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Evaluation of a fine-spaced angled rack with surface bypass in providing safe and timely downstream passage for salmon smolts and silver eels

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Abstract – Hydropower production can cause migration delay and fish mortality, impeding the safe and timely downstream migration of diadromous fish, such as Atlantic salmon (*Salmo salar*) and silver eels (*Anguilla anguilla*). To date, only a few field performance tests, especially for eels, have evaluated the efficiency of fine-spaced angled racks associated to a surface bypass entrance to protect fish. Here, 115 salmon smolts and 65 silver eels were radio-tracked over a 2 yr period to assess passage efficiency and passage time at a hydropower intake ($50 \text{ m}^3 \cdot \text{s}^{-1}$) retrofitted with a 20 mm rack associated to a surface bypass ($2 \text{ m}^3 \cdot \text{s}^{-1}$). Results showed high impediment (89.6% and 96.9% for smolts and eels, respectively), and passage efficiency for the angled rack (89.1% and 93.3%), with short passage times (median, 3 and 7.5 min). However, our results highlighted a strong influence of hydrological conditions, in enhancing fish passage, especially through the bear-trap gate. We conclude that this fish passage solution, making use of existing spillways on the study site, is highly effective for both species. Special attention must, however, be paid to bar-rack design and its cleaning system to ensure fish guidance and prevent impingement or passage through the rack, especially for salmon smolts.

Keywords: *Salmo salar* / *Anguilla Anguilla* / fish passage solution / hydropower / downstream migration

1 Introduction

Global biodiversity loss is increasing at an alarming rate (Pimm *et al.*, 2014). In European rivers, the Atlantic salmon (*Salmo salar*) and the European eel (*Anguilla anguilla*) are two diadromous species (*i.e.*, sharing their life cycle between ocean and rivers) of high concern (ICES, 2021; IUCN, 2022). The reasons for their decline are multi-factorial: overfishing, pollution, climate change, and habitat loss (Thorstad *et al.*, 2008; Otero *et al.*, 2014; Dekker, 2016). River fragmentation is also identified as one of the most significant causes of the decline of these two species (Thorstad *et al.*, 2008; Merg *et al.*, 2020), which need to migrate between their growing and spawning habitats to complete their life cycle. Barrier removal

to restore ecological continuity has proved effective (Koed *et al.*, 2020; Sun *et al.*, 2021), but is not an option in many cases (*e.g.*, power generation, water stocking, flood control, goods transport and/or waterway crossing). Therefore, it is usually crucial to mitigate the ecological impact of existing barriers with efficient fish passage solutions (FPS) (Silva *et al.*, 2018), especially in some rivers in which barriers are numerous, with cumulative impact over the catchment (Larinier, 2008; Lange *et al.*, 2018).

Mitigation of barrier impact on upstream migration has long been addressed by the development of various FPSs, whether “technical” or “nature-like” (Larinier, 2002; Porcher, 2002; Armstrong *et al.*, 2010). Barriers to downstream migration cause delay (Marschall *et al.*, 2011; Trancart *et al.*, 2020; Tétard *et al.*, 2021), and, in hydropower plants, turbines (Pracheil *et al.*, 2016) and spillways (Ruggles and Murray, 1983) can induce direct or

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delayed mortality (Ferguson *et al.*, 2006). For downstream migration, fish downstream passage solution (FDPS) already exists, and show high efficacy without substantial migration delay in small-to-medium size hydropower plants (HPPs): *e.g.*, racks with reduced bar spacing (≤ 20 mm), either horizontally inclined ($\leq 26^\circ$) or angled to the flow ($\leq 45^\circ$), and associated to a bypass or bypasses. *In situ* studies demonstrated that these solutions can be very effective (Calles *et al.*, 2013, 2021; Havn *et al.*, 2018; Nyqvist *et al.*, 2018; Tomanova *et al.*, 2018, 2021, 2023; Økland *et al.*, 2019; Kjærås *et al.*, 2023). In these studies, however, 10 out of 13 HPPs had intake capacities below $40 \text{ m}^3 \cdot \text{s}^{-1}$, or in some cases, studies were performed during low-flow periods. Most studies focused on inclined racks and on Atlantic salmon smolts, and evaluations for larger units (up to $100 \text{ m}^3 \cdot \text{s}^{-1}$) equipped with angled racks are scarce, notably for silver eels (but see, Calles *et al.*, 2021, 2021; Kjærås *et al.*, 2023).

Angled racks are less frequently implemented, but are the only suitable alternative when intake is too deep, as an excessively long cantilevered mechanical rack-cleaner arm would be needed for an inclined rack, and when water level vary too greatly, making surface bypasses difficult to design (Courret and Larinier, 2008). However, an important issue with the angled rack solution is fish guidance toward a surface bypass. While inclined racks guide fish present in the whole water column toward the surface bypass, angled racks do not. Consequently, a bypass entrance with an opening through the whole water column is recommended. Tests on salmon smolts, which navigate in the surface layer, showed good guidance by angled racks with a surface bypass (Nyqvist *et al.*, 2018; Tomanova *et al.*, 2018), but more research is needed for eels, which search more intensely but not exclusively near the bottom or in mid-water, close to obstructions (Brown *et al.*, 2009; Kjærås *et al.*, 2023). Several studies reported poor performance for surface bypasses (Klopries *et al.*, 2018; but see Travade *et al.*, 2010; Økland *et al.*, 2019), and bottom bypasses are therefore frequently recommended for eels (Fjeldstad *et al.*, 2018; Schwevers and Adam, 2020), although this raises issues of cleaning and maintenance. Recently, for silver eels, Calles *et al.* (2021) and Kjærås *et al.* (2023) reported a good efficacy for a bypass composed of a surface notch and a bottom orifice. The bottom orifice was used by the majority of the fish, but nearly 30% used the surface slot (Kjærås *et al.*, 2023). In fact, studies have involved different rack and bypass configurations (inclination, orientation, bar spacing, discharge), making it difficult to disentangle the influence of one parameter from another.

More broadly, there is clearly a need for a single solution suiting both salmon and silver eel, as both species are usually simultaneously targeted by FPSs, despite having different migratory behaviour. Moreover, a solution that is effective for these two very different species (in terms of length, shape, swimming performance and behaviour) would be promising for other fish species. Surface bypasses have been validated for salmon, but performance remains to be confirmed for eels when other recommended criteria for fish-friendly intakes are met: bar spacing, rack orientation, velocity, *etc.* (Courret and Larinier 2008).

The present study assessed the efficiency of a fine-spaced angled rack associated to a surface bypass to protect downstream-migrating salmon and eels in a medium-sized HPP. The study objectives were 1) to validate this FDPS for the

two species, and 2) to study the effect of various parameters on passage route selection and passage time.

2 Materials and methods

2.1 Study site

The study was conducted at Pébernat HPP, operated by Electricité de France (EDF) on the Ariège River, a tributary of the Garonne River, in southwestern France (Fig. 1). The river's hydrological regime is pluvio-nival, characterized by high flow periods during spring snowmelt. Mean annual discharge at Pébernat is $44.9 \text{ m}^3 \cdot \text{s}^{-1}$. The fish community (regularly monitored 8 km downstream of the HPP intake) is typical of the barbel zone (Huet, 1959), with the predominance of minnow (*Phoxinus phoxinus*), loach (*Barbatula barbatula*), gudgeon (*Gobio gobio*) and barbel (*Barbus barbus*), and presence of Atlantic salmon (*Salmo salar*) and European eel (*Anguilla anguilla*) (fish data available at: <https://naiades.eaufrance.fr>, "l'Ariège au Vernet" station). The Pébernat HPP (43.133819 N, 1.600293 E) has three main waterways (Fig. 1):

- A main dam on the left bank bypasses the riverbed, with a legal minimum flow of $4.49 \text{ m}^3 \cdot \text{s}^{-1}$, where floodwater can be discharged through a 45 m spilling weir and two 15 m flap-gates. The dam is equipped with a vertical slot fish pass for upstream migration.
- The intake channel on the right bank diverts water to the HPP 4.7 km downstream. The powerplant has a maximum intake capacity of $50 \text{ m}^3 \cdot \text{s}^{-1}$ (two Kaplan turbines of $25 \text{ m}^3 \cdot \text{s}^{-1}$). Four regulation gates control the diverted discharge.
- Adjacent to the intake channel entrance, there are 2 additional spillways: a 6 m radial gate (for debris and sediment evacuation, but never opened during the fish surveys) and a 17 m bear-trap gate (BTG) for reservoir level regulation (Fig. 2B). These two spillways discharge floodwater into a channel connected to the bypassed river stretch (non-diverted part of the river, under a legal minimum flow of $4.49 \text{ m}^3 \cdot \text{s}^{-1}$), approximately 700 m downstream of the dam. The BTG is automatically regulated with a float and is the first spillway used when river discharge exceeds the full capacity of the intake channel along with the minimum flow delivered by the dam.

In 2015, an FDPS was built at the entrance of the intake canal. A 20 mm bar-space rack, with vertical bars, was positioned in the right bank alignment, almost vertically (5° inclination to the vertical), so it can be considered as an angled rack (Fig. 1). The rack is 60 m long, with 1.75 m wetted height, resulting in a wetted surface of 105 m^2 and a maximum mean normal velocity of $0.48 \text{ m} \cdot \text{s}^{-1}$ under normal water level. It is built on a 0.75 m high concrete wall. Upstream of the rack, the bottom is not uniform (between 2.5 m and 3.65 m water depth). A 6 m-wide channel was built toward the radial gate to better evacuate sediment from the intake (see picture in Suppl. Materials). The rack is equipped with a mechanical trash cleaner with its own evacuation canal. From the rack to the 4 intake gates, the intake channel is divided into 4 openings by concrete guiding walls, each controlling the flow through one of the 4 sub-sections of the rack (Fig. 2A). A bypass was

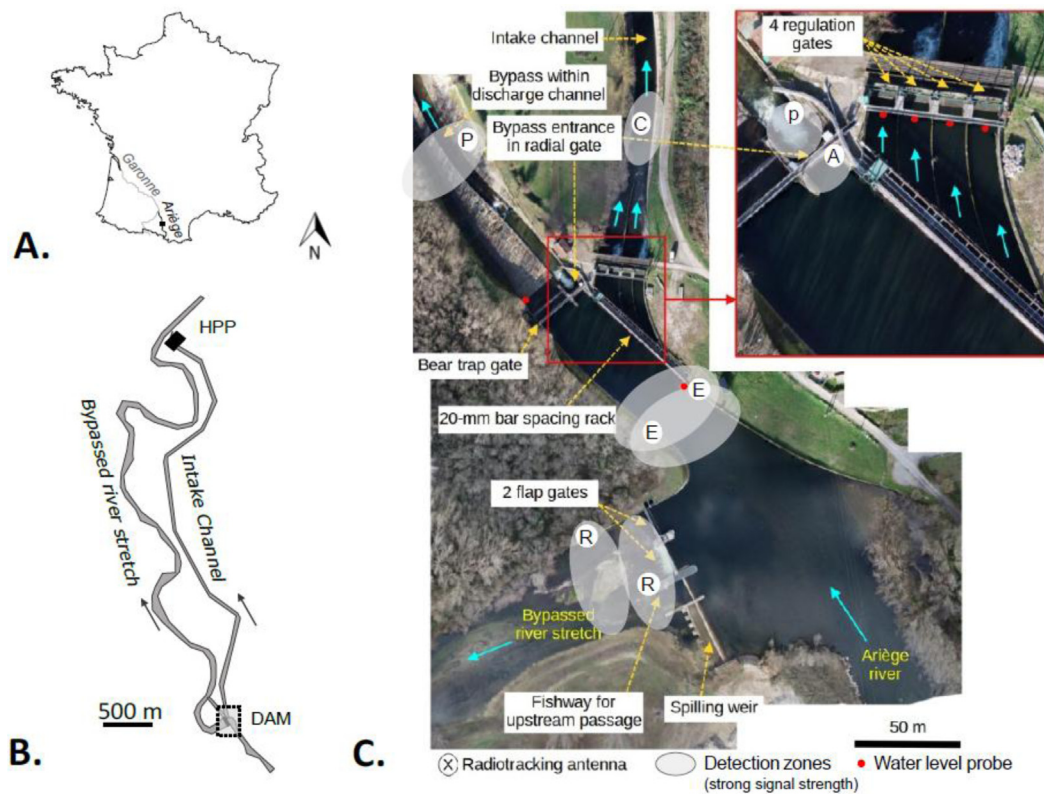


Fig. 1. A. Location of the Pébernat site in the Ariège river catchment, B. HPP configuration and C. Configuration of the Pébernat water intake with fish passage solutions, locations of radiotracking antennas in black circle (see 2.2. for antenna letters) and of water level probes in red circles. Blue arrows represent flow direction.

created in the radial gate, approximately 6 m from the downstream end of the rack, consisting of a 2 m wide 1.1 m long flap gate, automatically regulated according to reservoir level to ensure a continuous flow of $2 \text{ m}^3 \cdot \text{s}^{-1}$, representing at least 4% of intake capacity (Figs. 1, 2B and 2C). Water depth at the bypass entrance varies between 0.72 and 0.87 m, representing 20–23% of the water depth in front of the radial gate (3.56–3.71 m), and 44–48% of rack depth (1.65–1.75 m). A 6-meter distance between the bypass entrance and the downstream end of the rack is not optimal for fish guidance, but this design was validated by the local environmental authority because of structural requirements and considering the BTG's attractiveness (facing the main current, wide, and frequently open).

2.2 Salmon and eel monitoring

Radiotelemetry was used to assess the efficacy of the angled rack. The study was conducted with hatchery Atlantic salmon smolts (MIGADO hatchery) and with wild silver eels trapped in the Sèvre Niortaise River. Atlantic salmon smolts were equipped with an F1720 transmitter with a 20 cm external antenna (ATS[®]), which was 20 mm long, 8 mm in diameter and weighed 2 g. Silver eels were equipped with an F1215C transmitter with an internal antenna (ATS[®]), which was 64 or 53 mm long (manufacturer's change in model during the study period), 12 mm in diameter and weighed 13 g. Prior to handling and tagging, each fish was anesthetized in a bath with clove-oil-derived anesthetic. Transmitters were either carefully

inserted in the stomach (smolts) or surgically implanted into the peritoneal cavity (eels). Radio-transmitters, fish origin and tagging procedure were described in detail in previous studies (Tomanova *et al.*, 2021, 2023). The study was approved by the Ethics Committee N°073 (APAFIS#9437-2017032916355870 v4) and obtained the authorization of the French Ministry for Research.

For each species, the study was conducted during 2 migration seasons: spring 2017 and 2018 for smolts, and winter 2017–2018 and 2018–2019 for eels (see Tab. 1 in Supplementary Material). In total, 199 tagged hatchery smolts were released upstream of the study site, as follows: 6 groups of 24–25 individuals were released about 19.4 km upstream, with 3 HPPs to cross before reaching the Pébernat intake; 1 group was released 14.7 km upstream, with 2 HPPs to cross; and 1 group was released 1.5 km upstream, with no obstacles in between. This strategy was intended to balance the number of fish detected at each HPP site. In total, 194 silver eels were released 20.5 km upstream of the Pébernat HPP: 96 and 98 respectively during the 2 yr of the study.

The radio-antenna array was installed at the Pébernat site to monitor all possible passage routes (Fig. 1). Fish approach into the HPP water intake zone was recorded by 2 aerial antennas (E) which detected fish approaching the impoundment with a slight signal, and confirmed their entry into the intake zone with a strong signal. The bypass zone was equipped with 2 underwater antennas: antenna A, detecting Approach to the bypass, was located upstream of the bypass entrance and Antenna



Fig. 2. A. Front view of the Pébernat 20 mm bar spacing rack, showing 4 sub-sections divided by downstream guiding walls, B. Downstream view of bypass entrance and bear-trap gate, C. Zoom on the bypass entrance created in the radial gate.

p confirmed passage through the bypass. Note that antenna A had not yet been installed at the time of the first smolt study in 2017. As the Pébernat site allows fish to pass through the BTG during floodwater or HPP dysfunction episodes, an aerial antenna (P) was installed 50 meters downstream of the bypass entrance, screening the whole discharge channel. This antenna detected all fish that migrated through the discharge channel and, by deduction of fish detected by the p antenna, was able to determine the exact passage route: BTG or bypass. Fish passing through the protection rack were detected by antenna C in the intake channel. Finally, fish passing over the dam were detected by two aerial antennas, R, in the bypassed river stretch, downstream of the dam. When individuals entered a detection zone, the corresponding antenna recorded tag ID, date and time (hh:mm) along with the maximum signal and the pulse count received during a 1 min recording. Complementary manual radiotracking with a mobile antenna was frequently conducted to check tag status (on/off) and confirm fish movements within reaches, and confirmed ~100% detection probability for all antennas.

2.3 Environmental conditions and hydraulic parameters

Total river flow was measured at the Guilhot HPP, located 12 km upstream of the Pébernat intake, with no major tributary

in between. Therefore, the total river flow at the Pébernat intake Q_{tot} (hourly time-step) was considered equal to that at the Guilhot HPP, considering a transfer time of 2 h. The intake discharge Q_{int} (hourly time step) was determined using power production and waterhead data from the Pébernat HPP, located 4.7 km downstream of the dam, considering a transfer time of 1 h. The bypass discharge Q_{byp} is automatically regulated according to reservoir level, with a constant value of $2 \text{ m}^3 \cdot \text{s}^{-1}$.

Given the possible attractivity of the BTG route when open, an ultrasound level probe (Ijinus[®]) was installed immediately downstream (Fig. 1) to measure opening events (water level (WL) with 1 min time-step) and to assess spilled discharge. During the period from April 18 to May 12, 2017, BTG discharge (Q_{BTG}) was computed using the discharge measured in the river bypassed stretch ($Q_{byp \text{ stretch}}$) (see Fig. 1B), and given that the legal minimum flow of $4.49 \text{ m}^3 \cdot \text{s}^{-1}$ was the only discharge delivered at the main dam (Q_{dam}) ($Q_{BTG} = Q_{byp \text{ stretch}} - Q_{dam} - Q_{byp}$). Then, the relationship $WL \sim Q_{BTG}$ was established and applied to predict Q_{BTG} for all the study period. Since WL measurement downstream of the BTG was not precise due to strong water turbulence at the measuring location, Q_{BTG} was transformed into qualitative discharge classes to equalize fish passage numbers between classes with the BTG open; when the BTG was closed, a value is 0 was assigned. For silver eels, the following Q_{BTG} classes were

Table 1. Mean head-loss (HL) on four rack sections (see Fig. 2A) and proportion of whole tracking period, of eel and smolt passages (only 2nd campaign available for smolts) with >0.1 m head-loss (HL) differences between adjacent rack sections. Note: missing data for 1st smolt campaign, see Suppl. Materials.

Period	Mean HL (m) ±SD	>0.1 m HL differences between adjacent rack sections				>0.1 m HL differences between ≥2 adjacent rack sections
		S1-S2	S3-S4	S2-S3	S3-S4	
Whole tracking period	0.39 ± 0.26	0.41 ± 0.26	0.42 ± 0.26	0.39 ± 0.26	8.9%	12.5%
Eel passages (n = 44)	0.58 ± 0.29	0.60 ± 0.29	0.58 ± 0.30	0.56 ± 0.29	0%	0%
Smolt passages (2nd campaign) (n = 60)	0.22 ± 0.07	0.24 ± 0.07	0.25 ± 0.07	0.19 ± 0.07	18.3%	18.3%

used: [0;10] ($n=8$; 38%), [10;60] ($n=6$; 29%) and [>60] ($n=7$; 33%); and for smolts: [0;16] ($n=16$; 18.4%), [16;26] ($n=22$; 25.3%), [26;36] ($n=26$; 29.9%) and [>36] ($n=23$; 26.4%) (where n =the total number of fish in each class and %=(n over the number of all detected fish) × 100).

The Pébernat site, with a clean rack, is already close to the maximum recommended value for normal velocity ($0.5 \text{ m}\cdot\text{s}^{-1}$, the threshold value preventing fish impingement and passage through the rack; Courret and Larinier, 2008). However, variable clogging can increase this velocity in parts of the rack, due to loss of the filtering surface area, and be detrimental for fish protection. To survey this parameter, 5 other ultrasound water level probes (Ijonus[®]) were installed, 1 in the intake (upstream of the rack) and 4 in each of the subsections of the intake channel (downstream of the rack, Fig. 1). These data enabled calculation of head-loss (HL, measure of rack clogging by debris) through each sub-section in order to assess hydraulic conditions along the rack. A summary of the available data is presented in Sup. Material.

2.4 Data analysis

Following Calles *et al.* (2021) and based on the European standard “Water quality – Guidance for assessing the efficiency and related metrics of fish passage solutions using telemetry” (CEN, 2021), 3 metrics were computed: overall impediment passage efficiency (P_{ip}), FDPS-specific efficiency (P_{FDPS}), and passage time (P_t). However, due to site specificities and installation issues, overall impediment efficiency (P_{ip}) was adapted as follows:

$$P_{ip} = \frac{n_{dam} + n_{BTG+Bp}}{n_{tot}} \times 100,$$

where n_{dam} is the number of fish passing the main dam (detected at antenna R in the bypassed river stretch), n_{BTG+Bp} the number passing through the BTG or bypass (detected at antenna P in the discharge canal), and n_{tot} the number approaching the impediment, computed as the sum of the number of fish approaching the intake ($n_{Aintake}$, detected at E antennas) and passing the dam (n_{dam}). Given the short and shallow impoundment upstream of the HPP dam, the short passage times (see Results section) and no back-and-forth movements between the impoundment and the upstream river section recorded by manual tracking or the E antennas during the study, we considered n_{tot} to be a good descriptor of the number of fish approaching the impediment.

FDPS-specific efficiency (P_{FDPS}) was calculated as:

$$P_{FDPS} = \frac{n_{BTG+Bp}}{n_{Aintake}} \times 100,$$

BTG passages (n_{BTG}) were included in the P_{FDPS} computation, as the BTG is an integral part of the FDPS configuration. FDPS failure could occur if the fish turned back upstream (with no more passage attempts through the bypass/BTG) or passed through the protection rack into the intake canal.

P_t was computed as the time between the first fish detection at the E antennas and the maximum detection signal in the discharge channel (antenna P) or in the intake channel

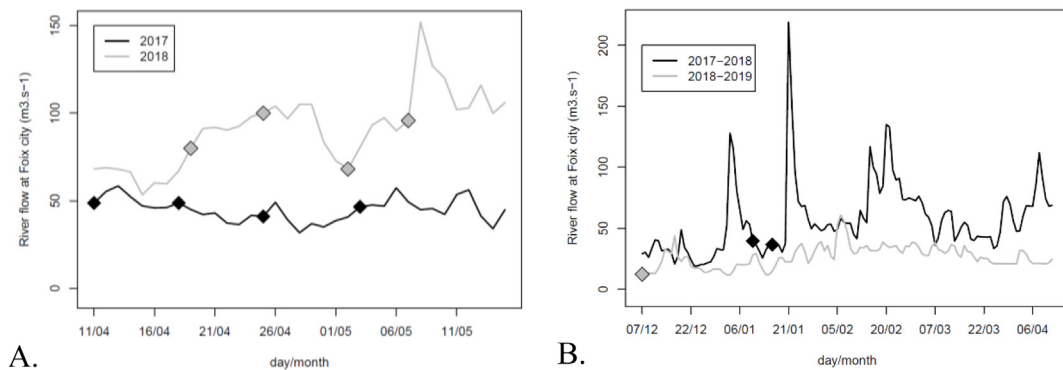


Fig. 3. River flow ($\text{m}^3 \cdot \text{s}^{-1}$) of the Ariège River at Foix during the salmon smolts (A) and silver eel (B) studies.

(antenna C), depending on the passage route. Passages when the HPP was stopped or operating at very low capacity ($<10 \text{ m}^3 \cdot \text{s}^{-1}$) were omitted.

Preliminary analyses ruled out logistic and log-normal linear models including several biological and environmental variables: the models were either poorly fitted or too sensitive to influential observations. For this reason, we chose simple statistical tests to analyze the available data. The potential effect of year, BTG opening and discharge class on passage route distribution was assessed with χ^2 tests. The Mann-Whitney test was used to compare the total length of fish passing through the bypass/BTG versus the rack, and to compare passage times between release campaigns. The effect of BTG discharge class on passage time was analysed with ANOVA, followed by Tukey HSD test, after log-transformation of raw data to normalize the distribution of residuals. For analyses using BTG discharge at passages, only passage times less than 120 min were considered, in order to have representative hydraulic parameters during a passage, BTG discharge being liable to change if the passage period was too long; 16 out of the 110 available passage times were thus removed.

Mean head-loss on the rack during smolt and eel passages was computed for the 4 rack subsections. Spatial heterogeneities were assessed by comparing adjacent rack sections (S1–S2, S2–S3, S3–S4) and screening for occurrence of 0.1 m differences in head-loss. Then, these occurrences were computed during the whole tracking period (% time) and during smolt and eel passages (% passages). The threshold of 0.1 m difference was set according to expert opinion for its likelihood of generating significant hydrodynamic heterogeneity.

All statistical tests were performed using R software (R Development Core Team, 2018), implemented with the MASS, ggplot2, Hmisc and corplot packages.

3 Results

3.1 Hydrology and hydraulic conditions along the rack

During both smolt and eel studies, hydrological conditions varied greatly between years (Fig. 3). During the smolt study period, mean daily discharge varied between 31 and $59 \text{ m}^3 \cdot \text{s}^{-1}$ in 2017 and between 68 and $152 \text{ m}^3 \cdot \text{s}^{-1}$ in 2018: *i.e.*, the HPP

was at about full capacity, with almost no spilling through the BTG in 2017, whereas the BTG was frequently open in 2018. Mean daily discharge during the eel study period varied between 25.6 and $219 \text{ m}^3 \cdot \text{s}^{-1}$ during the first winter, and between 11.7 and $60.9 \text{ m}^3 \cdot \text{s}^{-1}$ during the second.

During floods or for maintenance, the HPP turbines were sometimes stopped and the intake gates were usually closed. No turbine shutdowns happened during the first smolt campaign in 2017. From January 10 (beginning of 1st eel campaign) to May 15, 2018 (end of 2nd salmon smolt campaign), the turbines were stopped for 133 h. From December 7, 2018 to February 15, 2019 (2nd eel campaign), the turbines were stopped for 70 h.

Mean hourly head-loss (HL) on the 4 rack sections was usually high (Tab. 1), at about 0.4 m on each rack section, and higher during eel than salmon smolt passages (0.56–0.6 m for eels and 0.19–0.25 m for salmon smolts). Larger HL differences (>0.1 m) between rack sections, increasing the risk of hydraulic heterogeneities on the rack and potentially impairing FDPS efficiency, were detected 12.5% of the time, most frequently between S3 and S4. There were no >0.1 m HL differences during eel passages. However, there were >0.1 m HL differences between at least 2 adjacent rack sections for 18.3% of smolt passages, all concomitant with $>120 \text{ m}^3 \cdot \text{s}^{-1}$ total river discharge.

3.2 Fish passage route and FDPS efficiency

3.2.1 Salmon smolts

115 salmon smolts (total length (TL)=159–190 mm) approached the study site. Very few dam passages were recorded (2 in 2017, 3 in 2018), whereas 110 individuals entered the HPP intake. In total, 98 salmon smolts were successfully protected by the angled rack and crossed the HPP complex through the BTG or the bypass. Only 12 individuals crossed the angled rack and continued their migration through the HPP. The majority of individuals entering the HPP intake passed via the BTG (73/110). The proportion of fish passing through the BTG was higher in 2018 ($\chi^2=31.7$, $p < 0.001$) when hydrology was high. In periods with open BTG, 73% of individuals chose this route, versus 19% swimming through the bypass and 8% through the rack. When the BTG was closed, passages were more equally distributed between turbines and bypass (7 and 5 through bypass and turbines, respectively). The difference in turbine passage according to BTG opening

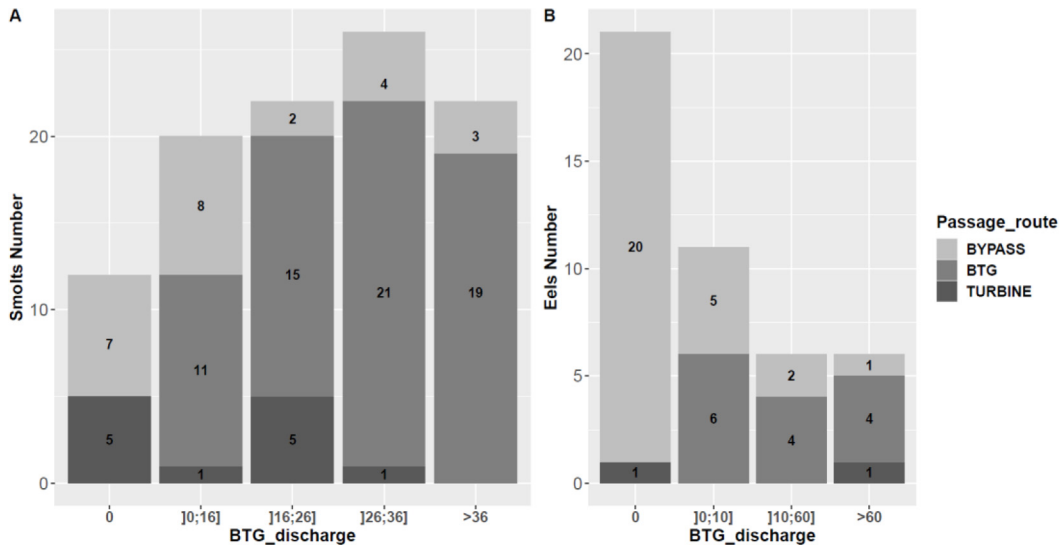


Fig. 4. Passage route distribution according to bear-trap gate discharge class (m³.s⁻¹) for salmon smolts (A) and eels (B).

Table 2. Number of smolts according to passage route. Proportions in brackets refer to intake approaches. P_{FDPS} and P_{ip} (FDPS specific and impediment efficiencies) are shown.

Year	Release group	Impediment approach	Dam passage	Intake approach	Turbine passage	Bypass passage	Bear Trap Gate	P_{FDPS}	P_{ip}
2017	1	8	0	8	0	1	7	100%	100%
	2	7	0	7	2	3	2	71.4%	71.4%
	3	22	1	21	6	7	8	71.4%	72.7%
	4	15	1	14	4	7	3	71.4%	73.3%
TOTAL		52	2	50	12 (24%)	18 (36%)	20 (40%)	76%	76.9%
2018	1	22	1	21	0	2	19	100%	100%
	2	16	0	16	0	1	15	100%	100%
	3	9	0	9	0	1	8	100%	100%
	4	16	2	14	0	3	11	100%	100%
TOTAL		63	3	60	0 (0%)	7 (11.7%)	53 (88.3%)	100%	100%
TOTAL		115	5	110	12 (10.9%)	25 (22.7%)	73 (66.4%)	89.1%	89.6%

was significant ($\chi^2=8.68, p < 0.01$) and, when open, BTG discharge class significantly impacted passage route distribution ($\chi^2=16.78, p < 0.05$; Fig. 4): the greater the discharge through the BTG, the more often smolts used it and the fewer passed through either the bypass or the rack.

Individuals crossing the 20 mm bar spacing rack were smaller (mean TL = 169 mm) than those going through the bypass or BTG (mean TL = 176 mm; Mann-Whitney $W=875.5, p < 0.01$). Finally, FDPS passage efficiency (P_{FDPS}) at the Pébernat site were 76% in 2017, 100% in 2018, and 89.1% taking both years together (Tab. 2). Overall impediment efficiency (P_{ip}) showed very similar values (76.9%, 100% and 89.6%, respectively). Total P_{FDPS} and P_{ip} both differed significantly between 2017 and 2018 ($\chi^2 P_{FDPS}=13.79, p < 0.001$; $\chi^2 P_{ip}=13.86, p < 0.001$).

3.2.2 Silver eels

In total, 65 silver eels (TL = 549–955 mm) approached the study site (Tab. 3). Twenty-one passed through the dam, 2 through the angled rack, 28 through the bypass and 14 through the BTG. The 2 eels that passed through the rack were 630 and 686 mm long with head width of 23.7 and 25.8 mm, respectively. One eel entered the HPP intake zone but turned back and finally passed through the dam. When the BTG was open (and information was available), this route accounted for 60.9% of passages, versus 34.8% and 4.3% for bypass and turbine passages, respectively. When the BTG was closed, the bypass accounted for 95.2% of passages. Finally, P_{FDPS} was 93.5% in 2017–2018 (with $P_{ip}=94.3%$), 92.9% in 2018–2019 (with $P_{ip}=100%$), and 93.3% ($P_{ip}=96.9%$) taking both years together.

Table 3. Number of silver eels according to passage route. Proportions in brackets refer to intake approaches. P_{FDPS} and P_{ip} (FDPS specific and impediment passage efficiency) are shown.

Campaign	Impediment approach	Dam passage	Intake approach	Turbine passage	Bypass passage	Bear trap gate	P_{FDPS}	P_{ip}
2017/2018	35	4	31	2 (6.4%)	15 (48.4%)	14 (45.2%)	93.5%	94.3%
2018/2019	30	16 + 1*	14	0 (0%)	13 (92.9%)	0 (0%)	92.9%	100%
TOTAL	65	20 + 1	45	2 (4.4%)	28 (62.2%)	14 (31.1%)	93.3%	96.9%

* One individual approached the intake but finally passed through the dam.

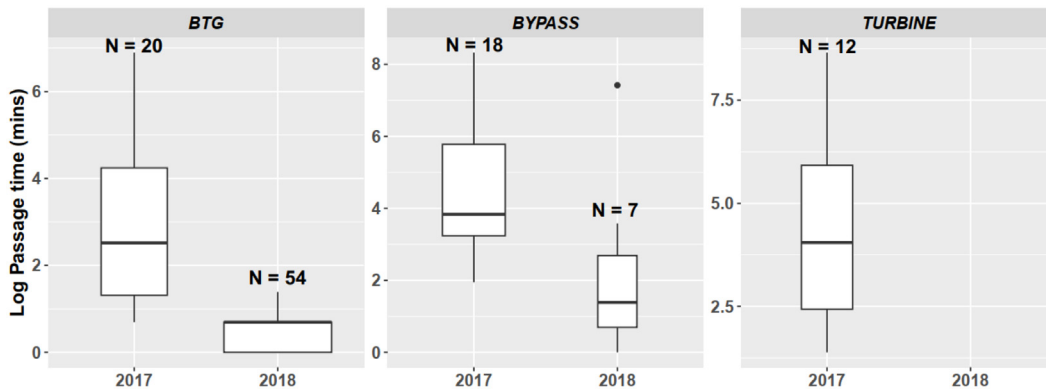


Fig. 5. Salmon smolt log-transformed passage time (minutes) according to passage route and study year. Note that the Y-axis scale differs between plots.

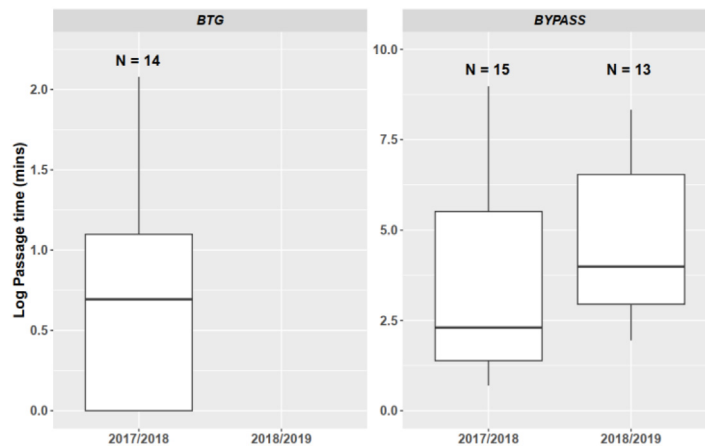


Fig. 6. Silver eel log-transformed passage times according to year and passage route (turbine route removed, with only 2 individuals). Note that the Y-axis scale differs between plots and 3 outliers were removed (with bypass passage times >50,000 min).

3.3 Passage time

3.3.1 Salmon smolts

For both years, overall median passage time (P_t) through the Pébernat site (independently of passage route) was 3 min, with 36, 2 and 58 min for median P_t through the bypass, BTG and turbines, respectively. P_t was always faster in 2018 than in 2017 for bypass and BTG passages (Fig. 5; Mann-Whitney, $p_{bypass} < 0.05$, $p_{BTG} < 0.001$).

ANOVA on log-transformed P_t confirmed that BTG discharge class also significantly impacted passage time (ANOVA, $F=5.47$, $p < 0.001$; Fig. 7). Model coefficients were more strongly negative the higher the BTG discharge, indicating that P_t decreased as BTG discharge increased ($\alpha_{BTG [0;16]} = -1.69$, $\alpha_{BTG [16;26]} = -2.17$, $\alpha_{BTG [26;36]} = -2.5$, $\alpha_{BTG >36} = -2.26$). All open-BTG discharge classes differed significantly from the zero-discharge class (Tukey HSD; $p_{BTG [0;16]} < 0.05$, $p_{BTG [16;26]} < 0.01$, $p_{BTG [26;36]} < 0.001$,

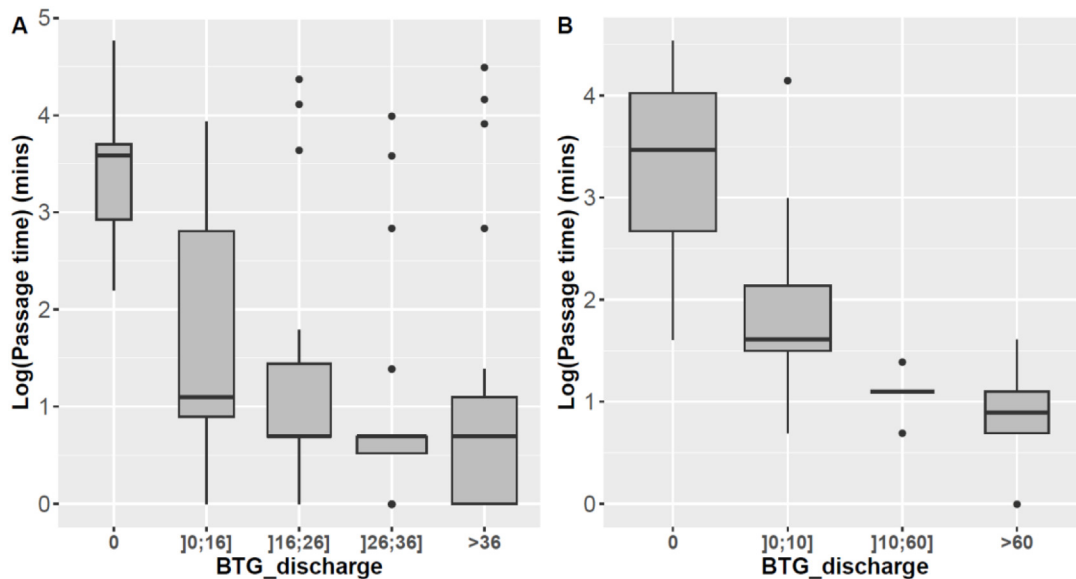


Fig. 7. Log-transformed passage time according to BTG discharge range ($\text{m}^3 \cdot \text{s}^{-1}$) for salmon smolt (A) and silver eel (B) passages.

$p_{\text{BTG} > 36} < 0.01$), but with no significant differences in passage time between open-BTG discharge classes.

3.3.2 Silver eels

Taking both years together, overall median Pt through the Pébernat site was 7.5 min, and median Pt was 47 and 2 min through the bypass and the BTG, respectively. Pt for the 2 individuals that crossed the rack was 4 and 92 min, respectively. Pt s were faster in 2017–2018 than in 2018–2019 for bypass passages (Fig. 6; Mann-Whitney, $p_{\text{bypass}} < 0.05$).

A linear model on log-transformed Pt confirmed that BTG discharge class also significantly impacted passage time (ANOVA, $F = 15.75$, $p < 0.001$). Similarly to those for salmon smolts, model coefficients were negative ($\alpha_{\text{BTG } [0;10]} = -1.38$, $\alpha_{\text{BTG } [10;60]} = -2.23$, $\alpha_{\text{BTG } > 60} = -2.44$) and significant (Tukey HSD: $p_{\text{BTG } [0;10]} < 0.01$; $p_{\text{BTG } [10;60]} < 0.001$; $p_{\text{BTG } > 60} < 0.001$), showing that Pt decreased as BTG discharge increased.

4 Discussion

The effectiveness of an angled fine-spaced rack (20 mm with vertical bars) in protecting salmon smolts and silver eels and guiding them to a surface bypass was assessed in a medium-sized HPP, with a higher intake capacity than in the majority of previous studies (Havn *et al.*, 2018; Nyqvist *et al.*, 2018; Tomanova *et al.*, 2018, 2021, 2023; Økland *et al.*, 2019; Calles *et al.*, 2021; Kjærås *et al.*, 2023). Globally, impediment passage efficiency (89.6% and 96.9% for salmon smolts and eels, respectively), FDPS specific passage efficiency (89.1% and 93.3%), and passage times (median 3 and 7.5 min) were very satisfying, although, admittedly, high hydrological conditions favored passage (Ben Jebria *et al.*, 2021). This also reflects a great improvement in fish protection, as salmon smolt passage efficiency in the former FDPS (bypass

associated to a conventional trash-rack with 45 mm bar spacing) was 64.7% (Lauters and Segura, 1998).

4.1 Comparison with similar FDPSs

The efficiency of the Pébernat FDPS was equal to or better than in other efficiency tests on fine-spaced angled racks and a surface bypass. The configuration most similar to that of the Pébernat site is that of the Herting HPP in Sweden with an intake capacity of $40 \text{ m}^3 \cdot \text{s}^{-1}$, 15 mm bar spacing rack and a bypass composed of a surface notch and a bottom orifice. FDPS efficiency was between 70–95% for salmon smolts (Nyqvist *et al.*, 2018) and 69%–72% for silver eels (Calles *et al.*, 2021; Kjærås *et al.*, 2023), with additional passages through the nature-like fishway, achieving high impediment passage efficiency (84% and 95%–100%, for smolts and eels, respectively). On a smaller HPP ($30 \text{ m}^3 \cdot \text{s}^{-1}$), equipped with a 20 mm bar spacing angled rack and a surface bypass, Tomanova *et al.* (2018) reported very similar efficiency values (87%) for salmon smolts.

Our study confirmed that silver eels can efficiently use a surface bypass (62.2% of total passages) when physically blocked and guided by an angled rack. We also highlighted the great benefit for fish protection of an alternative safe passage route, like the BTG, which accounted for 66.4% and 31.1% of smolt and eel passages, respectively. This point was already mentioned in several studies with alternative passage routes, such as upstream fishways (Nyqvist *et al.*, 2018; Calles *et al.*, 2021; Kjærås *et al.*, 2023), spillways (Nettles and Gloss, 1987) or undershot sluice gates (Egg *et al.*, 2017).

4.2 Performance with closed BTG

When the BTG was closed, FDPS performance was much poorer for salmon smolts, with bypass passage rates of around 58%, whereas silver eels showed high bypass passage (rates of 95%, Fig. 4). However, although the salmon smolt passage rate

appears very low, there is a lot of uncertainty, as it was based on only 12 individuals (Fig. 4).

Passage times (P_t) were longer for both species (median, 79.5 and 83 min for salmon smolts and eels, respectively) than those recently reported by Tomanova *et al.* (2021 and 2023) for inclined fish-friendly racks (median, 1–2 min. for salmon smolts, and 2 min. for eels). These differences can partly be explained by the location of the radiotracking antennas used for P_t computation, with a greater distance between the intake entrance antenna (E) and the bypass antenna in the Pébernat site (≈ 60 m) than in the sites studied by Tomanova *et al.* (2021) (12.5–19 m). Another explanation is the larger size of the intake zone, requiring longer search behavior to find a passage route, as previously reported for salmon smolts in other studies (Ben *et al.*, 2021; Ben Jebria *et al.*, 2021; Renardy *et al.*, 2023). Several other reasons, linked to bypass location and hydraulic conditions on the rack may, however, also explain this poorer performance. Firstly, with an angled rack, fish are guided toward the downstream end, where a full-depth bypass entrance should ideally be positioned (Courret and Larinier, 2008; Larinier *et al.*, 2020). However, structural factors at the Pébernat intake led to a suboptimal bypass position (approximately 6 m downstream from the rack end), and design (a wide but shallow entrance), perhaps making the bypass less attractive. Fish were not guided vertically toward the surface bypass, which they may have taken longer to find, resulting in longer P_t . Silver eels swim more frequently close to the bottom third of the rack (Kjærås *et al.*, 2023), and, it would be preferable to create a full-depth bypass entrance, or at least a deeper surface entrance (Courret and Larinier, 2008; Larinier *et al.*, 2020). Secondly, a 20 mm angled rack acts as a behavioral barrier for salmon smolts, which are more sensitive than eels to hydraulic conditions (*i.e.*, normal and tangential velocities). Hydraulic conditions at the Pébernat rack were frequently impacted by the inefficiency of the rack cleaning system: an excessively long cleaning cycle and poor debris collection resulted in heterogeneous rack clogging and spatial variations in head-loss (Tab. 1). This may lead to variations in tangential velocity along the rack and normal velocities that could locally exceed the recommended maximum of 50 cm. s⁻¹. Detrimental upwelling currents were also observed in the zone between the rack and the bypass entrance. These two factors may impair guidance toward the bypass entrance and increase the risk of fish impingement and passage through the rack. The Pébernat rack cleaner is clearly unsatisfactory, penalizing both energy production and fish protection. Equal attention needs to be paid to both rack design (profiled bars and supports) and the cleaning system (cycle duration, rake with teeth entering between bars) (David *et al.*, 2022).

Unlike salmon smolts, the bypass passage rate for eels was high even when the BTG was closed, despite the sub-optimal design of the shallow bypass and the disturbed hydraulic conditions. Silver eels are known to be able to force their way through a rack, and passages through a 20 mm rack are theoretically possible for eels smaller than 714 mm (Calles *et al.*, 2013). In our study, the two eels that passed through the rack were 630 and 686 mm long, but 79% of eels detected at the intake (and 73% when the BTG was closed) were smaller than 714 mm. We therefore conclude that the 20 mm angled rack acted as not only a physical but also a behavioural barrier,

and effectively blocked silver eels longer than 550 mm (Courret and Larinier, 2008).

4.3 Particular configuration of the Pébernat intake and role of river flow

Pébernat's fish-friendly intake has a particular configuration because of the BTG, which is close to the rack and perpendicular to the main flow direction (Figs. 1 and 2B). It is used as the first spillway, and thus can be very attractive for downstream-migrating fish. The predominant role of the BTG in the approach and passage behaviour of both species was clearly proved in our study (Fig. 4, Tabs. 2 and 3): the attractiveness of this passage route increased with its discharge rate, shortening passage times. This was particularly true for salmon smolts, for which the probability of rack passage increased in the absence of BTG spill. The river discharge data (available at <https://hydro.eaufrance.fr/>) show that this passage route was frequently open, and always when total river flow exceeded 56.5 m³.s⁻¹. Thus, during the smolt migration period (March 1 to May 15) over the period 2003–2022, the BTG spilled about 55% of the time on average (between 100% and 10% of the time, depending on the year). Similarly, during the eel migration period (September 1 to March 31), BTG spilling frequency was about 15% on average. This may seem low, but the BTG is likely to be spilling during nearly all eel migration events, which occur mostly at peak flow (Durif *et al.*, 2003; Travade *et al.*, 2010). The BTG is thus an integral and important part of the fish protection system at the Pébernat site. This shows how FDPS can benefit from existing spillways, and this possibility should be investigated during the design process to enhance FDPS performance (especially if not all design criteria can be respected, as in the case of Pébernat).

Due to its particular configuration, and probably to its inefficient cleaning system, the performance of the Pébernat FDPS was lower when the BTG was closed due to low flow in the river. Under the usual hydrological conditions of the Ariège River, low-flow conditions are not very common during smolt and eel downstream migration periods and successful migration should not be affected. Nevertheless, the fact that FDPS efficiency depends on spilling requires stakeholders to pay attention to future changes in river hydrology and to adopt a more precautionary approach in designing passage solutions in the context of climate change.

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Supplementary Material

The Supplementary Material is available at <https://www.kmae.org/10.1051/kmae/2023020/olm>.

Table 1. Biometrical characteristics of tagged smolts and eels, release dates and points (with the number of HPPs to cross before reaching Pébernat HPP).

Table 2. Hydraulic parameters used in the study, acquisition time and availability periods.

Figure 1. Picture of Pébernat fine-spaced rack during construction.

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