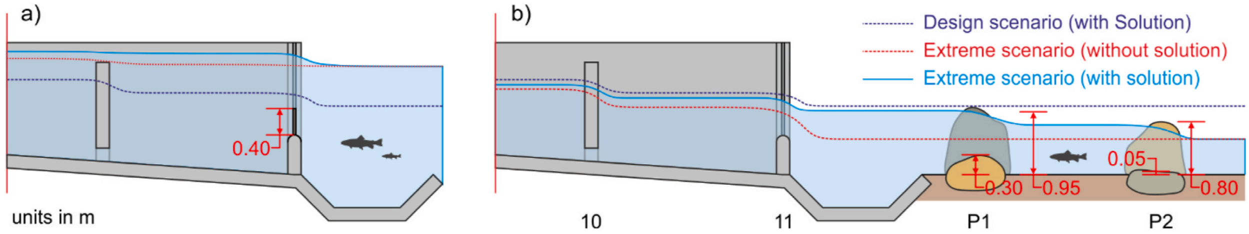

Fig. 9. Fishway adaptations (units in meters). a) Increment of notch sill to ensure a higher water drop at the fish entrance during high flow scenario. b) Stone pre-barrages to reduce the water drop in the fish entrance during low flow scenarios.

fishway localization by the fish.

Low discharges through the river generate a drawdown profile in ΔH distribution ($\Delta H > \Delta Z$) (Fig. 7b), exceeding the maximum velocity recommended for target cyprinids in the fish entrance ($\Delta H = 0.481$ m, $V_{max} = 3.07$ m/s) and increasing the turbulence, which may limit the fish entrance and increase the energy expenditure [47–49]. [43] defines an optimal water speed for salmonids and large migrants in the order of 2.0–2.4 m/s ($\Delta H = 0.2$–0.3 m). Similar values can be considered for species with comparable swimming abilities such as Iberian barbel and northern straight-mouth nase (*Pseudochondrostoma duriense*) [39]. Consequently, extreme scenarios will have negative repercussions on the fishway performance that need to be corrected to achieve an adequate performance during the target period (Section 3.3).

The design of a fishway with *Escalas* produces an ideal representation of its performance, however, once the fishway has been constructed there are some geometrical deviations that can alter its performance [50]. Even with these deviations, if they are measured accurately, Escalas can still provide reliable simulations for assessing the fishway's performance. To illustrate this, Fig. 8a–k shows the simulation algorithm output of a real PWF fishway subject to different modifications in cross-wall connections (notches and orifices). The simulated water level profiles closely align with the observed profiles (Fig. 8b–k), evidenced by a mean absolute error of just 0.9 cm and a global R^2 of 0.974 (Fig. 8a). This underscores the software's utility for retrofitting applications.

3.3. Fishway adaptations

In light of the issues identified in extreme scenarios for the designed fishway, *Escalas* allows testing different solutions to overcome the detected limitations (the reader is referred to Video S5). For instance, to increase the water drop in the entrance during backwater profiles, it is possible to design a notch with variable sill height (Fig. 9a), for example using grooves running along the side of the opening and a metal or wooden board. Increasing p in the most downstream notch by 0.4 m ($p_{11} = 1$ m) will move upstream the backwater profile under maximum discharge to the above cross-walls and increase the water drop in the fish entrance up to 0.195 m (Fig. 7a).

Regarding low discharge scenarios, it would be also possible to reduce the sill height; however, this would only move the high drop of the entrance inside the fishway, causing an insufficient water depth for fish to access by swimming or even jumping to the fishway [51]. A better solution is to design a succession of pre-barrages that will only work under extremely low discharge scenarios (Fig. 9b). Fig. 7b shows the results of adding two successive pre-barrages (Fig. 9b) below the fish entrance. These pre-barrages will absorb the high drop at the entrance and, consequently, V_{max} and *VDP* will be reduced to admissible values, as well as, maintaining a sufficient water depth at the entrance.

Escalas facilitates solution testing and dimensioning and, in the same way, it can be used to schedule an adaptive management plan, considering the river dynamics, to achieve an optimum fishway performance during all the target periods/scenarios. Optimizing the use of barriers and fish migration devices (i.e. adaptive management) is key for balancing human water needs with freshwater ecosystem conservation, allowing to address uncertainty and accommodate for future scenarios [52].

4. Summary and conclusions

Escalas is a tool for engineers and researchers that aims to study, design, or optimize the use of stepped fishways. However, its use needs a basic understanding of the field of fishway hydraulics and biological constraints, to guarantee an adequate design for the target species. Due to its assumptions and discretization, some limitations have to be considered to generate an appropriate fishway design.

Escalas discretizes fish preferences in a few parameters (Table 2). These parameters are well-known for the most important migratory fish species and they are well-defined in classical guidelines. However, it is common to point out in the research field of fishways that there are great unknowns regarding swimming abilities, migration periods, and motivation of many fish species [3, 53–55]. This seems to justify the need for more studies about fish preferences as well as their specific constraints on the fishway design, but also to continuously update the design guidelines (e.g., using an online database for fishway engineers) to take into account the increasing number of studies about species that historically have been disregarded [39,40,56–59]. Considering the increasing number of research in this field, it seems that the fast transfer of research output to engineers and regulations is still a pending task.

The discharge equations pre-defined have been previously validated in several studies [6,8,10,19]. However, it is important to note that new fishway types will require the development of new equations. These equations must take into consideration the non-uniform behavior of connections. In addition, special features of the fishway, such as resting or turning pools, depending on their design, may modify the discharge equation of the successive cross-walls [20,60,61], which can result in mixed non-uniform performances inside the fishway [20]. *Escalas* allows the definition of independent equations for any connection in the cross-walls. However, there is still a lack of studies on this phenomenon and the possible implications in the overall hydraulics performance of the fishway or fish behavior.

In recent years, a plethora of studies has been conducted on the evaluation of fishways from a biological perspective [54,62–64]. However, many of these studies lack a thorough hydraulic characterization, not considering the effect of river dynamics in the fishway, simplifying it, or assuming a uniform performance in the full study period [56,59,65–67]. Since rivers are dynamic systems, the operational regime of a fishway inevitably varies. This variation is not solely determined by geometric parameters but is also influenced by the river's boundary conditions. Consequently, any biological fishway assessment must follow a deep hydraulic analysis of the fishway dynamics; this will allow to study in detail and take into account the hydraulic cofactors that may affect the fish passage and to develop more efficient fishways that encompass adequate adaptive management [68]. In this context, *Escalas* emerges as a fitting tool to supplement biological assessments and to facilitate the incorporation of accumulated knowledge into new designs or solutions.

Data availability statement

Some or all data, models, or code generated or used during the study are available in a Repository or online in accordance with funder data retention policies.

Software availability

The latest version of *Escalas* software together with the video tutorials are supplementary materials to the paper. Additionally, they can be also found at the institutional repository of GEA and ZENODO:

1) https://www.gea-ecohidraulica.org/GEA_en/software/escalas.html
2) https://doi.org/10.5281/zenodo.7471315

Data availability

Data used for testing and validation of the simulation algorithm in this paper are openly available at ZENODO repository: https://doi.org/10.5281/zenodo.5770714.

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CRediT authorship contribution statement

Juan Francisco Fuentes-Pérez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Funding acquisition, Project administration. **Ana García-Vega:** Data curation, Formal analysis, Investigation, Software, Validation, Writing – review & editing. **Andrés Martínez de Azagra Paredes:** Investigation, Methodology, Resources, Supervision, Writing – review & editing. **Francisco Javier Sanz-Ronda:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Notation

The following symbols are used in this paper

A	orifice surface (for rectangular orifice $A = a_o \cdot b_o$) (m^2)
a_o	height of the orifice (m)
B	pool width (m)
b_n	notch width (m)
b_o	orifice width (m)
C_o	discharge coefficient for orifices
C_p	discharge coefficient for the plunging regimen

C_s	discharge coefficient for the streaming regimen
e	thickness of the cross-wall (m)
g	acceleration due to gravity (m/s^2)
H	total height of the obstacle (m)
h_0	mean water level in the pool in relation to the center of the pool (m)
h_1	mean water level of the flow in the pool upstream of the cross-wall measured from the sill (m)
$h_{1,i}$	mean water level of the flow in the pool upstream of the cross-wall measured from the sill in the cross-wall number i (m)
h'_1	mean water level of the flow in the pool upstream of the cross-wall (m)
h_2	mean water level of the flow in the pool downstream of the cross-wall measured from the sill (m)
$h_{2,i}$	mean water level of the flow in the pool downstream of the cross-wall measured from the sill in the cross-wall number i (m)
h'_2	mean water level of the flow in the pool downstream of the cross-wall (m)
H_c	height of the channel walls (m)
H_t	height of the cross-walls (m)
i	cross-wall number
j	connection number
L	pool length (m)
m	total number of connections in a cross-wall
n	total number of cross-walls
p	sill height (m)
p'	height from the water level downstream to the top of the sill (m)
Q	discharge or flow rate (m^3/s)
$Q_{associated}$	discharge through associated structures (m^3/s)
Q_n	discharge through notches (m^3/s)
Q_o	discharge through orifices (m^3/s)
$Q_{fishway}$	fishway discharge (m^3/s)
Q_{fn}	Discharge through notches in plugging conditions (m^3/s)
Q_{river}	river flow (m^3/s)
Q_s	Discharge through slots (m^3/s)
Q_{sn}	Discharge through notches in streaming conditions (m^3/s)
Q_T	Total discharge (m^3/s)
R^2	determination coefficient
S	slope of the fishway (m/m)
VDP	volumetric dissipation power (W/m^3)
V_{max}	maximum velocity at the cross-wall (m/s)
Z	topographic altitude (m)
ΔH	difference in water level between pools or head drop ($\Delta H = h_1 - h_2$) (m)
ΔZ	topographic difference between cross-walls (m)
ρ	density of water (kg/m^3)
σ^2	variance

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e25996.

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