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RESEARCH PAPER — OPEN ACCESS

Bypass discharge, approach velocities and bar spacing: the three key-parameters to efficiently protect silver eels with inclined racks

Sylvie Tomanova[1,3,*], Laurence Tissot[7], Stéphane Tétard[7,8], Sylvain Richard[2,3], Olivier Mercier[1,3], Vincent Mataix[5], Aurélien Frey[6], Thierry Lagarrigue[6], Pablo A. Tedesco[4] and Dominique Courret[1,3]

[1] Office français de la biodiversité, Direction de la recherche et de l'appui scientifique, Toulouse, France
[2] Office français de la biodiversité, Direction de la police et du permis de chasser, Service prévention appui prospective, Toulouse, France
[3] Pôle R&D écohydraulique, OFB-IMFT-PPRIME, Toulouse, France
[4] UMR EDB, IRD 253, CNRS 5174, UPS, Université Paul Sabatier, Toulouse, France
[5] EDF CIH, Pôle Énergies Renouvelables, Toulouse, France
[6] ECOGEA, Muret, France
[7] EDF R&D LNHE – Laboratoire National d'Hydraulique et Environnement, Chatou Cedex, France
[8] ICEO, Talmont Saint Hilaire, France

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Abstract – Hydropower energy can contribute to achieve the carbon neutrality goals, but also needs to reach environmental sustainability. Hydropower plants (HPP) constitute barriers to fish migrations that are essential for accomplishing their complete biological cycle. Fish downstream passage solutions (FDPS) have to be implemented to maximize their survival, guiding them away from the turbine intakes towards a safe passage alternative. Recent telemetry studies confirmed the efficiency of 26° inclined low bar spacing (20 mm) rack associated to surface bypasses, installed upstream HPPs, to protect downstream migrating Atlantic salmon smolts. Here we tested the efficiency of such FDPS for eel protection using radiotelemetry at four successive HPPs (with intake capacities from 28 to 45 $m^3.s^{-1}$) in the Ariège River (southern France). Between 52 and 74 eels, longer than 550 mm, entered the HPP intakes and 100% of them were protected from turbine passage. All eels crossed the HPP water intake using the surface bypasses, and the great majority in few minutes from their first presentation in front of the rack. These results showed that in such rack configuration, it is not necessary to add a specific bottom bypass, usually recommended for eels. We also showed the importance of optimal hydraulic conditions, mainly tangential (parallel to the rack) velocity and bypass discharge, to efficiently guide the eels towards the surface bypasses, reducing their passage time. Overall, our study provided key elements to water managers for designing an efficient FDPS for eels.

Keywords: Hydropower plant / fish protection / downstream passage / surface bypass

1 Introduction

The European Union, by means of the European Green Deal, clearly encourages a renewable energy production (European Commission, 2020a). Hydropower is already widely developed in Europe and will probably increase even more in the next decades owing to the carbon neutrality goals (Wagner *et al.*, 2019). However, this development must also consider the biodiversity protection goals (European Commission, 2020b). Hydropower installations can have significant environmental impacts (Ocko and Hamburg, 2019; Dorber *et al.*, 2020) and for the upcoming development of this sector, the best available mitigation measures must be applied to ensure environmental sustainability of this energy production (Oberdorff, 2022).

Hydropower dams constitute barriers for migrating fish. The European eel (*Anguilla anguilla*), a species with alarming population status (Aalto *et al.*, 2016), grows in inland rivers and migrates to the Sargasso sea to spawn (Wright *et al.*, 2022). During their seaward migration, eels may experience migration delay within dam impoundments, be damaged on the hydropower plant (HPP) intake screens or trashracks, or be exposed to direct turbine mortality or injuries (Bruijs and Durif, 2009; Calles *et al.*, 2010; Dębowski *et al.*, 2016; Dainys *et al.*, 2018). Mortality rates of migrating eels mainly depend

*Corresponding author: sylvie.tomanova@ofb.gouv.fr

on the type and size of the turbine, being particularly high in small and fast-spinning turbines (Gomes and Larinier, 2008; Dainys *et al.*, 2018). In order to prevent these damages, fish downstream passage solutions (FDPS) exist today and can be installed in front of HPP turbines. Among the FDPS, bar racks associated to bypasses are the most applied devices in France.

Eels are known for their ability to cross narrower spaces than their head and body diameter (Travade *et al.*, 2009) and depending on bar spacing and fish size, the racks have shown varying degrees of efficiency as mechanical barriers for eels. While 90 mm of bar spacing seems totally inefficient (Calles *et al.*, 2012), 10–15 mm usually offers complete protection for eels larger than 600 mm (Økland *et al.*, 2017, 2019; Calles *et al.*, 2021). Calles *et al.* (2010) also observed eels between 500 and 700 mm of body length passing through a 20 mm spaced bar rack, and Russon *et al.* (2010) detected eels between 443 and 687 mm able to cross 12 mm of bar spacing. The smallest bar spacing is obviously the most efficient to protect eels from the turbine entrance, but may also imply important operational difficulties (by increasing the rack clogging) and negatively impact the energy production (by increasing the head loss through the rack). The challenge is to find a bar spacing ensuring eel (and other fish) protection together with HPP optimal functioning.

In addition to the bar spacing, the rack inclination and the position of the bypass entrances can impact the FDPS efficiency. Following laboratory tests on potamodromous species, Cuchet *et al.* (2011) and Geiger *et al.* (2018) showed that the low inclination angle of the rack relative to the horizontal (20–30°) does effectively limit fish passages through the 20 mm bar rack and increases the fish guidance to the surface bypass. Field studies using 26° inclined racks relative to the horizontal, 20 mm of bar spacing and surface bypasses have shown very satisfactory efficiency results (high fish protection rate along with very low passage time) for seaward migrating salmon smolts (Tomanova *et al.*, 2018, 2021). Still, the same test on eels has not been performed yet and some doubts remains concerning the best bar spacing and the bypass position in the water column for this species. As Russon *et al.* (2010) detected eels crossing a 30° inclined rack with 12 mm of bar spacing, the capacity of 26° inclined rack with 20 mm of bar spacing to stop eels remains to be demonstrated. Moreover, eels are clearly bottom oriented species during their migration (Brown *et al.*, 2009; Russon *et al.*, 2010; Calles *et al.*, 2013), and low efficiency of surface bypasses is usually observed for this species (Klopries *et al.*, 2018). The general recommendation for the bypass position for eels is therefore “close to the river bottom” (Fjeldstad *et al.*, 2018; Schwevers and Adam, 2020). Gosset *et al.* (2005) already observed higher passage efficiencies for eels with bypass entrances near the bottom, but this result is not systematically confirmed by other studies (Travade *et al.*, 2010; Økland *et al.*, 2019). Eels may present a searching behaviour with vertical excursions (Haro *et al.*, 2000; Brown *et al.*, 2009; Travade *et al.*, 2010), suggesting that surface bypass, which are efficient for other species (*e.g.* salmon smolts, see Tomanova *et al.*, 2018, 2021), might be useful for eels if they are efficiently guided to the entrances. Favorable rack inclination (Cuchet *et al.*, 2011; Geiger *et al.*, 2018), combined with optimal bypass discharge (Tomanova *et al.*, 2021) could encourage eels to vertical searching for a free way, allowing us to expect a good protection efficiency of the 26° inclined racks, with 20 mm bar spacing and surface bypasses, for this species.

To confirm this assumption, we conducted a two-years study with radiotelemetry at four successive HPPs (with intake capacities from 28 to 45 $m^3. s^{-1}$) equipped with 26° inclined racks of 20 mm bar spacing and surface bypass entrances to assess the efficiency of this FDPS for eels. To better understand the behavioural choices of eels in front of the rack, we analysed the variability in eels passage time under different hydraulic conditions near the rack (*e.g.* as a function of variable flow velocities on the rack and variable bypass discharges).

2 Material and methods

2.1 Study sites

The study was performed on four HPPs, constructed on diversion channels on a 8 km-long middle section of the Ariège River in southwestern France. The river and HPP characteristics (for three of four HPPs) have been previously described in Tomanova *et al.* (2021) and all are summarized in Table 1. All four HPPs (from upstream to downstream): Crampagna (43°1’37.98”N, 1°36’23.96”E), Las Rives (43°2’12.55”N, 1°36’57.06”E), Las Mijeannes (43°3’29.69”N, 1°37’26.92”E) and Guilhot (43°4’2.77”N, 1°37’0.05”E) (Ondulia hydroelectric company), are equipped with upstream fish passes at the dam and with inclined (26° from the horizontal) low bar spacing (20 mm) racks with bypass (3 surface entrances) at the beginning of their intake channels (Fig. 1, see also photos in Suppl. material). The 26° rack inclination is based on hydraulic studies (Raynal *et al.*, 2013, 2015) and respects the threshold value for normal velocity in the proximity of the rack ($V_n < 0.5\,m\,s^{-1}$) recommended by Courret and Larinier (2008), preventing the fish impingement. Each rack is equipped with a mechanical trash cleaner with debris evacuation into the fish bypass. The main conception of all four sites is quite similar (Fig. 1), although there are some differences in HPP intake and bypass dimensions (Tab. 1), especially at the Las Rives site differing in total intake depth and the obstruction of the upper part of the rack producing transversal currents guiding the fish to the bypass (see schema in Tomanova *et al.*, 2021). The bypass discharge (Q_{bp}) is controlled by a fixed weir placed at the downstream end of the gallery connecting the three bypass entrances and was fixed to a minimum of 3% of the maximum HPP discharge. Q_{bp} can however vary depending on the impoundment level. In particular, Q_{bp} increases when high river discharges cause water level elevation and spilling events over the dam. Minimum discharges delivered to the river section bypassed by the hydroelectric facilities reach at least 10% of the mean annual river discharge (~4 $m^3.s^{-1}$), and even more during spilling events.

2.2 Eels downstream passage monitoring

The silver eel passage ways were studied using radiotelemetry during two seaward migration periods (Durif and Elie, 2008; Righton *et al.*, 2016): during the winters 2017–2018 and 2018–2019. The methodological approach was the

Table 1. Main parameters of the studied HPPs and FDPS.

		Crampagna	Las Rives	Las Mijeannes	Guilhot
Mean discharge of the Ariège River	$m^3.s^{-1}$	41.8	41.8	44.2	44.2
HPP					
Max turbine capacity (Q_{HPP})	$m^3.s^{-1}$	28	45	45	33
Intake width	m	12	14	21.6	15
Intake water depth	m	2.6	4.18	2.58	2.65
Fish protection rack					
Inclination	°	26	26	26	26
Bar spacing	mm	20	20	20	20
Rack surface	m^2	71.2	117.5	127.2	90.8
Max approach velocity	$m.s^{-1}$	0.90	0.77	0.81	0.83
Max normal velocity	$m.s^{-1}$	0.39	0.38	0.35	0.35
Max tangential velocity	$m.s^{-1}$	0.81	0.69	0.73	0.75
Bypass					
Nb of entrances	–	3	3	3	3
Width of each entrance	m	0.5	1	0.72	0.57
Min water depth in the entrance	m	0.63	0.5	0.7	0.65
Total bypass discharge	$m^3.s^{-1}$	0.84	1.35	1.35	0.99
Total bypass discharge / Q_{HPP}	%	3	3	3	3

same as in Tomanova *et al.* (2021) with salmon smolts, and only key information will be presented hereafter.

We used pulsecoded radio tags (functioning at two radio frequencies) and receivers developed by ATS® (Advanced Telemetry Systems). Each site was equipped with the following antenna arrays to monitor all possible passage ways (Fig. 1): underwater antenna E to monitor fish *Entrance* into the HPP water intake, underwater antenna A (located upstream of the discharge control weir in the bypass) detecting fish *Approach* to the bypass (fish can still turn back), underwater antenna P confirming fish *Passage* through the bypass (impossible to turn back), underwater antenna C detecting fish passing through the protection rack into the intake *Channel*, and aerial antenna R monitoring fish passing over the dam in the *River* (and also confirming fish passing through the bypass). Preliminary detection tests, performed during antenna calibration, brought to light difficulties in decoding simultaneously passing tags in small and fast-flowing zones. For this reason, we doubled antennas A and P (two independent antennas/receivers were installed, each scanning only one frequency). All radio-receivers were checked each week during the survey. Complementary manual radiotracking with a mobile antenna was conducted each week to check tag status (on/off) and confirm fish movements within the studied river reaches, confirming ~100% detection probability for all antennas.

Due to low population abundance of eels in the Ariège River, the study was conducted with silver eels trapped in the Sèvre Niortaise River, as part of the eel monitoring program of the Parc naturel régional du Marais poitevin. Silver eels, in good general condition and without pathologies, were transported upstream of the study section, stocked in holding tanks, tagged and released in the Ariège River in 3–5 days following their capture in the Sèvre Niortaise River. Prior to handling and tagging, each eel was anaesthetized in a bath with clove oil-derived anaesthetic (10% clove oil in 70% ethanol, applied concentration: 8–10 ml/10 L of water). Once loss of equilibrium was attained, total length (*TL* in mm), wet weight (in grams), vertical and horizontal diameter (in mm) of the eel head and body were recorded. The transmitter F1215C with an internal antenna was surgically implanted into the peritoneal cavity. Tags were 64 or 53 mm long (model modification made during the study), had a diameter of 12 mm, and weighed 13 g including the battery (implicating a ratio tag/body mass between 0.7% and 4.4%, 2.5% on average). Each tag was transmitting 45 code signals per minute and we chose the most energy-saving codes on two different frequencies. Tagged fishes were then stocked under reduced light conditions to limit fish stress and at least one day before release (post-surgical survey), into holding tanks supplied with water from the Ariège River.

The close location of the HPPs on the same river section allowed to reduce the number of fishes needed for the study (*i.e.* individuals travelling through the study section contributed to the evaluation of several sites). In total, 194 individuals were tagged and released 600 m upstream from the first site, 96 during winter 2017–2018 and 98 during winter 2018–2019. This sample size was defined to ensure a robust efficiency evaluation of the FDPS, assuming that not all individuals will be detected during the survey at each site (*e.g.* because of migration stops or fish predation) and that a part of these individuals will pass directly over the dam. All tagged individuals were females with mean *TL* of 651 mm (min–max: 549–930 mm) in 2017–2018 and 695 mm (min–max: 585–955 mm) in 2018–2019, ensuring good size comparability between the two years (see other biometry data in Suppl. material). The eel surveys were conducted from January 10 to April 19, 2018 (with two fish releases on January 10 and 16), and from December 7, 2018 (fish release) to March 28, 2019. The study was validated by the Ethic Committee N°073 (APAFIS#9437-2017032916355870 v2) and obtained the authorization of the French Ministry for Research.

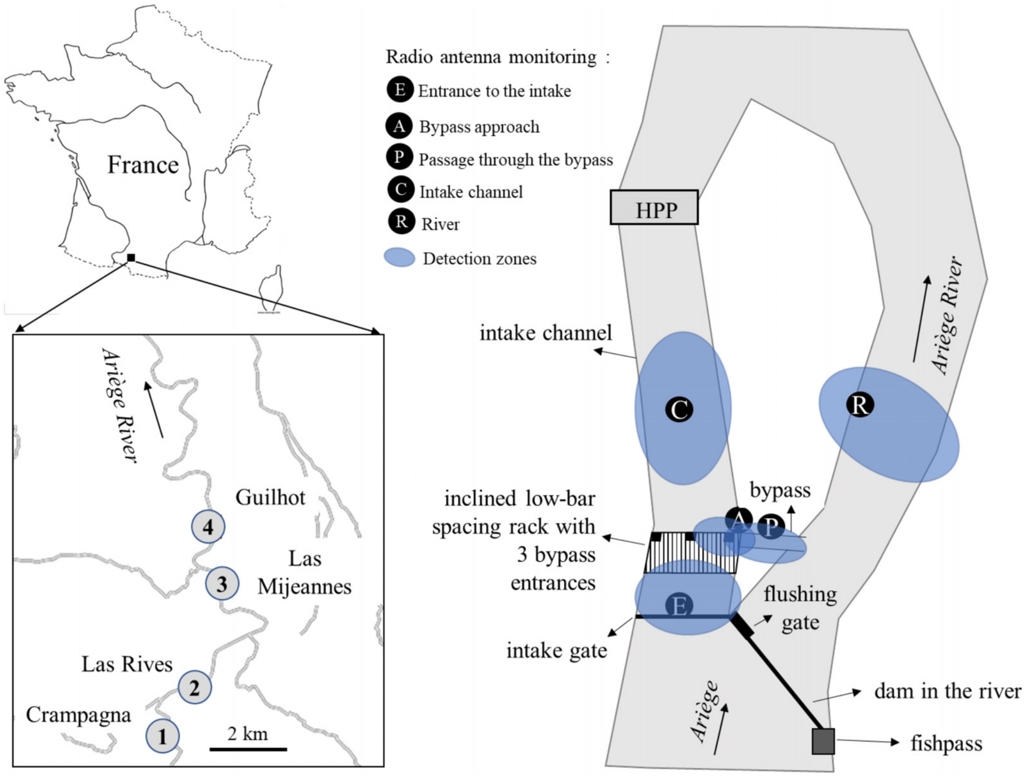

Fig. 1. Localisation of studied sites and their equipment with radio antenna array used for the eel downstream migration survey (all four sites have the same configuration and similar radio antenna array; only Crampagna could not be equipped with the antenna A; detection zones in blue).

2.3 Environmental conditions and HPP functioning

Hydrological conditions were highly contrasted between the two studied winters (Fig. 2), with higher river discharge (Q_{riv}) during December – March 2017–2018 ($Q_{riv\ mean} = 53.9$ $m^3.s^{-1}$, $Q_{riv\ max} = 219$ $m^3.s^{-1}$) compared to the same period in 2018–2019 ($Q_{riv\ mean} = 26.3$ $m^3.s^{-1}$, $Q_{riv\ max} = 60.9$ $m^3.s^{-1}$). Excepting Guilhot HPP, there was no (or very limited) spilling over the dams in 2018–2019 and all flushing gates remained closed. In contrast, continuous water spilling over dams was observed in 2017–2018 at all four sites. Flushing gates (near HPPs intakes, see Fig. 1) were frequently opened to evacuate water and sediments during flood events (flushing gates always opened when river discharge exceeded 100–120 $m^3.s^{-1}$). During the flood events of January 21 and 22, 2018 (Fig. 2), the HPPs shut down the electricity production and the intake gates were closed to protect the installations.

Using water level monitoring and the power production data recorded each 10 minutes (kindly provided by Ondulia hydroelectric company), we computed the HPP intake discharge (Q_{HPP} in $m^3.s^{-1}$), the bypass discharge (Q_{bp} in $m^3.s^{-1}$), the bypass discharge ratio ($Q_{bp\%} = [Q_{bp}/Q_{HPP}]*100$), the dam discharge ($Q_{dam}$ in $m^3.s^{-1}$), and the river discharge upstream of each HPP (Q_{riv} in $m^3.s^{-1}$) following the methodology applied by Tomanova *et al.* (2021). The openings of the flushing gates during floods were not recorded and discharges passing through were thus unknown. Consequently, high Q_{riv} values were underestimated. Hydraulic conditions immediately upstream from the rack were assessed by three velocity vectors in front of the rack (Fig. 3). Mean upstream approach velocity V_a ($V_a = [Q_{HPP} + Q_{bp}]$/[intake width* water depth]) was decomposed into two other velocity vectors: mean normal velocity V_n (perpendicular to the rack, $V_n = V_a$*sin [26°rack inclination]) and mean tangential component V_t (parallel to the rack, ($V_t = V_a$*cos[26°rack inclination]). Both velocities are involved in the FDPS efficiency: low normal velocity is needed to prevent fish impingement and injuries on the rack, while tangential velocity guides the fish toward the surface bypass entrances. All these data were available for each fish passage event (first fish detection in front of the rack).

2.4 Data analysis

For each site and each fish individual, multiple radio signals received over time and from different antennas were evaluated to determine the eel passage way. Unclear or illogical records were excluded from the dataset (*e.g.* a false parasitic signal or a fish detected after bird predation).

Two main metrics were assessed to evaluate the efficiency of FDPS: passage efficiency and passage time. Passage efficiency (P_{eff}) was computed as the proportion of fish detected at the entrance of the HPP intake gate (antenna E) and successfully passing through the bypass (antennas A and P). Accordingly, FDPS failures may occur if the fish, detected at the entrance of the HPP intake gate, definitively turned back upstream (with no further passage attempts) or if the fish passed through the protection rack into the turbines. Passage time (P_t) was the time between the fish detection at the

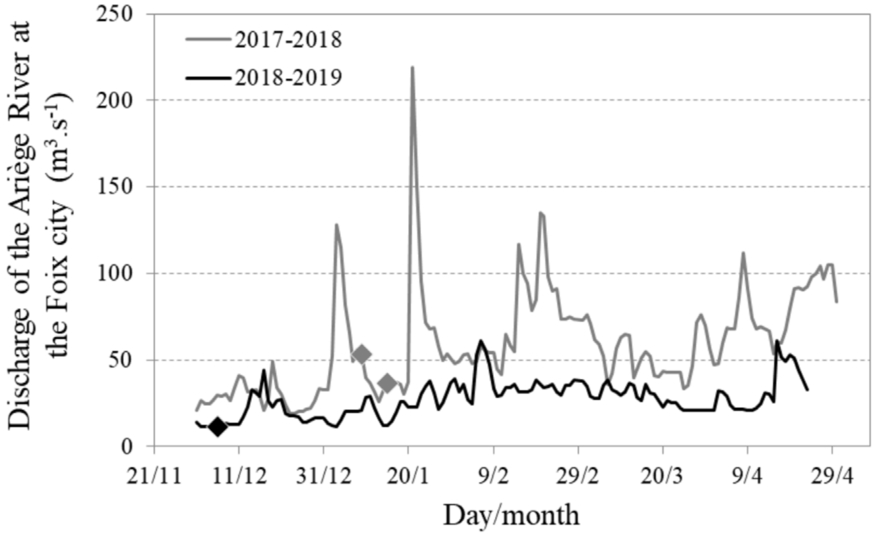

Fig. 2. Mean daily discharge of the Ariège River at Foix (about 10 km upstream of the study area) during the study period (dots: days of eel releases, discharge data source http://hydro.eaufrance.fr).

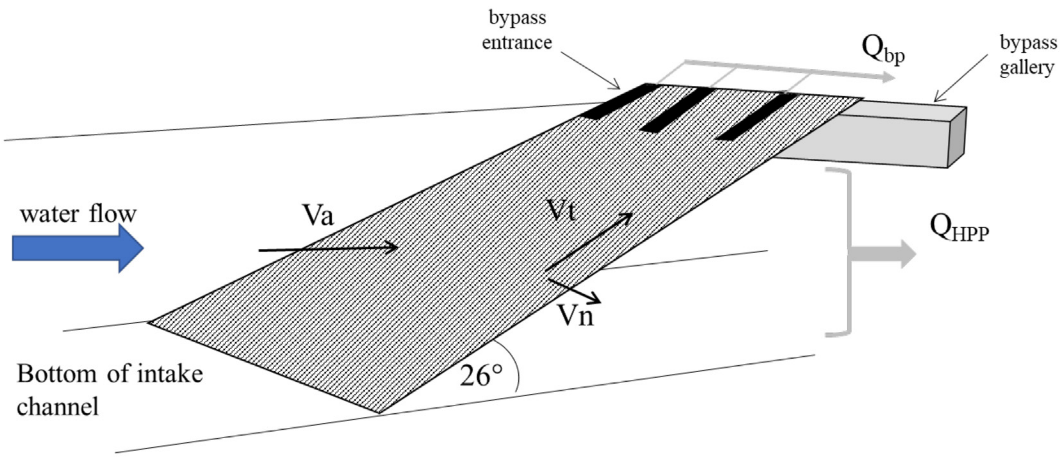

Fig. 3. Hydraulic parameters of velocity and discharge on the inclined low bar spacing rack (side view) with surface entrances to the bypass: *Va* – approach, *Vt* – tangential, *Vn* – normal velocities, Q_{HPP} – HPP intake discharge, Q_{bp} – bypass discharge.

entrance of the HPP intake gate (first detection with antenna E) and its maximum detection signal in the bypass (antenna P). Because this metric did not follow normality assumptions, Kruskal–Wallis or Wilcoxon tests were used to detect differences in P_t among sites or years.

We applied logistic regressions (generalized linear model that fits a binary response; Hosmer and Lemeshow, 2000) to analyse if the likelihood of fish passage through the bypass without hesitation can be mediated by the bypass discharge ratio $Q_{bp\%}$, velocity conditions in front of the rack (V_t), the fish total length (*TL*), and FDPS specificities (adding *site* as factor). In this analysis, sites were separated in two groups: Crampagna, Las Mijeannes and Guilhot (sites with similar conception, see Tab. 1), and Las Rives (see rack design difference in the Material and methods). To build the binary response, P_t was set to 1 if lower or equal to 5 min (*i.e.* considered as passage without hesitation, similarly as in Tomanova *et al.*, 2021), and to 0 if P_t was longer (passage with some hesitation or longer searching behaviour). We consider this duration ($\leq$5 min) as short enough to ensure successful migration, although a longer time to pass is not necessarily problematic. River discharge (Q_{riv}) and approach velocity (V_a) were not included in the models because they are highly related to V_t (with decreasing river discharge, Q_{HPP} decreases and so do the velocities in front of the rack) and because V_t is considered more relevant as directly related to the guiding effect of the rack. Two models were tested, the first one including all four parameters: $Q_{bp\%}$, V_t, *TL* and *site*, and the second one further adding the interaction between $Q_{bp\%}$ and V_t. The logistic models were performed using the *glm* function

Table 2. Number of migrating eels (total and by passage way) and passage time through the bypass (P_t) by site and studied season.

		Nb of migrating eels (+during HPP stops)	Nb of eels crossing through		Passage time P_t (min)				
			Dam	HPP intake & bypass (with known P_t)	25th percentile	Median	75th percentile	90th percentile	Max.
Crampagna	2017–2018	59 (+19)	44	15 (15)	1	1	4.5	23.6	46 min
	2018–2019	75	22	53 (53)	1	2	6	131	64 days
	Total	**134**	**66**	**68 (68)**	**1**	**2**	**5**	**54.7**	**64 days**
Las Rives	2017–2018	50 (+24)	31	19 (19)	1	2	3.5	12.6	29 min
	2018–2019	63	12	51 (51)	2	5	14	1058	7.5 days
	Total	**113**	**43**	**70 (70)**	**1.3**	**4**	**12**	**427.7**	**7.5 days**
Las Mijeannes	2017–2018	54 (+16)	26	28 (24)	1	1	2	2	4 min
	2018–2019	51	5	46 (46)	1	1	3	15.5	73 days
	Total	**105**	**31**	**74 (70)**	**1**	**1**	**2**	**10.4**	**73 days**
Guilhot	2017–2018	47 (+13)	26	21 (19)	1	1	2	4	12 min
	2018–2019	40	9	31 (31)	1	2	4.5	1395	20 days
	Total	**87**	**35**	**52 (50)**	**1**	**2**	**3.5**	**111.9**	**20 days**
All sites and years		**439**	**175**	**264 (258)**	**1**	**2**	**5**	**38**	**73 days**

from R (R Core Team, 2019). To compare both models, we used the *anova* function with the Chi-square test. To visualize the interaction between parameters we used the *interact_plot* function (package interactions, Long, 2021).

3 Results

During the study, we recorded 439 eel passages on all four sites, with HPP in operation (between 87 and 134 passages per site, Tab. 2). Passages over the dam, occurring at different sites during HPP shutdown (72 recorded events, Tab. 2), were not included in the results.

A total of 68, 70, 74 and 52 individuals were detected at Crampagna, Las Rives, Las Mijeannes and Guilhot HPP intakes, respectively (Tab. 2). The proportions of eels entering the HPP intakes were lower in 2017–2018, ranging from 25% at Crampagna to 52% at Las Mijeannes (Fig. 4), because of the high discharge levels and consequently increased water spilling over dams during this season. Higher proportions of migrating eels were detected at the entrance of the HPP intakes during winter 2018–2019 (between 71% and 90% following the site), when the water spilling over dams was very limited.

3.1 Efficiency and passage time

All individuals present in front of the inclined racks successfully passed through the surface bypass (Tab. 2). The passage efficiency (P_{eff}) at each site was therefore 100%.

Passage times through the bypass ($P_{t,}$ available for 258 from 264 recorded bypass passages) were usually very short at all four sites (Tab. 2). After passing the intake gate (antenna E), 75% of fish continued their migration through the bypass (antennas A and P) in a few minutes at all sites. A significant difference in P_t was observed among sites (Kruskal-Wallis test; $\chi^2 = 23.5, p < 0.001$) and pairwise comparisons confirmed that P_t was significantly longer at Las Rives (median $P_t = 4$ min) than on the other sites (median $P_t = 1$–2 min, Wilcoxon tests with $p < 0.05$ for all comparisons). Differences appeared also between years, with longer P_t during 2018–2019 (Tab. 2), but significant only at Las Rives ($W = 284.5, p < 0.01$) and Guilhot HPPs ($W = 156.5$, $p < 0.01$). Even if statistically significant, these differences in passage times were altogether marginals in term of migration delay (*i.e.* usually a few minutes).

3.2 Key parameters for quick eel passage through the surface bypass

Both tested logistic models (Models 1 and 2, with and without the interaction term between V_t and $Q_{bp\%}$ respectively) were valid ($p < 0.05$, Fig. 5) and were not significantly different from each other (ANOVA Chi-square test, $p = 0.06487$). In Model 1 (Fig. 5a and b), both V_t and $Q_{bp\%}$ were significantly and positively related to the probability of bypass passage without hesitation $p(P_{wh})$. This $p(P_{wh})$ reaches maximum values (>0.9) when V_t exceeds 0.65 m .s^{-1} (Fig. 5a). The $Q_{bp\%}$ effect appears less strong (Figs. 5b), as $p(P_{wh})$ increases only from 0.8 to 0.9 when the $Q_{bp\%}$ increases from 3 to 7.5%. The fish length and *site* (as factor) had no effect on the probability of passage without hesitation. When the interaction term is included (Model 2), only V_t still explains a significant part of the variability ($p = 0.01$), and the interaction $V_t{*}Q_{bp\%}$ is nearly significant ($p = 0.08$, Fig. 5). Although adding the $V_t{*}Q_{bp\%}$ interaction did not significantly improve the model (only slight changes in estimated pseudo-R^2 and AIC can be observed), the relationship between V_t and $Q_{bp\%}$ was explored and presented here (Figs. 5c and d) because potentially useful for FDPS designers. At intermediate V_t values (around 0.5 m s^{-1}, Figs. 5c and d), a positive effect of increasing

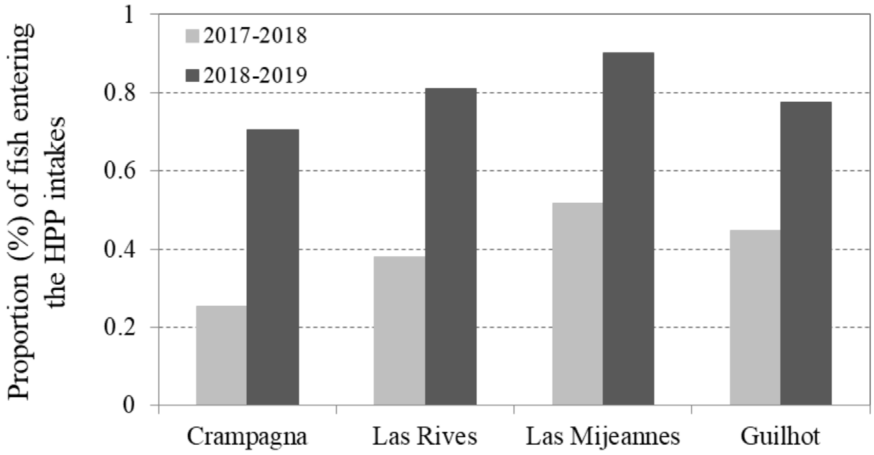

Fig. 4. Proportion of eels detected at the entrance of each studied HPP intake (antenna E) per study season (100% – all detected fish (including dam passages) crossing the complex with HPP turned-on).

$Q_{bp\%}$ can be observed: higher $Q_{bp\%}$ (*e.g.* 8% or more) eliminates eel passage hesitation ($p(P_{wh}) > 0.9$) under these V_t conditions. Under very low V_t values (<0.3 m s^{-1}), high $Q_{bp\%}$ still influences fish hesitation, but all probability curves under different $Q_{bp\%}$ yield very low and unsatisfactory $p(P_{wh})$ (Fig. 5c). On the opposite, when V_t exceeds 0.7 m s^{-1} all probability curves under different $Q_{bp\%}$ predict very high $p(P_{wh})$ (>0.9 except for $Q_{bp\%} = 1\%$, Fig. 5c), and the positive $Q_{bp\%}$ effect is only visible for values from 1% to 5% (Fig. 5c), and then stabilizes for $Q_{bp\%}$ beyond 5%. With the minimum $Q_{bp\%}$ of 3%, set by French authorities, the V_t needs to reach at least 0.7 m s^{-1} to ensure very low eel passage hesitation ($p(P_{wh}) \sim 0.9$ in average). This value is reached or exceeded when the HPP are at full operation (Tab. 1).

4 Discussion

The first objective of our study was to evaluate the efficiency for eels of horizontally inclined (26°), low bar spacing (20 mm) racks with surface entrances to the bypass, which is one of the two currently recommended FDPS in France to protect downstream migrating fishes (Courret and Larinier, 2008; Courret *et al.*, 2015). We demonstrated 100% passage success for eels longer than 550 mm. All eels crossed the studied HPP water intakes using surface bypass (in most cases in a short time; Tab. 2), indicating that no significant delay is added to the eel migration by this FDPS, once entered in the intakes (note that the potential influence of the impoundments was not measured in the present study). Our study confirmed the efficiency of this device on HPPs with intake discharge capacities between 28 to 45 m^3. s^{-1}. These findings complete previous efficiency results for salmon smolts (Tomanova *et al.*, 2018, 2021), broadening the interest of this solution and confirming the previously proposed design criteria (Courret and Larinier, 2008; Courret *et al.*, 2015). Although further studies would be needed, good efficiency results for these two species displaying very different morphologies and behaviours suggest that these devices may also be efficient for a wide spectrum of other amphidromous and holobiotic species.

The main weakness of our study is that it focused only on large female individuals (with body size > 550 mm), making results not directly applicable to sites where smaller eel males (with body size < 500 mm) are present (*i.e.* coastal and lower catchment basins in France). Our study focused on large individuals for two reasons: only large individuals inhabit upper catchment parts where numerous HPPs are installed in France, and only large eels could be tagged with available radio-transmitters. In zones inhabited by smaller eel males, tested FDPS with 20 mm bar spacing should be less efficient to act as a physical barrier, the head width of eel males being lower than the bar spacing. Bar spacing of 10 mm would be required to physically stop all males (Courret and Larinier, 2008; Schwevers and Adam, 2020). However, considering the possible increasing operational constraints with reduced bar spacing, a value of 15 mm is currently recommended in France by Courret and Larinier (2008). A specific study should be conducted to confirm the bar spacing needed to protect eel males. Meanwhile, other possible mitigation measures should be considered (*e.g.* installation of harmless turbine, turbine shutdown during the migration period) depending on the local ecological and energy production challenges.

Our study was performed during two hydrologically contrasting years (Fig. 2), offering a great opportunity to test this FDPS under different hydraulic conditions. Some differences did appear: longer passage time (P_t, time to find the bypass) was observed during the year with lower river hydrology (Tab. 2) suggesting a lower bypass attractivity. However, the hydrology during this year was not representative of silver eel migration conditions (migration during high flow events is usually reported; Durif *et al.*, 2003; Acou *et al.*, 2008; Travade *et al.*, 2010), and eel movements were certainly artificially induced in our study by their geographical origin (trapped during the seaward migration in a different river in flood, and released in the Ariège River with low hydrology at that time). However, years with low to medium flow conditions during autumnal and winter eel migration period have already occurred (Spinoni *et al.*, 2017; Peña-Angulo *et al.*, 2022), and their frequency are increasing in some European regions due to climate, human activities (water management) and land-use

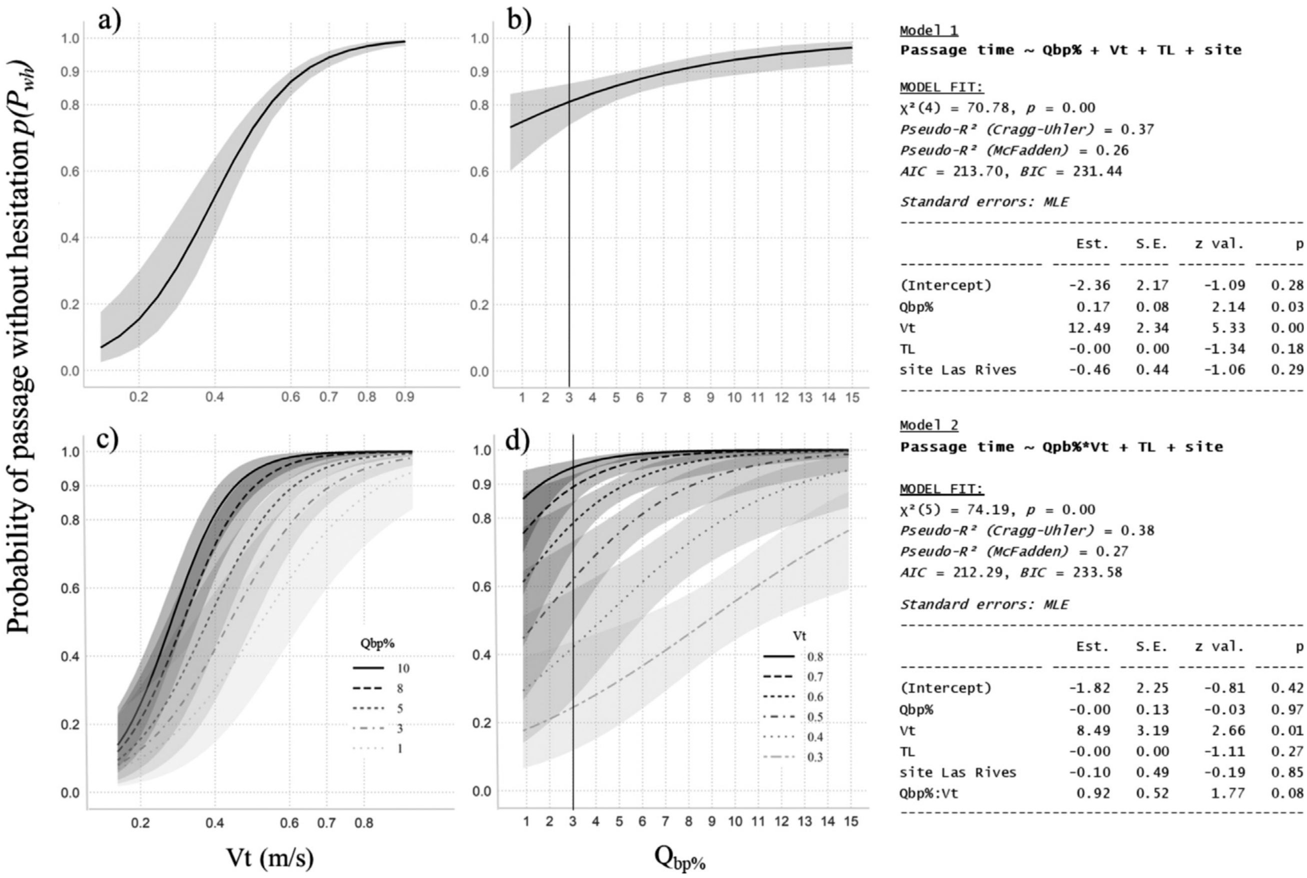

Fig. 5. Predicted probabilities of eel bypass passage without hesitation ($p(P_{wh})$, mean with 80% confidence interval in shaded areas) as a function of the tangential velocity *Vt* ($m\,s^{-1}$) in the proximity of the rack and the bypass discharge $Q_{bp\%}$ (expressed as a proportion (%) of exploited HPP discharge), resulting from logistic regression Model 1 (a and b) and Model 2 (c and d, including *Vt* and $Q_{bp\%}$ interaction); *TL* – fish total length (mm), *site* as factor, straight lines on b and d indicate $Q_{bp\%}$ of 3%, set by French authorities.

changes (IPCC, 2021). Our results obtained under low hydrology conditions remain therefore interesting and useful, demonstrating that passage efficiency is not greatly impacted by low hydrology conditions (Tab. 2), with only a few cases of long P_t. These few long P_t values were linked to low guiding velocity in front of the rack (Fig. 5), when the HPP reduced its intake discharge during low river discharge period. On the other side, very short P_t during high flows could be somewhat favoured by the configuration of the studied sites. Considering the importance of $Q_{bp\%}$ (Fig. 5), all four studied sites are in fact favourable to reduced P_t during high flows as their bypass discharges increase automatically with upstream water level elevation, once the HPPs are at full turbine capacity and spilling occurs. This is not the case at HPPs where upstream water level is regulated and remains stable independently of river hydrology. Overall, considering all 4 studied sites and 2 years, we can advance that 75% and 90% of eels were able to successfully cross the tested FDPS in less than 5 and 38 min, respectively. These P_t values are short enough for not penalizing a successful eel seaward migration.

P_t for eels are slightly longer at the Las Rives site compared to the others, while it was the reverse for salmon smolts (Tomanova *et al.*, 2021) (interpreted as a positive effect of transversal currents produced by the obstruction of the upper part of the rack). However, this difference between the two species may be explained by the greater depth of Las Rives intake (4.18 m compared to 2.58–2.65 m for three other sites, Tab. 1), and the behavioural differences during their downstream migration, between the bottom-oriented eels (Brown *et al.*, 2009; Russon *et al.*, 2010; Calles *et al.*, 2013) and smolts that migrate in the first 2–3 m of depth below the water surface (Hesthagen and Garnås, 1986; Rivinoja, 2005). Note however that Las Rives site show the lowest maximum passage time for eels (Tab. 2), as for salmon smolts (Tomanova *et al.*, 2021).

Passage time was used as a proxy for the eel searching behaviour for free passage. Among all tested factors and whatever the model used, tangential velocity V_t results as a key factor significantly influencing the eel passage time (Fig. 5). It appears that, for the recommended minimum $Q_{bp\%} = 3\%$ (Courret and Larinier, 2008; Courret *et al.*, 2015), more than 90% of the eels were efficiently guided to the top of the rack when $V_t > 0.7\,m.s^{-1}$, and found in less than 5 minutes the bypass entrances (Figs. 5c and d). Complementing the recommendation about the threshold V_n value, not to exceed $0.5\,m.s^{-1}$ to prevent fish impingement (Courret and Larinier, 2008; Fjeldstad *et al.*, 2018) and the minimum $Q_{bp\%}$ (3%), we suggest that the V_t along inclined racks should be at least

Table 3. Computed values of approach (V_a), tangential (V_t) and normal velocities (V_n) (m. s^{-1}) on the rack following different rack inclination (see Fig. 3 and Materiel and methods for computation formulae, bold values – fixed and used for the computation of other velocities, in grey – when the recommendation on V_t or Vn threshold values are not respected).

Rack inclination (°)	Velocities (m.s^{-1}) on the rack		
	Vt	*Vn*	*Va*
26	1,03	**0,50**	1,14
26	**0,70**	0,34	0,78
30	0,87	**0,50**	1,00
30	**0,70**	0,40	0,81
35	0,71	**0,50**	0,87
35	**0,70**	0,49	0,85
40	0,60	**0,50**	0,78
40	**0,70**	0,59	0,91
60	0,29	**0,50**	0,58
60	**0,70**	1,21	1,40
80	0,09	**0,50**	0,51
80	**0,70**	3,97	4,03

0.7 m s^{-1} during eel migration events to guarantee their guidance to the surface bypass entrances. In front of the inclined racks, V_t is uniformly linked to V_a and V_n (see Sect. 2.3). Recalculating V_a, V_t and V_n velocities for different rack inclinations (using $V_t = 0.7$ m.s^{-1} or $V_n = 0.5$ m s^{-1} as fixed values), we can observe that these two hydraulic conditions ($V_n \leq 0.5$ m s^{-1} and $V_t > 0.7$ m s^{-1}) could not be simultaneously matched if the rack inclination exceeds 35° (Tab. 3). It should also be very difficult to reach them if the rack inclination is between 30° and 35° (possible only under very stable discharge conditions, rarely found in the field). Overall, our analysis of eel passage time under variable hydraulic parameters consolidated the choice of 26° rack inclination, previously defined by Courret and Larinier (2008).

Interspecific variation in behaviour remains a key challenge in developing multi-species fish protection devices. The general recommendations to build an efficient downstream bypass solution for eels include usually a bottom position for bypass entrances (Schwevers and Adam, 2020). This should however be of poor attractiveness for other species swimming in the water column, and building several species-specific bypasses at the same site is sometimes proposed (Klopries *et al.*, 2018). Our study showed that the surface bypass, useful for downstream migration of salmonids (Tomanova *et al.*, 2018, 2021), can also be very efficient for eels if hydraulic conditions in front of the inclined rack are optimal to guide the eels towards the bypass entrances, suggesting that building a specific eel bypass entrance is not systematically necessary.

There are few evaluations of inclined racks that report passage efficiency and time for silver eels that are comparable to our study. Indeed, previous works frequently assessed global eel passage success through the whole HPP complex, including impoundment effect and other passage possibilities (spilling, flushing gates or fish passes). 100% rack protection success for eels was, until now, usually observed on racks with lower bar spacing than in our study: at the Unkelmühle HPP in Germany, equipped with 27° inclined rack with 10 mm bar spacing (Økland *et al.*, 2019), at a HPP at the Franconian Saale in Germany (Egg *et al.*, 2017) or at Herting HPP in Sweden (Calles *et al.*, 2021), both equipped with to the flow oriented racks with 15 mm of bar spacing. Contrarily to Calles *et al.* (2010), also studying a rack with 20 mm of bar spacing but with 63° inclination, we didn't observe eels crossing the rack (from all the 264 HPP intake passages detected in our study). Clearly, it indicates a positive effect of the rack inclination and related flow velocities. A too high V_n velocity value was observed with 63° rack inclination in Calles *et al.*'s study resulting in fish impingement on the rack or in fish frequently crossing the rack. As we show here, 26° inclination results in better flow Vn and V_t velocities, motivating eels to follow the screen to its upper part rather than to cross it through.

Rack designs most similar to our studied sites were followed by Calles *et al.* (2013) who studied the eel passage at the Ätrafors HPP in Sweden equipped with 35° inclined rack, 18 mm of bar spacing and surface bypasses. They reported five eels crossing the rack and entering turbines, and also numerous other individuals (16 from 38) that swam to the rack and then back upstream into the reservoir. Most eel retreat events observed by Calles *et al.* (2013) were recorded at V_n between 0.45–0.53 m s^{-1} and V_t of 0.65–0.76 m s^{-1}, however still judged as optimal hydraulic conditions for eel guidance in our study. This discrepancy could only be explained by the difference in bypass configurations. In Calles *et al.* (2013), Q_{bp}, divided in 6 small bypass entrances, represented between 1% and 2% of Q_{HPP} (HPP intake capacity was 72 m^3 s^{-1}). In our sites, Q_{bp}, divided in 3 bypass entrances, represented usually at least 3% of Q_{HPP} (Tab. 1), and 5% in average during the eel passage events (Fig. 5a). Even if not always significant, our analysis showed that $Q_{bp\%}$ can have an importance (Fig. 5), because under optimal V_t conditions, the probability of passage without hesitation is lower with 1% of $Q_{bp\%}$ (value approaching the situation at the Ätrafors HPP) compared to 3 or 5% of $Q_{bp\%}$ (Figs. 5c and d). Setting a threshold $Q_{bp\%}$ value to 3–5%, along with the design criteria on entrance velocity, dimensions (width and water depth) and spacing between bypass entrances proposed by Courret *et al.* (2015), seems therefore to be a good choice to ensure very good efficiency results also for eels.

As a conclusion, the efficiency of an inclined fish protection racks is related to three principal parameters: 1) bar spacing, 2) normal and tangential velocities on the rack (driven by the approach velocity and the rack inclination) and 3) bypass entrance attractiveness, driven by its position and discharge. All these three parameters need to be considered when designing a new project (or retrofitting an existing one). For the best efficiencies, the three parameters should theoretically be maximized, *i.e.* with the lowest possible rack bar spacing (*e.g.* 10 mm as in Økland *et al.*, 2019), with low rack inclination to the horizontal (*e.g.* 20° as in Cuchet *et al.*, 2011) and the highest bypass discharge (*e.g.* 8% of QHPP yielding the best probabilities of passage in Tomanova *et al.*, 2021). This theoretical best solution would however conduct to important impacts on energy production and could be very complex to implement on existing intakes. Our study showed that the maximization of design criteria is not necessary because we can achieve very high efficiency (100% for eels in the present study, more that 80% for salmon smolts in Tomanova *et al.*, 2018, 2021) with less strict rules: 20 mm of bar spacing, 26° of rack inclination and between 3% and 5% of $Q_{bp\%}$. Sometimes however, these three rules cannot be applied together, especially when retrofitting existing HPP intakes. New compromises are to be found, and a compensation of a deficient parameter with another one could be considered in those cases. For example, if 26° rack inclination cannot be respected in the field (because of the site specificities), higher rack inclination will produce lower suboptimal V_t on the rack which can be partially compensated with increased bypass discharge ($Q_{bp\%}$, Figs. 5c and d). Our results also showed that there are some compensation limits, since under very unfavourable hydraulic conditions (very low tangential velocity), even very high discharge allocated to the bypass ($Q_{bp\%}$ = 10%, Figs. 5c and d) is not efficient to quickly attract eels to this passage way. Thus, our study provides key elements for water managers to better identify a compromise between fish environmental suitability and hydropower energy production.

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Supplementary Material

Table 1. Biometry of eels used for efficiency evaluation of 26° inclined racks with 20 mm of bar spacing and surface bypass.
Figure 1. Studied 26° inclined racks (out of water) with three surface bypass entrances.

The Supplementary Material is available at https://www.kmae-journal.org/10.1051/kmae/2023011.

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