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Fish passage assessment in stepped fishways: Passage success and transit time as standardized metrics

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ABSTRACT

Fishways are used worldwide to restore fish migration routes. However, there are few standardized metrics that allow the comparison of their performance in a consistence manner. This paper aims to assess fishway internal passage using two standardized metrics: passage success and transit time. Data from selected 20 field stepped fishways evaluation were gathered from a systematic review and own field experiments, considering potamodromous species as target fish. The influence of main biological and hydraulic parameters on these metrics was analyzed and modeled by logistic regression and survival analysis techniques. Passage success and transit time described reliably fishway performance. Both metrics were significantly influenced by fishway type, volumetric power dissipation, height drop between pools, slope, obstacle height, pool depth, species and fork length in fishway passage. This work may serve as a guide for all engineers and managers working in fishway assessment, design and management to assess and compare other fishways, select proper design parameters and open the discussion and future research on these topics.

1. Introduction

Fishways are extensively used to mitigate the loss of longitudinal connectivity in rivers for fish fauna. However, to date there are few standardized and verifiable metrics (Cooke and Hinch, 2013; Larinier, 2002b) that help to know if these structures work well or not and that make possible the comparison of fish passage between different fishway typologies. The main purpose of this article is to assess upstream fish passage in stepped fishways with standardized metrics using several field test cases of Iberian Peninsula as an example of application. Stepped fishways (also named pool-type fishways) are the most used fishway type worldwide (FAO/DVWK, 2002; Santos et al., 2012). They consist of sloped channels divided by cross-walls into a series of pools. Considering the type of connections between pools, the most common configurations are single vertical slot (*VS*, Fig. 1a) and submerged notch with bottom orifice (*SNBO*, Fig. 1b) (Clay, 1995; Larinier, 2002b). Both configurations have demonstrated to maintain hydraulic conditions inside fish capabilities despite a large variation in upstream and downstream water levels of the barrier (Fuentes-Pérez et al., 2017; Fuentes-Pérez et al., 2016; Quaranta et al., 2019).

The type and design of a fishway plays an important role in the passage performance, understood as the ability to provide adequate conditions to allow fish to successfully pass through the fishway (Bunt et al., 2012; Bunt et al., 2016; Noonan et al., 2012; Roscoe and Hinch, 2010). Passage performance depends not only on fishway geometry and hydraulic conditions, but also on biological and experimental factors used for its evaluation, as well as on the interactions among those variables. Geometric and hydraulic features have been widely studied and analyzed (Fuentes-Pérez et al., 2017; Rajaratnam et al., 1989; Rajaratnam et al., 1986). However, research on hydraulic parameters coupled with biological factors is still a pending task. Tagging and tracking systems for fish fauna are becoming more accessible, and the increasing need to ensure a correct performance of fishways, after their installation, has promoted a significant progress in research about biological factors affecting passage performance (*i.e.* species, fish length, sex, *etc.* (Castro-Santos et al., 2013; Romão et al., 2017; Sanz-Ronda et al., 2016)). However, the influence of experimental design on passage performance is still poorly considered (*i.e.* sample size, trial duration, handling,

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confinement, *etc.*). So far, there is not a standardized methodology for fishway biological assessment and experimentation (Bunt et al., 2012; Bunt et al., 2016; Silva et al., 2018).

The efforts in last decade to standardize metrics have considerably increased (Castro-Santos et al., 2009; Castro-Santos and Haro, 2010; Cooke and Hinch, 2013), having some examples of meta-data analyses about fishways performance (Bunt et al., 2012; Noonan et al., 2012). These analyses have a great interest for fishway design, although they are still controversial due to the difficulty of comparing different experiments (Kemp, 2016). Study of passage performance ideally comprise three stages or topics: attraction, entrance and internal passage (Castro-Santos, 2011). Therefore, it is very important to define the stage that the metric is referred to or if it comprises the overall passage (which includes all stages).

In order to increase the knowledge about stepped fishway assessment, the present study analyses internal passage in several fishways, focusing on two standardized metrics: passage success and transit time, to allow their analysis and comparison. Passage success, also named or understood as passage efficiency or ascent success, is defined as the proportion of fish that successfully ascended the fishway with respect to the fish that entered into it (Bunt et al., 2012). In the other hand, transit time is defined as the time that fish spent passing the fishway once they entered on it (Castro-Santos et al., 1996), and it is also named or understood as time to pass, ascent time or passage time. This variable directly contributes to explain the time that fish spent passing the fishway, which has important effects on fish, as an excessive time may produce for example a loss of motivation, a deterioration of physiological conditions before arriving to spawning grounds, or a reduction of the probability of finding optimal environmental conditions (Castro-Santos and Haro, 2003; Caudill et al., 2007; Nyqvist et al., 2017). There are some studies that show results for transit time in stepped fishways (*e.g.* (Caudill et al., 2007; Forty et al., 2016; Thiem et al., 2011)), but few of them with a common definition (*i.e.* relativized unit of measure) that make possible the comparison of involved biological and hydraulic factors between experiments (Bravo-Córdoba et al., 2018; (Ovidio et al., 2017; Sanz-Ronda et al., 2019)).

The main goal of this paper is to assess, *i.e.* review, summarize, quantify and compare, upstream fish internal passage in stepped fishways using standardized metrics. To achieve this, firstly, data from a systematic review using PRISMA guidelines (Moher et al., 2009) and own field experiments were collected. All considered data corresponded to stepped fishways (*VS* and SNBO) assessed in the last decade with PIT tag technology on field conditions, being Iberian native potamodromous fish the target species. Secondly, passage success and transit time metrics were used to analyze, model and compare fishways performance. The main contributions of this paper are to: (1) evaluate the proportion of passage success and usual ranges of transit time for the target species on both fishway types, (2) compare fishway types and species, (3) predict the influence of main hydraulic and biological parameters on passage success and transit time, and (4) demonstrate the potential of passage success and transit time metrics for fishway assessment and comparisons. This information will help to future comparative studies using standardized metrics as well as for all engineers and managers working in fishway assessment, design and management.

2. Materials and methods

2.1. Data collection

Data from the literature as well as from own field experiments were used. A systematic literature search was carried out following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al., 2009). This systematic search was performed in Google Scholar from conception to October 2019 for peer reviewed articles and grey literature (*e.g.* technical reports) on fishway passage. Eligibility criterion was based on experiments carried out in stepped fishways (*VS* and *SNBO*) on field conditions, with Iberian native potamodromous fish species (both cyprinids and salmonids) and PIT (Passive Integrated Transponder) tag technology. Likewise, as only English and Spanish were used for the search, this might have introduced a language bias. To standardize and minimize errors only studies containing appropriate data and methodology descriptions were considered. At this regard, only documents with detailed hydraulic and geometric information about fishways and experiments with at least two antennas (pass-through type) per fishway were considered. This allows to obtain data of passage success (proportion of fish which are recorded in the downstream antenna and reach the most upstream antenna (Bunt et al., 2012)) and transit time (*Ttime*, time lapse between the last read of the downstream antenna and the first read of the upstream antenna (Castro-Santos et al., 1996)). Four data selection criteria were considered: (1) Only those fish with some attempts *(i.e.,* at least with one read on the first antenna) were included; (2) For transit time calculation, only ascent events with success were taken into account; (3) If a fish had more than one success event, only the fastest transit time was selected,

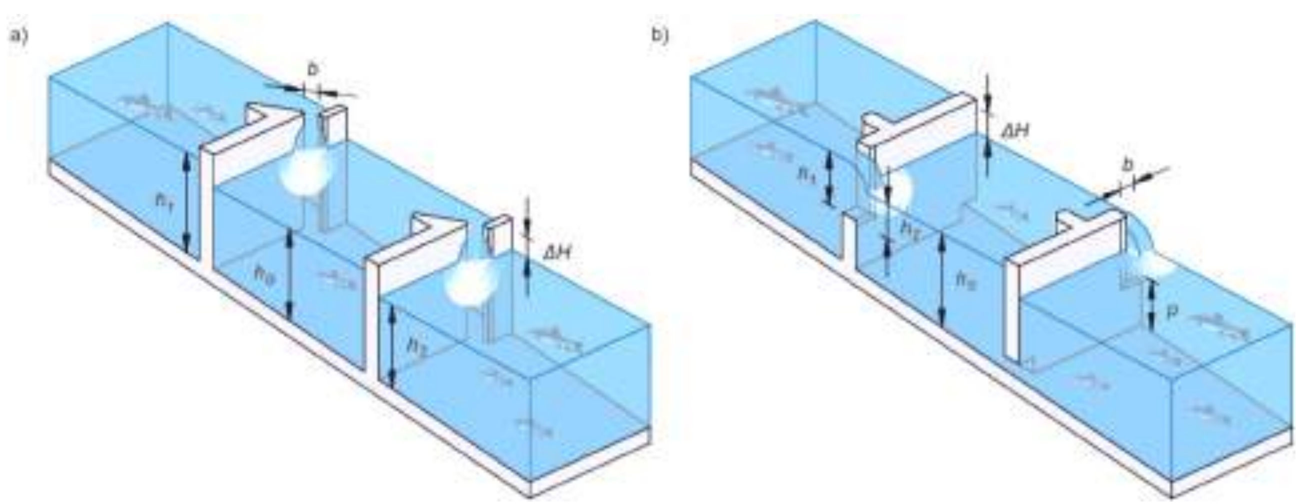

Fig. 1. 3-D scheme of (a) vertical slot fishway (*VS*) and (b) submerged notch with bottom orifice fishway *(SNBO*) together with principal hydraulic variables. h_0: Mean water depth in a pool (m); h_1: Height difference between the top of the notch in SNBO, or the bottom of the pool in *VS*, and the water level in the upstream pool (m); h_2: Height difference between the top of the notch in SNBO or the bottom of the pool in *VS*, and the water level in the downstream pool (m); *b*: Width of the slot/notch (m); *p*: Sill height (m); *ΔH*: Difference in water level between pools or head drop ($\Delta H = h_1 – h_2$).

resulting in one event per fish; (4) To make possible the comparisons among fishways, data of transit time was relativized by the water height difference between antennas, resulting in a transit time per meter of height ascended (*Ttime/m*) (Bravo-Córdoba et al., 2018).

Table 1 summarizes the information after the systematic review. In total, twenty field trials were considered (see Fig. 2 for location), five from technical reports, and fifteen from own field experiments, of which eight have been published in peer review journals. Detailed information on the studies can be found in the corresponding references mentioned in Table 1. For all unpublished studies, experiments were carried out during the season with strong migratory activity. That is to say between May and July for cyprinids (Iberian barbel *Luciobarbus bogaei,* Southern Iberian barbel *Luciobarbus sclateri,* Northern straight-mouth nase *Pseudochondrostoma duriense,* and Iberian straight-mouth nase *Pseudochondrostoma polylepis*) (Doadrio, 2002; Rodriguez-Ruiz and Granado-Lorencio, 1992), and between October and December for salmonids (brown trout *Salmo trutta*) (García-Vega et al., 2018; García-Vega et al., 2017).

Fish were captured by electrofishing (Erreka model 2000 W, or Hans-Grassl ELT60II backpack equipment; 180–250 V and 1.5–3 A) in an upstream river section close to each fishway. Within two hours after capture, fish were transported to the vicinity of the corresponding fishway in aerated tanks. They were held in acclimation tanks (usually into the pools of the fishway inside nets) at ambient temperatures and with water supplied directly from the river.

All fish were anaesthetized with MS-222 (100 mg/L) or eugenol (50 mg/L diluted in ethanol in proportion 1:10), measured (fork length (*FL*), ± 0.1 cm), weighted (± 1 g) and tagged intraperitoneally with a HDX PIT tag by an incision posterior to the left pectoral fin. Tags measured 12 or 23 mm long by 2.12 or 3.65 mm diameter and 0.1 or 0.6 g (in all cases respecting the relationship of tag weight lower than 2% of fish weight). After tagging, fish were allowed to acclimate to their new environment at least for two hours before starting the experiments, always after visual evidences of recovery from anesthetic effects.

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

2.2. Data analysis

All data analyses were performed in SAS statistical software version 9.4.

Firstly, species were grouped in three categories: (1) trout, (2) barbel (includes L. *bocagei* and L. *sclateri)* and (3) nase (includes *P. duriense* and *P. polylepis).* Both species of barbel and nase were grouped together based on their phylogenetic similarities (Robalo et al., 2007; Yang et al., 2015) and swimming capacity during fishway passage (Sanz-Ronda et al., 2019).

Mann-Whitney (MW) and Kruskal-Wallis (KW) tests (PROC NPAR1WAY) were carried out to evaluate if there were significant differences in passage success and transit time between fishway type as well as among species. These tests were selected due to the non-normal distribution of the data.

In order to evaluate the passage success (binary predictor variable: failure or success) and its possible explanatory variables (continuous: *H, Slope,* V_{max}, h_1, h_2, h_1/h_2, *FL, Ttime/m*; categorical: *fishway type* (*SNBO, VS*), *VPD* (Low: < 125 W/m^3; Medium: 125–150 W/m^3; or High: > 150 W/m^3), ΔH (0.15 m, 0.20 m, 0.25 m, 0.30 m), *trial condition* (Free: fish released into the river section downstream the fishway; or Confined: fish released into the fishway with closed mesh in the upper and lower pools of the fishway avoiding fish entrance or exit) and *species* (Trout, Barbel and Nase), logistic regression was used (PROC LOGISTIC) (see Glossary for variable definition). For this procedure, logit link function was selected without adjusting for over-dispersion (scale = none) but weighting according to the sample size of each trial. Stepwise selection process was used for variable selection (significance level: $\alpha = 0.05$). Deviance, Pearson and Hosmer-Lemeshow goodness of fit test, as well as, Area Under the Curve (*AUC*) and Akaike Information Criterion (*AIC*) were used for model assessment and selection (different variable combinations for passage success prediction).

To evaluate the transit time (*Ttime/m*) and the influence of the recorded variables (continuous: *H, Slope,* V_{max}, h_1, h_2, h_1/h_2, *FL*; categorical: *fishway type* (*SNBO, VS*), *VPD* (Low, Medium, High), ΔH (0.15 m, 0.20 m, 0.25 m, 0.30 m), *trial condition* (Confined, Free) and *species* (Trout, Barbel, Nase)), survival (time-to-event) analysis *via* a parametric log-logistic regression (Cox proportional hazards regression) was used (PROC LIFEREG), with stepwise procedure for variable selection ($\alpha = 0.05$).

3. Results

3.1. Passage success model

Global passage success was greater than 50% in all trials, with a median value of 72% and an interquartile range (*IQR)* of 62–94% (Fig. 3a). No significant differences were found between *fishway type* or *species* (Fig. 3b and c; MW and KW test *p*-value >0.400 in both cases).

Table 2 shows the best fitted logistic regression model for passage success. The max-rescaled *R*-square for the model was 0.457 and results of goodness of fit tests were: deviance *p*-value = 0.321; Pearson *p*-value = 0.341; Hosmer-Lemeshow *p*-value = 0.354 and *AUC* = 0.695. According to the model, confined trials together with highest values of ΔH and lowest values of *VPD, Slope*, and *Ttime/m* produced greater passage success. Variables related to pool depth and water levels (h_1, h_2, h_1/h_2), v_{max}, *H, fishway type, FL* or *species* were not significant in the model.

Fig. 4 shows the relation of the most significant explanatory variables in the passage success according to the modeled logistic regression. On the one hand, Fig. 4a illustrates the differences between Confined and Free experiment and how, in both cases, the proportion of passage success was greater under lower values of *VDP*. On the other hand, Fig. 4b shows the effect of ΔH under different *VPD* configurations. In both cases, regardless of the influence of other explanatory variables, *Slope* was inversely proportional to passage success.

3.2. Transit time model

Transit time was less than 45 min/m in all trials, with a median value of 11.3 min/m and an *IQR* of 6.2–21.6 min/m (Fig. 5a). Significant differences were found between *fishway type* (Fig. 5b), with lower transit times in *VS* than in *SNBO* (median of 8.8 *vs.* 13.5 min/m respectively; MW test *p*-value <0.001). Regarding fish *species* (Fig. 5c), barbel and nase ascended significantly faster than brown trout (median of 10.5 and 5.3 min/m *vs* 15.8 min/m respectively; KW test *p*-value <0.001).

Regarding the log-logistic survival model (Table 3) vertical slot, barbel and nase, 0.25 m of ΔH and *FL* have a positive effect; that is to say, a decrease in transit time is expected under the presence of these categories and with the increase of the variable *FL*. On the other hand, according to the model, an increase in *H* and in the presence of *SNBO,* ΔH of 0.15 or 0.20 m and brown produce greater transit times. T*rial condition, VPD,* v_{max}, h_1 and h_1/h_2 showed non-significant relationship with transit time.

3.3. Summary of effects of the variables

Table 4 shows a compilation of the effects of all the variables under study, for both passage success and transit time. Overall, the studied variables do not affect both metrics in the same way, except for *Slope* and ΔH.

Table 1
Summary of the considered trials (see Glossary for nomenclature details). *VPD*: low: < 125 W/m^3; medium: 125–150 W/m^3; or high: > 150 W/m^3. Trial conditions: Free: fish released into the river section downstream the fishway; or Confined: fish released into the fishway with closed mesh in the upper and lower pools of the fishway avoiding fish entrance or exit (for more details of Free and Confined trials an example can be seen in (Bravo-Cordoba et al., 2018a, 2018b).

Location	Ref.	Fishway type	*H* (m)	*ΔH* (m)	*VPD*	Slope (%)	V_{max} (m/s)	h_1 (m)	h_2 (m)	Trial condition	Species	*FL* (mm) Mean (range)	*Success %* ($N_{success}/N_{total}$)	*Ttime/m* Median (*IQR*) (min/m)
Pereruela (Duero River, Zamora)	Own data Unpublished	SNBO	0.87	0.15	Low	5.5	1.51	0.62	0.47	Free	*L. bocagei*	460 (362–580)	54 (10/19)	36.5 (29.9–83.1)
Padilla de Duero (Duero River, Valladolid)	Bravo-Córdoba et al. (Bravo-Córdoba et al., 2018b)	SNBO	1.65	0.20	Low	8.8	1.68	0.51	0.36	Free	*L. bocagei*	157 (132–186)	71 (14/20)	30.6 (12.1–58.8)
Calasparra (Segura River, Murcia)	Sanz-Ronda et al. (Sanz-Ronda et al., 2019)	SNBO	1.80	0.20	Medium	7.3	1.72	0.60	0.40	Confined	*P. polylepis* *L. sclateri*	160 (128–196) 185 (128–437)	100 (6/6) 79 (19/24)	5.2 (3.9–6.5) 14.6 (10.0–22.2)
San Miguel del Pino (Duero River, Valladolid)	Bravo-Córdoba et al. (Bravo-Córdoba et al., 2019)	SNBO	3.65	0.25	Low	9.4	1.95	0.36	0.11	Free	*L. bocagei*	268 (145–470)	85 (60/71)	11.9 (7.7–21.3)
Cespedosa de Tormes (Tormes River, Salamanca)	Own data Unpublished	SNBO	4.50	0.25	Medium	14.7	1.95	0.42	0.17	Free	*P. duriense* *L. bocagei*	162 (142–178) 326 (305–346)	50 (5/10) 50 (11/22)	9.5 (6.7–51.4) 10.3 (8.0–12.9)
Guma (Duero River, Burgos)	Bravo-Córdoba et al. (Bravo-Córdoba et al., 2018a)	SNBO	2.25	0.25	Medium	8.8	1.90	0.58	0.33	Confined	*P. duriense* *L. bocagei*	159 (132–210) 180 (130–277)	100 (4/4) 94 (37/39)	7.6 (5.0–11.3) 8.6 (4.4–13.2)
Guma (Duero River, Burgos)	Own data Unpublished	SNBO	8	0.25	Medium	8.8	1.90	0.58	0.33	Free	*P. duriense* *L. bocagei*	168 161 (91–275)	100 (1/1) 73 (68/93)	12.6 26.4 (10.8–115.9)
Navapalos (Duero River, Soria)	Own data Unpublished	SNBO	4.3	0.25	High	10.0	1.95	0.42	0.17	Free	*P. duriense* *L. bocagei*	174 (155–200) 203 (145–485)	56 (5/9) 84 (27/48)	11.7 (8.7–14.9) 9.3 (7.6–12.9)
Padilla de Duero (Duero River, Valladolid)	Bravo-Córdoba et al. (Bravo-Córdoba et al., 2018b)	SNBO	2.15	0.25	High	8	1.90	0.48	0.23	Free	*L. bocagei*	161 (132–197)	81 (18/22)	15.2 (7.9–24.7)
Santesteban (Bidasoa River, Navarra)	GAN-NIK (2019)	SNBO	6	0.30	High	15.4	2.17	0.45	0.15	Free	*S. trutta*	314 (222–410)	67 (8/12)	16.1 (8.8–23.8)
Berastegui (Leizarán River, Guipúzcoa)	Ekolur (Ekolur, 2016)	SNBO	2	0.30	High	15.0	2.17	0.45	0.15	Free	*S. trutta*	253 (232–282)	57 (4/7)	12.5 (10.5–14.0)
Bera (Bidasoa River, Guipúzcoa)	GAN-NIK (GAN-NIK, 2017)	SNBO	2.6	0.30	High	9.0	2.15	0.45	0.15	Free	*S. trutta*	300 (225–391)	50 (6/12)	29.6 (14.2–77.3)
Yanci (Bidasoa River, Guipúzcoa)	GAN-NIK (GAN-NIK, 2017)	SNBO	3.3	0.30	High	7.9	2.14	0.45	0.15	Free	*S. trutta*	292 (225–338)	93 (12/13)	19.4 (15.6–30.0)
Elduain (Leizaran River, Guipúzcoa)	Ekolur (Ekolur, 2016)	SNBO	5.1	0.30	High	12.5	2.17	0.45	0.15	Free	*S. trutta*	248 (219–296)	90 (15/17)	16.0 (12.0–21.0)
Abarán (Segura River, Murcia)	Sanz-Ronda et al. (Sanz-Ronda et al., 2019)	*VS*	1.80	0.15	Low	6.5	1.51	0.98	0.83	Confined	*P. polylepis* *L. sclateri*	152 (135–198) 202 (128–282)	95 (37/39) 95 (54/57)	4.4 (3.3–7.2) 7.0 (4.1–11.3)
Vadocondes (Duero River, Burgos)	Bravo-Córdoba et al. (Bravo-Córdoba et al., 2018a)	*VS*	2.25	0.15	Medium	6.5	1.51	1.00	0.85	Confined	*L. bocagei*	175 (110–240)	96 (38/40)	9.9 (5.9–17.6)
Vadocondes (Duero River, Burgos)	Own data Unpublished	*VS*	2.25	0.15	Medium	6.5	1.51	1.00	0.85	Free	*L. bocagei*	139 (99–212)	70 (50/71)	5.6 (2.9–12.3)
Vegas del Condado (Porma River, León)	Sanz-Ronda et al. (Sanz-Ronda et al., 2016)	*VS*	1.00	0.20	High	7.7	1.75	1.01	0.81	Confined	*S. trutta* *P. duriense* *L. bocagei*	231 (145–297) 309 (240–345) 295 (160–440)	70 (34/49) 70 (9/13) 71 (33/47)	30.0 (14.5–58.2) 5.2 (2.7–9.0) 5.5 (2.8–9.6)
Liérganes (Miera River, Cantabria)	Own data Unpublished	*VS*	1.20	0.20	Medium	6.2	1.74	1.29	1.09	Confined	*S. trutta*	197 (126–250)	88 (29/33)	15.8 (13.4–21.2)
Liérganes (Miera River, Cantabria)	Own data Unpublished	*VS*	2.25	0.25	High	11.4	2.00	0.98	0.63	Confined	*S. trutta*	209 (120–415)	68 (24/35)	11.5 (8.3–13.9)
														Total (638/833)

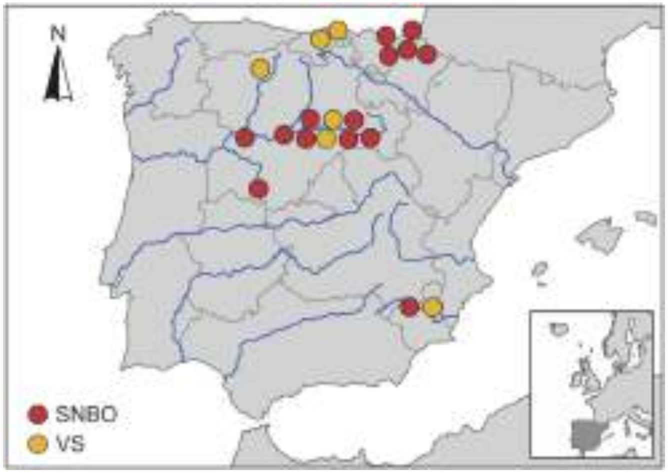

Fig. 2. Study site locations of the submerged notch and bottom orifice (*SNBO*) and vertical slot (*VS*) fishways considered for the study of passage success and transit times in the Iberian Peninsula (See Table 1 for more details about the study cases).

4. Discussion

4.1. Passage success and transit time metrics

Passage success is one of the most relevant and commonly used metrics for fishway assessment, however, it has multiple definitions in the specialized literature, what can lead to a misunderstanding when comparing studies (Bunt et al., 2012; Noonan et al., 2012). Therefore, it is important to state its definition and calculation procedure in any study. In the same way, it is necessary to consider migration behavior of a particular species to define any fishway evaluation metric, as for instance it may not work in the same way for species with partial migrations (Brodersen et al., 2008; Chapman et al., 2012) or semelparous anadromous fish (Roscoe and Hinch, 2010).

Results from the present literature review and own field experiments showed passage success ranging from 50 to 100% for the target species, with a mean value of 72%. It seems a great proportion when comparing to other studies (Bunt et al., 2016; Noonan et al., 2012). A possible reason can be that these fishways have been designed and constructed in recent years (from 2000 onwards) following current hydraulic criteria (FAO/DVWK, 2002; Larinier, 2002b). Recent studies in the Duero River basin (Iberian Peninsula) have shown a positive correlation between construction year and fishway effectiveness (Valbuena-Castro et al., 2020).

In combination with passage success, transit time can provide a general perspective in fishway assessment, as it serves as an indicator of the internal passage (Silva et al., 2018). Box-plot distributions and survival models associated to this metric can be directly used as a reference to compare time spent by fish during the internal passage. However, to make comparisons among fishways, transit time must be relativized. Although other studies have tried similar approaches, for example time per horizontal distance, time per pool (Bell, 1973), transit speed (Ovidio et al., 2017), or energy expenditure per time (Geist et al.,

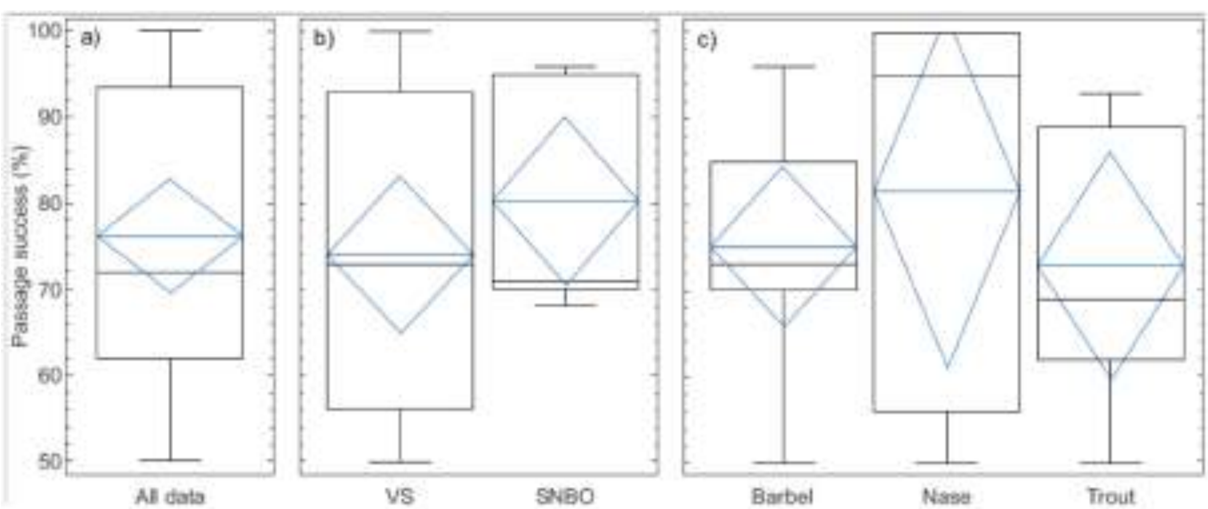

Fig. 3. Box plot and diamond distribution of passage success (%). a) All data, b) by type of stepped fishway (*VS*: Vertical Slot; *SNBO*: Submerged Notch with Bottom Orifice) and c) by species. Box: median (horizontal line inside de box), interquartile range *(IQR)* (bottom and top lines of the box), 1.5**IQR* (bottom and top edges of the whiskers), outliers (empty squares). Diamond: mean (horizontal line) and 95% confidence interval (upper and lower corners).

Table 2
Results of logistic regression for passage success ascending stepped fishways for significant variables (α = 0.05) (see Glossary for nomenclature details). *Ttime/m*: median transit time per meter of height (min/m). *Coeff*: log odds coefficient estimates; *SE*: standard error; *OR*: odds ratio; *CI*: odds ratio 95% confidence interval; *p*: p-value. Reference level for categorical variables: Trial condition = Free; *VPD* = Medium; *ΔH* = 0.30 m.

Variable	level	*Coeff*	*SE*	*OR*	CI_{lower}	CI_{upper}	*p*
Intercept		3.795	0.567	–	–	–	<0.001
Trial condition	Confined	0.640	0.140	3.595	2.075	6.230	<0.001
VPD	High	−0.722	0.161	0.474	0.302	0.744	<0.001
	Low	0.697	0.183	1.958	1.143	3.354	0.001
ΔH	0.15 m	−0.750	0.250	0.104	0.036	0.298	0.003
	0.20 m	−0.929	0.265	0.087	0.031	0.245	<0.001
	0.25 m	0.167	0.158	0.261	0.123	0.551	0.290
Ttime/m		−0.020	0.010	0.980	0.962	0.999	0.042
Slope		−0.211	0.054	0.810	0.729	0.900	<0.001

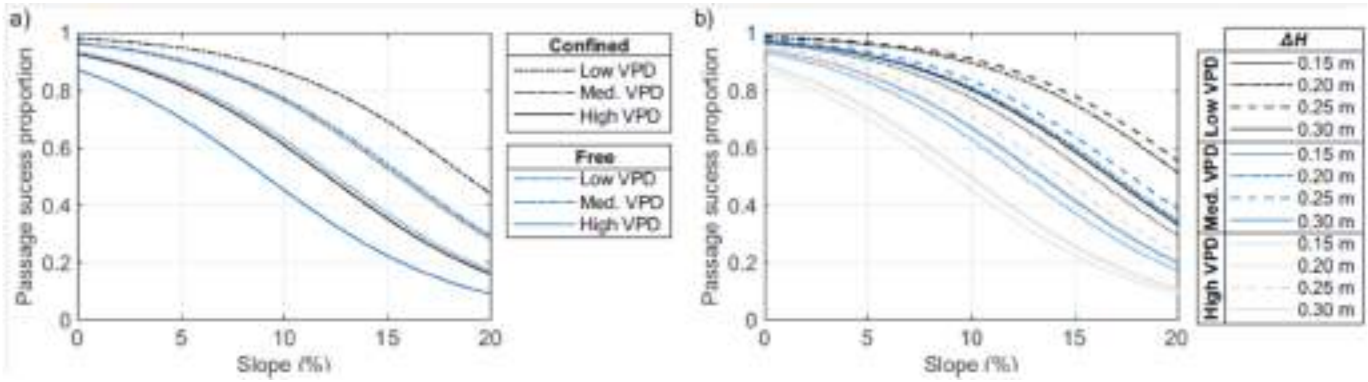

Fig. 4. Graphs of logistic curves for the proportion of passage success as a function of the slope and different explanatory variables. a) Curves for different trial conditions and Volumetric Power Dissipation (*VPD*). b) Curves for different *VPD* and water drop between pools (*ΔH*).

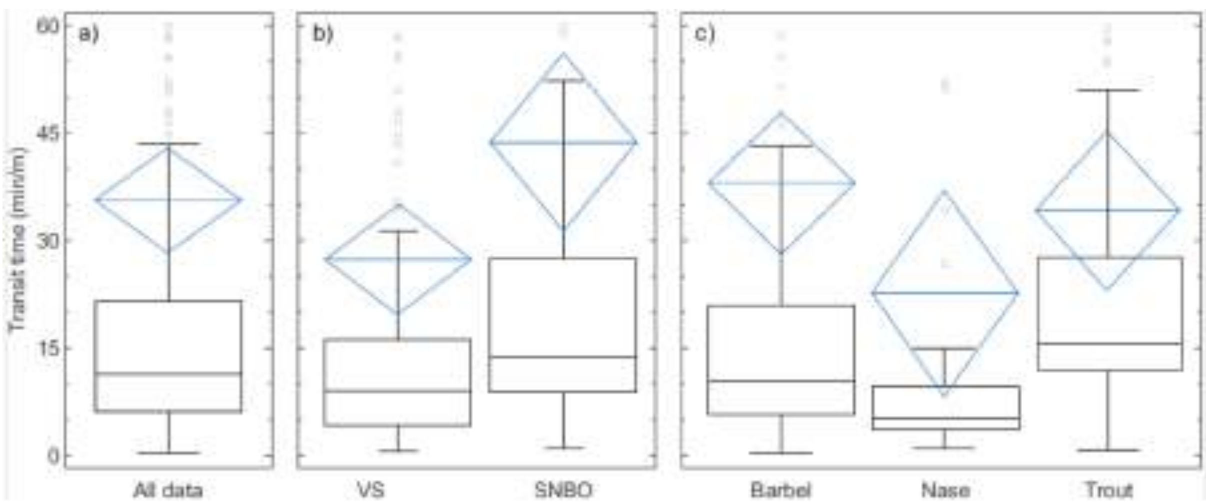

Fig. 5. Box plot and diamond distribution of transit time (min/m) per meter of height ascended: a) all data, b) by type of stepped fishways (*VS*: Vertical Slot; *SNBO*: Submerged Notch with Bottom Orifice) and c) by species. Box: median (horizontal line inside de box), interquartile range (*IQR*) (bottom and top lines of the box), 1.5**IQR* (bottom and top edges of the whiskers), outliers (empty squares). Diamond: mean (horizontal line) and 95% confidence interval (upper and lower corners). Note: Although Y-axis has been cut off in 60 min/m for a better visualization, there were some outliers above (71 outliers with a maximum of 1380 min/m).

Table 3
Estimation of the parameters of the log-logistic survival model of transit time, for significant variables (α = 0.05) (see Glossary for nomenclature details). *β*: regression coefficient; *CI:* 95% confidence interval for *β*. Reference level for categorical variables: Fishway type = *VS*; Trial condition = Free; *ΔH* = 0.30 m; Species = Brown trout; *VPD* = Medium.

Variable	Level	*β*	CI_{lower}	CI_{upper}	Chi-square	*p*-value
Fishway type	*SNBO*	0.735	0.193	1.277	7.05	0.008
Species	Barbel	−1.685	−2.048	−1.323	82.94	<0.001
	Nase	−2.051	−2.451	−1.651	100.97	<0.001
ΔH	0.15 m	2.303	1.526	3.080	33.74	<0.001
	0.20 m	2.076	1.407	2.745	37.04	<0.001
	0.25 m	1.212	0.748	1.675	26.23	<0.001
FL		−0.012	−0.024	−0.001	4.20	0.040
H		0.170	0.112	0.228	32.71	<0.001
Slope		−0.086	−0.145	−0.027	8.08	0.005
h_2		−1.397	−2.492	−0.301	6.25	0.012
Intercept		3.006	1.806	4.206	24.09	<0.001
Scale		0.5653	0.527	0.602		

2000), the total height of the obstacle was not considered. Transverse barriers and their impacts for fish movement are mainly characterized by their height dimension. Thus, the idea of a relativized metric by height is the best approach to consider this variable during the passage assessment. An important observation is that transit time data rarely present normal distribution (Bravo-Córdoba et al., 2018; (Castro-Santos and Haro, 2003; Caudill et al., 2007)) and thus, summary and statistics of data should be referred to median and ranges, and not only to mean and its spread measures.

Considering the collected data, in most cases, fish expended less than 45 min to ascend one meter of height, with a median value of 11 min/m. Literature review brings a similar range of transit times for these species and fishway types, with values below 1 h per meter height (Forty et al. (Forty et al., 2016) for *S. trutta* in SNBO; Benitez et al. (Benitez et al., 2015), Grimardias (Grimardias, 2015) and Ovidio et al. (Ovidio et al., 2017) for *S. trutta* in *VS*; Romão et al. (Romão et al., 2018) for L. *bocagei* in *VS*). Thus, it seems that for the reported values and the height of the included barriers (≤ 8 m), passage in the studied fishways will not have an important effect on upstream migration delay.

4.2. Variables under study and their effects

a) Fishway type is one of the most important decisions when someone faces a fishway design. Although no significant differences were found on passage success between the two studied types, they presented significant differences on transit time. Fish ascending through *VS* were faster than in *SNBO*. Nevertheless, it could be discussed whether such

Table 4
Summary of variables under analysis (see Glossary for nomenclature details) and their effects on the percentage of success and transit time per meter of height ascended. + and - represent positive and negative effect respectively (understood positive effect as an increase in Success % or decrease in *Ttime/m*). *NS*: non-significant (α = 0.05). Ref. level: level of reference in the analysis for categorical variables.

Variable	Level	*Success %* ($N = 833$)	*Ttime/m* ($N = 638$)
Trial condition	Confined	+	NS
	Free	Ref. level	
Fishway type	*SNBO*	*NS*	–
	VS	Ref. level	
Species	Barbel	*NS*	+
	Nase	*NS*	+
	Trout	Ref. level	
ΔH	0.15	–	–
	0.20	–	–
	0.25	NS	–
	0.30	Ref. level	
VPD	Low	+	NS
	Medium	Ref. level	
	High	–	NS
FL		*NS*	+
H		*NS*	–
Slope		–	+
V_{max}		*NS*	*NS*
Ttime/m		–	NOT APPLY
h_1		*NS*	*NS*
h_2		*NS*	+
h_1/h_2		*NS*	*NS*

differences are relevant enough, for example in migration delay or for practical purposes (*i.e.* select one or the other design). Median difference between both types was about 5 min/m and at least for small-scale barriers, it might be not an important delay, making necessary to complement this metric with others related, for example, to motivation (Castro-Santos et al., 2013; Sanz-Ronda et al., 2019), as well as other possible considerations *(e.g.* operating discharge, structure dimensions, *etc.*). Regarding *VS*, it better tolerates larger variations in water levels and allow fish movements at any desired depth (Larinier, 2002b). However, for the same slot and notch width (*b*), same ΔH and mean pool water level (h_0), *VS* requires significantly greater discharge than *SNBO* (Fuentes-Pérez et al., 2017; Larinier, 2002b). Therefore, for large fish (*i. e.* when a significant *b* is required) the discharge through *VS* will be greater than *SNBO*, and pool depth for low flows is not often suitable. In absence of high discharge (*i.e.* with low h_0) *a VS* with wide b will generate incompatible hydraulic conditions in the pool (*e.g.* excessive volumetric power dissipation (*VPD*)). *SNBO* surpasses this issue by the sill height (*p*) which ensures a minimum h_0 in the pool for any hydraulic scenario. In addition, the bottom orifice of *SNBO* allows benthic fish passage. Nevertheless, depending on orifice dimensions, it could be easily clogged by debris (FAO/DVWK, 2002; Larinier, 2002b).

b) Variable Species has a significant effect on transit time but not for passage success. Although brown trout showed a *Ttime* in *VS* greater than those for cyprinids, no significant differences were found in *SNBO*. This may imply a better swimming ability of cyprinids than the expected, at least on the case of studied Iberian cyprinids, based on the general assumption that cyprinids are weaker swimmers than salmonids (Larinier, 2002a). It can be explained by the adaptation of these species to the severe hydrological variability in Mediterranean areas (Alexandre et al., 2013). In addition, water temperature differences between trials may be another source of variability (warmer for barbel and nase). However, all experiments were carried out during reproductive season of the target species, and thus, with a representative temperature of peak migrations.

c) Water drop between pools is an important variable in fishway design. Based on the model, if ΔH increases, both passage success and transit time improve. These results could be related to motivation and a possible effect of attraction increase. It is necessary to clarify that the range of ΔH assessed was between 0.15 and 0.30 m, that is inside the main design recommendations for different species and/or fishway types for temperate climates (FAO/DVWK, 2002; Larinier, 2002b). Hence, extrapolate this result outside of this range is not recommended. A higher ΔH can produce excessive water velocities or turbulence, disorienting or increasing the energy expenditure of fish (Enders et al., 2003; Enders et al., 2005; Guiny et al., 2005). The effect of ΔH choice is related to the dimensions of the construction (greater water drops means lower number of pools) and how demanding is the fishway for fish ascent (lower drops are related to lower *VPD* and turbulence levels). As maximum water velocity is correlated to water drop between pools ($V_{max} = (2 \cdot g \cdot \Delta H)^{0.5}$), the former was excluded from the model due to better fit test scores and because ΔH is easier to measure in field conditions.

d) Volumetric power dissipation is a variable related to turbulence and air entrainment in pools and it can reflect how demanding a fishway is in terms of hydraulic conditions. Similar to water drop between pools, there are different recommendations for *VPD* in the literature, with maximum levels around 125–150 W/m^3 for cyprinids and 175–200 W/m^3 for salmonids (FAO/DVWK, 2002; Larinier, 2002b). All trials here analyzed had *VPD* lower than 200 W/m^3. According to the results, Low *VPD* (125–150 W/m^3) means a greater rate of success, however *VPD* was not a significant covariate in transit time model. Silva et al. (Silva et al., 2011) in trials with barbel and *VPD* between 35 and 78 W/m^3 did not find significant relationships between *VPD* and transit time either. It is worth to mention that *VDP* is a controversial variable, despite its extended use by fishway design community and the recommendation of its verification in well stablished guides (FAO/DVWK, 2002; Larinier, 2002b), some authors disagree about the relevance in the use of this parameter for fishway design and assessment as it oversimplifies turbulence characteristics in a simple indicator (Towler et al., 2015).

e) Slope (considered as hydraulic slope: $S = 100 \cdot \Delta H/\text{pool length}$) has shown a significant relationship with both passage success (negative effect, *i.e.* the greater the slope the lower the success) and transit time (positive effect, *i.e.* the greater the slope, the lower the transit time). Noonan et al. (Noonan et al., 2012) and Bunt et al. (Bunt et al., 2012) showed similar relationship between slope and passage success and Quaranta et al. (Quaranta et al., 2019) related to lower slopes with more compatible hydraulic conditions for fish swimming capabilities.

f) Fork length a biological factor with clear influence on swimming performance (Beamish, 1978; Haro et al., 2004; Ruiz-Legazpi et al., 2018). In fact, transit time model showed an inverse relationship between *FL* (*FL* range in trials: 10–60 cm) and *Ttime/m* (*i.e.* the larger the fish, the faster passage). However, no significant relation to *FL* was found for passage success model.

g) Trial condition was divided in two categories: Free or Confined experiments, due to the possibility of finding differences between those experiments with fish confined inside the fishway and those released outside (*e.g.* swimming performance changes between confined and free experiments (Castro-Santos et al., 2013; Peake, 2008). In free experiments, fish have freedom of entry the fishway and ascend volitionally, and thus, the localization of entrance in free fish could act as preselection of more motivated individuals. On the other hand, confined fish may be forced to move. In this study trial condition only showed significance in passage success, being the rate of success greater for confined fish. Therefore, despite the absence of effect in transit time, the observed relevance in passage success reinforces the inclusion of this variable. However, it needs a deeper analysis in future experiments with trials designed specifically for it.

h) Total height of the fishway assessed is key in fish passage. Although transit time has been relativized to 1 m of height ascended, it is necessary to introduce a covariate for controlling the effect of different fishway heights. It arises from the hypothesis that fish show differences depending on the accumulated height ascended, for example due to fatigue. *Ttime/m* shows a direct relationship between fatigue and *H*, *i.e.* the higher the barrier, the slower the ascent. Bunt et al. (Bunt et al.,

2012) showed a similar link between fishway height and passage success, although our results did not show a clear relationship (assessed *H range: 0.87–8 m*). Regardless, to corroborate these results, it would be advisable to design specific experiments with partial data by fishway sections (more than two antennas). It would improve the knowledge of this variable regarding cumulative effects over migration delay. In addition, this information could provide specific clues to select the location of resting pools inside fishways.

i) Water level downstream the slot/notch has shown a significant effect on transit time, with faster transit time for higher values of h_2. This is a relevant design parameter, with influence on the passage area through the notch/slots, and it is also related to the submergence level and thus with the hydraulic regime between pools (plunging or streaming) (Fuentes-Pérez et al., 2016).

4.3. Recommendations and future steps

Regarding fishway selection, considering the studied geometrical and hydraulic ranges, model results and their analyses, it seems that for the target species the optimal fishway would consist on a vertical slot fishway with ΔH between 0.20 and 0.25 m, *VDP* 125–150 W/m^3 and low slope. This conclusion arises from an assessment that only considers the passage. Under a global fishway assessment, that also takes into account attraction and entrance stages (Castro-Santos, 2011), this result may change.

Taking into account that passage assessment is affected by multiple factors of diverse nature, there are some other interesting parameters that can be considered for the passage study and assessment, and that could not be considered here due to the limited available studies with a deep characterization. For instance, water temperature and other physical-chemical and environmental factors that can interact with fish movements, such as air pressure (Bravo-Córdoba et al., 2018), non-uniform hydraulic conditions inside the fishway (Fuentes-Pérez et al., 2018), or the fishway-river discharge relation (Sanz-Ronda et al., 2016). Regarding possible additional biological variables, the origin of fish (captured upstream or downstream the barrier) can have relevance (Bravo-Córdoba et al., 2018). Furthermore, it would be advisable to carry out more trials with other fish species with different swimming and migration behaviors, and a wider range of parameters such as ΔH or *VPD*.

A holistic assessment of a fishway is a complex task due to the dimensionality of the problem (influenced by a variety of factors, such as fishway type and configuration, species, seasons, non-uniformity, environmental variables, *etc.*). Thus, some controversial has arisen last years about the use of meta-data analysis on fishway assessment and its possible conclusions (Bunt et al., 2016; Kemp, 2016; Williams and Katopodis, 2016). Therefore, the use of standardized metrics is vital to provide a reference point and make comparisons.

Passage success and transit time have shown to be useful metrics to assess and make comparisons of the internal passage in stepped fishways. The assessment of each of the single variables that could affect these metrics one by one in a specific experiment could improve its understanding. However, this is a difficult task in field conditions. Their joint analysis may improve the knowledge about their combined effect on passage success and transit time, allowing not only the selection of best design parameters and ranges in a fishway but also to open the discussion and future research works on these topics.

Credit author statement

Francisco Javier Bravo-Córdoba: Conceptualization, investigation, formal analysis, writing-original draft-review & editing. Jorge Valbuena-Castro: investigation, visualization, writing - review & editing. Ana García-Vega: investigation, validation, writing - review & editing. Juan Francisco Fuentes-Pérez: investigation, validation, visualization, writing - review & editing. Jorge Ruiz-Legazpi: investigation, resources, writing - review & editing. Francisco Javier Sanz-Ronda: investigation, Conceptualization, Project administration, Supervision, 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.

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Glossary

ΔH	Difference in water level between pools or head drop ($\Delta H = h_1 - h_2$)
β	regression coefficient
AIC	Akaike Information Criterion
AUC	Area Under the Curve
b	Width of the slot/notch (m)
CI	Confidence Interval
Coeff	log odds coefficient estimates
FL	Fork length (mm)
H	Water elevation between antennas (m)
h_0	Mean water depth in a pool (m)
h_1	Height difference between the top of the notch in SNBO, or the bottom of the pool in *VS*, and the water level in the upstream pool (m)
h_2	Height difference between the top of the notch in SNBO or the bottom of the pool in *VS*, and the water level in the downstream pool (m)
IQR	InterQuartile Range ($IQR = Q_1 - Q_3$)
N	Number of fish
NS	Non Significant
OR	Odds Ratio
p	Sill height (m)
R-square	Determination coefficient
SE	Standard Error

(*continued on next page*)

(*continued*)

Slope	Hydraulic slope (%) (Slope = ΔH *100/pool length)
SNBO	Submerged notch with bottom orifice fishway
Success %	Percentage of fish with success in the ascent (Number of fish with success *100/ Number of fish that make some attempt)
Ttime	Transit time (min)
Ttime/m	Transit time per meter of ascended height (min/m)
V_{max}	Maximum water velocity in the slot/notch/orifice (m/s)
VPD	Volumetric power dissipation (W/m^3)
VS	Vertical slot fishway
α	Significance level

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