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Research article

Protecting the downstream migration of salmon smolts from hydroelectric power plants with inclined racks and optimized bypass water discharge

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ABSTRACT

The sustained development of hydropower energy in the last century has caused important ecological impacts, promoting recent advances in efficient mitigation measures to be implemented in existing and future hydropower plants. Although upstream fish migration has been largely addressed with the development of fish-pass infrastructures, downstream passage solutions are often missing or inefficient, strengthening the need for their improvement and efficiency assessment. The efficiency of horizontally inclined (26°) low bar spacing racks associated to a bypass was assessed using salmon smolts radiotelemetry along three successive hydropower plants (HPP) in the Ariège River (southern France). In average, nearly 90% of the smolts were successfully protected by the racks and rapidly guided to the bypass, within few minutes in most cases. Furthermore, we detected a significant positive influence of the bypass discharge ($Q_{bp\%}$ expressed as the proportion of concurrent HPP discharge) on the probability of successful bypass passage, reaching 85% of successful passage with a $Q_{bp\%}$ of only 3%, and more than 92% when the $Q_{bp\%}$ exceeded 5%. The probability of bypass passage without hesitation (*e.g.* passage within the first 5 min) also increased with $Q_{bp\%}$, and reached 90% with 5% of $Q_{bp\%}$. Passage without hesitation was especially detected on the site having larger bypass entrances and transversal currents, providing better guidance into the bypass. High-efficiency results of inclined racks yielded with reduced $Q_{bp\%}$ confirmed their relevance to mitigate some of the HPP ecological impacts, re-establishing safe downstream salmon migration with lower impact on energy production than older less efficient solutions.

1. Introduction

Hydropower is considered as a clean and renewable source of energy (Berga, 2016; Ranzani et al., 2018). Continued investments have led to over 90 000 hydropower plants around the world, with many thousands more expected to be implemented in the upcoming decades (Couto and Olden, 2018; Zarfl, 2015), especially in developing countries. This global expansion of hydropower plants (HPP) and related river barriers (dams) can however have important environmental costs (Moran et al., 2018), implying strong and spatially extensive upstream and downstream effects, producing deep ecosystem changes in habitat, flow, water quality, aquatic communities (see e.g. Aguiar et al., 2016; Turgeon et al., 2019; Wu et al., 2019 and related citations) and river connectivity loss (fragmentation - Fuller et al., 2015; Nilsson, 2005). Many diadromous fish species (i.e. species performing long migrations spending part of their lives in freshwater and part in saltwater) of economic importance, e.g. salmonids, sturgeons, eels, lampreys and shads, are strongly affected by river fragmentation, the decline of their populations currently reaching alarming proportions (Costa-Dias et al., 2009; Puijenbroek et al., 2019). These consequences will likely expand to other species and ecosystems facing the same threat in the near future, as dam construction keeps reducing the number of free-flowing rivers

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(Zarfl, 2015). Clearly, there is an urgent need to anticipate these ecological impacts and to develop and deploy (on new but also on existing hydropower complexes) efficient mitigation measures allowing the coexistence of economic development with biodiversity preservation (Moran et al., 2018).

Different technical solutions exist to mitigate the impact of HPP dams on fish migration. A variety of fish ladders for upstream migration (technical or natural-like, see e.g. Armstrong et al., 2010; Larinier, 1992) have been developed and tested on several fish species, with varying degrees of success (Bunt et al., 2012; Noonan et al., 2012). However these passage devices are usually unsuitable for downstream fish migration (Tomanova et al., 2018), and specific additional systems are needed. An efficient Fish Downstream Passage Solution (FDPS) must prevent fish passage through the HPP turbines (source of physical damage) and must provide an alternative and attractive way for a safe fish passage without delay. The challenge of safe downstream migration was overlooked for a long time (Fjeldstad et al., 2018) but since 2000, several guidelines have been edited (see e.g. Calles et al., 2013a in Sweden; Courret and Larinier, 2008 in France; Schwevers and Adam, 2020 in Germany; USFWS, 2019 in USA). From a variety of proposed solutions, two types of FDPS are considered as best practice for small to medium-sized HPP: angled or inclined racks with reduced bar spacing and a bypass, installed in the HPP water intake (Calles et al., 2013b; Courret et al., 2015; Fjeldstad et al., 2018; Havn et al., 2020; Økland et al., 2019; Tomanova et al., 2018). In France, 20–25 mm bar spacing racks, either horizontally inclined (<26°) or angled to the flow (<45°), with specific criteria on bypass design and position, are recommended for HPPs receiving up to 100 $m^3 s^{-1}$ water flow (Courret and Larinier, 2008). *In situ* telemetry studies, initiated in 2015 on first equipped sites with intake capacities between 3.9 and 20 $m^3 s^{-1}$, demonstrated their efficiency with 80% of successful fish passages in average (Tomanova et al., 2018). However, the efficiency of this bypass solution using angled or inclined racks needs to be tested on larger HPPs for a greater spread and implementation of this solution. Moreover, minimum levels of bypass water discharge (a key parameter for FDPS performances) needed to achieve high FDPS efficiency levels are currently based on expert opinion, lacking any quantitative evaluation. Best-practice guidance for this key parameter and the thresholds to apply, guaranteeing high efficiency levels, is needed.

Here we fill these two knowledge gaps conducting a two-year study with fish radiotelemetry at three successive HPPs (with intake capacities from 32 to 47 $m^3 s^{-1}$ during the study) recently equipped with low bar spacing inclined racks and bypass. The study was conducted on juveniles of a declining migratory species, the Atlantic salmon (*Salmo salar*) smolts, an economically important anadromous species distributed over the North Atlantic river basins (Chaput, 2012; Limburg and Waldman, 2009) and aimed by habitat restoration and protection programs in many countries (Council Directive 92/43/EEC, 1992). We assessed FDPS performances based on the rate of and time for salmon smolts safe passage through the bypass. The downstream fish passage was assessed under different flow conditions allowing to evaluate the influence of bypass discharge variability on FPDS performances. We finally compared our results with performances observed on the same sites, under previous configurations equipped with near-vertical trashracks with 30–40 mm of bar spacing and a bypass (Croze, 2008).

2. Material and methods

2.1. Study area

The study was performed during the outmigration period of Atlantic salmon smolts in 2017 and 2018 on a 6 km-long middle section of the Ariège River in southwestern France (Fig. 1). Historically, abundant salmon populations were established in the Ariège River, including this river reach, and are now strongly impacted and under a restoration program. The Ariège River originates in the Pyrenean Mountains and ends at the confluence with the Garonne River upstream of Toulouse and has a catchment area of approximately 4100 km^2. The hydrological regime is pluvio–nival, characterized by high-flow events especially during spring (snowmelt in mountains). Mean annual discharge of the Ariège River at Foix (about 10 km upstream of the study area) is 39 $m^3 s^{-1}$. Mean monthly discharges during the migration period of Atlantic salmon smolts are 42, 57, and 79 $m^3 s^{-1}$ during March, April, and May respectively (established from 116 years of data available on http://h

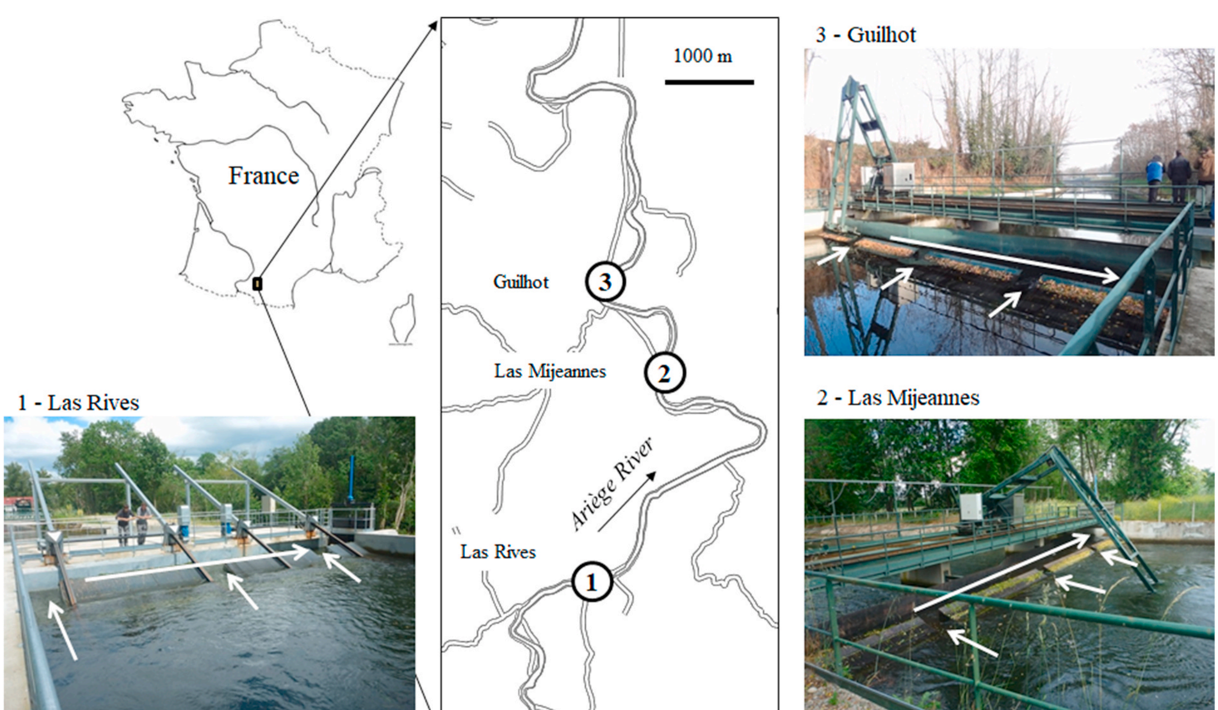

Fig. 1. Study area with HPP location and fish protection racks with bypasses (white arrows indicate entrances and bypass, see site coordinates in the text).

ydro.eaufrance.fr).

2.2. Studied HPP intakes

The study was performed on three run-of-river HPPs (Fig. 1) constructed on diversion channels and grouped on the same river reach, with mean water intake discharges between 32 and 47 $m^3 s^{-1}$ during the study (Table 1): 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). Las Mijeannes is located 4.2 km downstream from Las Rives, and Guilhot 1.7 km downstream from Las Mijeannes. All HPPs are equipped with upstream fish passes at the dam and with recently constructed FDPS at the beginning of the intake channels: inclined (26° from the horizontal) low bar spacing (20 mm) racks with bypass (3 surface entrances), following the recommendations of Courret and Larinier (2008). Each rack is equipped with a mechanical trash cleaner with debris evacuation into the bypass. There are some slight differences in bypass dimensions among sites (Table 1). Bypass entrances are shallower at Las Rives with a minimum water depth of 0.5 m, while Las Mijeannes and Guilhot have 0.7 and 0.65 m depth respectively. Bypass entrances at Las Rives are wider (1.0 m per entrance, Fig. 2) representing in total 21.4% of rack width, compared to 10% at Las Mijeannes (0.72 m per entrance) and 11.4% at Guilhot (0.57 m per entrance). Another feature of Las Rives is that the space between bars is completely sealed at the upper part of the rack, from the top of the rack to the bottom of the bypass entrances, decelerating the flow between the entrances and generating transversal currents (Fig. 2). This rack modification intended to improve the fish guidance through the flow into the bypass entrances. Design bypass discharge, expressed as a ratio to concurrent HPP discharge ($Q_{bp\%}$), was fixed to a minimum of 3% by French authorities. Controlled by a fixed weir placed at the downstream end of the gallery connecting the bypass entrances, $Q_{bp\%}$ can however vary and be lower or greater depending on the HPP functioning and on the river discharge (Q_{bp} increases with water level elevation). During the study (April–May months), the $Q_{bp\%}$ in the studied sites was in average between 3.4% and 3.6% in 2017, and between 3.9% and 7.3% in 2018 (Table 1). Discharge levels on the river section bypassed by the hydroelectric facility (Fig. 3) reach at least 10% of the mean annual discharge of the river, and even more during spilling events.

2.3. Radio transmitters and antenna array

We used pulsecoded radio tags transmitters developed by ATS® (Advanced Telemetry Systems; model F1720) with a 20 cm external antenna. The tag, including the battery, was 8 mm diameter and 20 mm long, and weighed 2 g. With 45 pulsations per minute, the battery lifetime was at least 7 days functioning in the field with the most energy-saving codes. For this reason, the monitoring at each site lasted only one week after fish release.

At each site the antenna arrays were designed to monitor all possible passage ways (through the bypass, turbine, and dam), with several underwater (in small zones) or aerial (large zones) antennas (Fig. 3). Fish *Entrance* into the HPP water intake was detected with antenna E. Bypass zones, with higher water speed and turbulence, were equipped with two antennas to secure fish detections: A – detecting fish *Approach* (located upstream the discharge control weir in the bypass), P – confirming fish *Passage*. Fish passing through the protection rack were detected with the antenna C in the intake *Channel*. Finally, fish passing over the dam, were detected with the aerial antenna R in the *River* section, downstream of the dam. When individuals occur in a detection zone, the corresponding antenna recorded the tag ID, date and time (hh:mm) along with the maximum signal listen and the pulse count received during 1 min record. Complementary manual radiotracking with a mobile antenna was conducted 2–3 times a week to check tag status (on/off) and confirm fish movements within the studied river reaches, confirming ~100% detection probability for all antennas.

2.4. Fish tagging and release

The study was conducted with hatchery Atlantic salmon smolts provided by the MIGADO association (Migrateurs Garonne Dordogne Charente Seudre; www.migado.fr). The nearby location of the studied HPPs on the same river reach allowed reducing the number of fish individuals needed (i.e. individuals travelling through the study reach contributed to the evaluation of several sites). The fish were transported upstream of the study section, stocked in holding tanks, tagged and released the same day.

Prior to handling and tagging, each fish was anaesthetized 3–5 min in a bath with clove oil. Once loss of equilibrium was attained, total length (*TL* in mm) and weight (wet weight in grams) were recorded. For gastric implantation of transmitters, fish was held in a shallow tray of water with the dorsal side upward. The transmitter was carefully inserted into the mouth using a 10 cm plastic tube (diameter: 5 mm) and gently pushed into the anterior portion of the stomach. The external antenna, coated in a flexible plastic material, was passed out through the gill cavity. This tagging procedure lasted less than 45 s. Tagged fishes were then stocked into the holding tanks at least 4 h before release, supplied with water from the Ariège River and under reduced light conditions limiting fish stress.

In total, 174 individuals were tagged and released, 74 in 2017 and 100 in 2018. This sample size was defined to ensure a robust efficiency analysis with a low margin of error, assuming that not all individuals will be detected during the survey at each site (e.g. because of short fish survey, fish predation or migration stops). For instance, this margin of error would be 7% with only 100 individuals presented in front of each FDPS, and a hypothesized efficiency of 85% (similar to the efficiencies observed by Tomanova et al. (2018); margin error estimated under a confidence level of 0.95 with the *nsize* function from the PASWR R package (Arnholt, 2012)). Mean *TL* was 173 mm (min – max: 159–187 mm) in 2017 and 175 mm (min – max: 161–190 mm) in 2018, ensuring full comparability in size between the two study years. The tag represented 4% of the fish body weight on average (between 3.3% and 5.6%),

Table 1
HPPs discharges during the study and details on the studied fish downstream passage solutions.

	HPP intake discharge	Fish protection rack (horizontally inclined at 26° with 20 mm of bar spacing)				Bypass entrance				Bypass discharge
	Q_{HPP}[a]	width	water depth	submerged surface	normal flow velocity[b]	number	width	water depth	flow velocity	$Q_{bp\%}$[a]
	($m^3.s^{-1}$)	(m)	(m)	(m^2)	($m.s^{-1}$)		(m)	(m)	($m.s^{-1}$)	(% of Q_{HPP})
Las Rives	40–47	14	4.2	117.5	0.4	3	1	0.5	0.9	3.4–3.9%
Las Mijeannes	37–44	21.6	2.6	127.2	0.35	3	0.72	0.7	0.9	3.6–6.1%
Guilhot	32–34	15	2.7	90.8	0.37	3	0.57	0.65	0.9	3.5–7.3%

[a] Mean value 2017–2018 during the study.
[b] Max velocity near the rack (ratio between the discharge and the rack area) which must not exceed 0.5 m s^{-1} to prevent fish impingement.

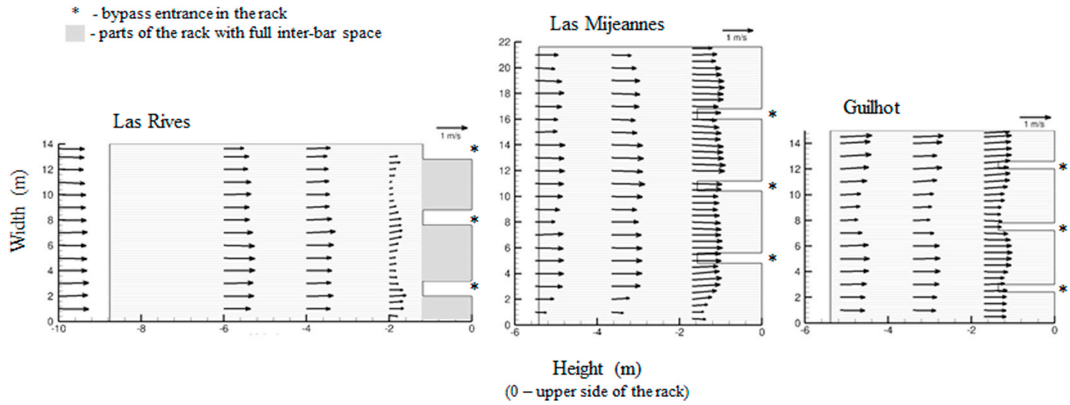

Fig. 2. Flow direction and velocity measured with Acoustic Doppler Current Profiler (ADCP) at several transects upstream from the racks (Dewitte et al., 2020; Lemkecher et al., 2018).

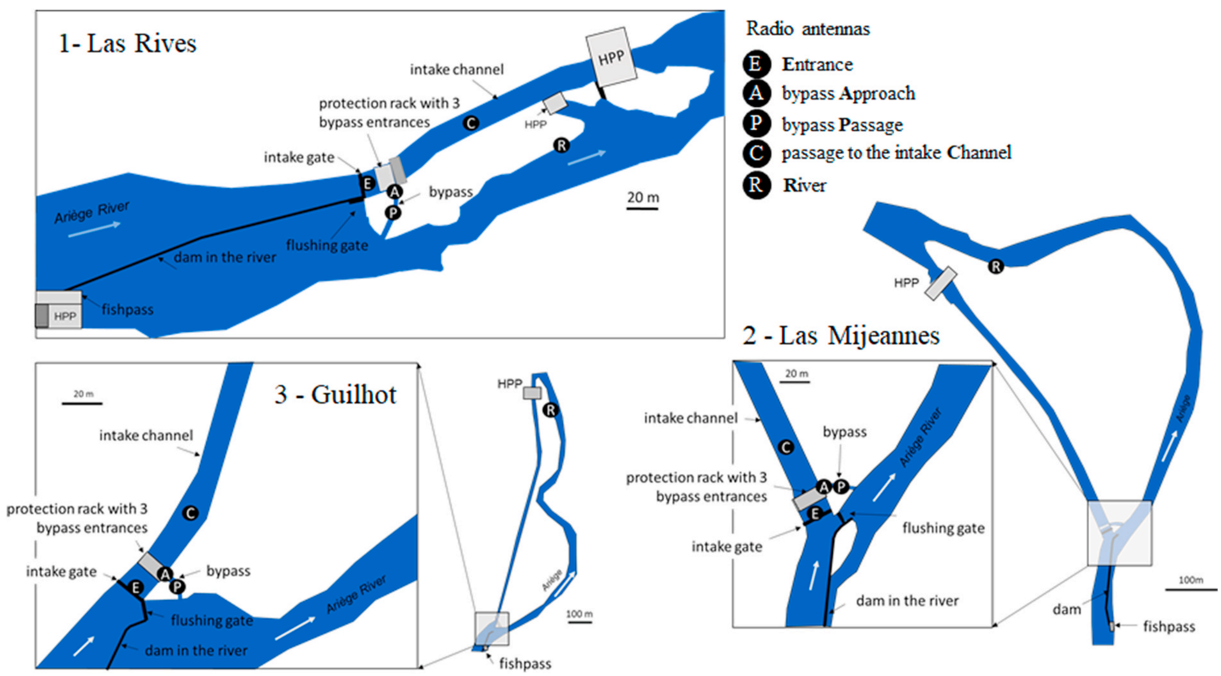

Fig. 3. Studied sites and their antenna configurations for downstream passage survey of salmon smolts.

well below the maximum recommended transmitter weight ratio to prevent transmitter-related mortality in juvenile salmonids (i.e. 5.8% of fish body mass, Hall et al., 2009). Preliminary detection tests, performed during calibration of the antenna, showed some difficulties to decode simultaneously passing tags in small and fast-flowing zones. For this reason, we limited the number of released/tracked fish at the same time to groups of 24–25 individuals with approximately one-week interval. Seven groups of fish were released during the two years. Fish were released at the beginning of the night, between 21:00 and 23:00 (UTC+2:00), about 1.5 km upstream of Las Rives, except for one group which was released 1 km upstream of Las Mijeannes HPP in 2017 to balance the number of detected fish among sites. The nocturnal time of release was set to mimic the dominant migration events of wild salmon smolts, especially during their early migration period (Ibbotson et al., 2006; Larinier and Boyer-Bernard, 1991). The study was validated by the Ethic Committee N°073 (APAFIS#13977-2017032916355870v4) to obtain the authorization of the French Ministry for Research.

2.5. Environmental conditions and HPP functioning during the study

Hydrological conditions were highly contrasted between 2017 and 2018, with lower mean daily river discharge during April–May 2017 (43 $m^3 s^{-1}$ in average) compared to the same period in 2018 (91 $m^3 s^{-1}$ in average) (Fig. 4). Water temperature variations were however very similar (9–11 °C in 2017 and 8–11 °C in 2018). During our study, all three HPPs functioned without major stops, fulfilling the minimal river and bypass discharges required. Only Las Mijeannes HPP was stopped once on May 9th, 2018 because of a serious damage on spillway near the power plant. Knowing the head water of each HPP (H in m) and the power production (Pw in W), recorded each 10 min and kindly provided by Ondulia hydroelectric company, the HPP intake discharge (Q_{HPP} in $m^3.s^{-1}$) was computed as $Q_{HPP} = Pw * (\rho * g * T_{eff} * H)^{-1}$, with $\rho = 1000$ kg m^{-3}, $g = 9.81$ m s^{-2} and turbine efficiency $T_{eff} = 0.8$ as constants. Based on a water level survey up- and downstream of the HPP water intake and topographical schemas of bypass and dam structures, the bypass (Q_{bp}) and dam (Q_{dam}) discharges (in $m^3.s^{-1}$) were computed as $Q = C_Q * w * \sqrt{2g} * h^{1.5}$, with C_Q as the discharge coefficient of sluice, w (in m) the width of the hydraulic structure (bypass or dam), and h (in m) the

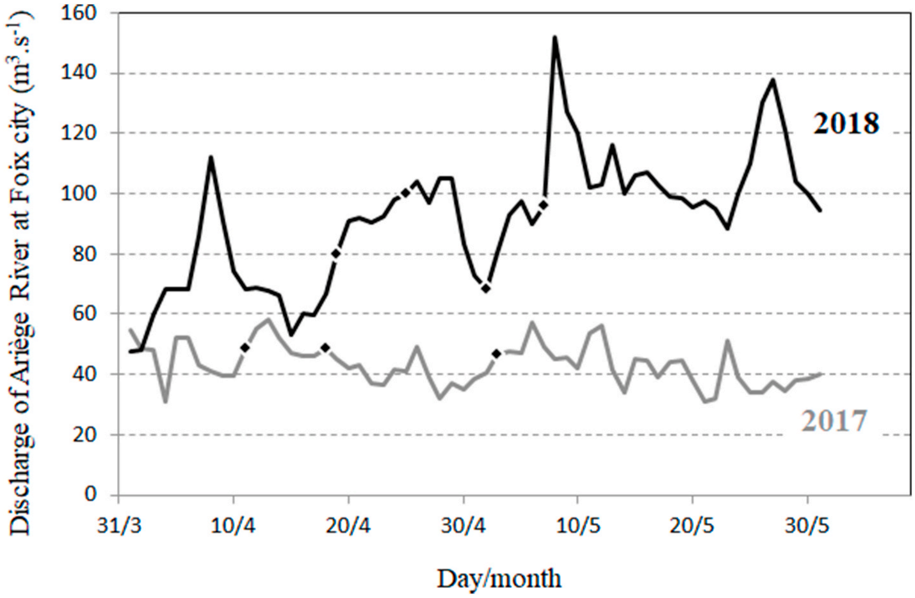

Fig. 4. Mean daily discharge of the Ariège River at Foix during the study (dots: days of fish release). The low and median discharge levels (respectively the 5 and 50 percentile flow, Q_{95} and Q_{50}) for the Ariège River at Foix are respectively 11.8 and 30.3 m^3 s^{-1} (established from 116 years of data available on http://hydro.eaufrance.fr).

water level spilling over the hydraulic structure. Finally, the river discharge (Q_{riv}) upstream of each HPP was estimated summing Q_{HPP}, Q_{bp}, Q_{dam} and the minimum river flow (considered constant and delivered through the upstream fishpass structure and a notch at the dam to the river section concerned by the water diversion). All these discharge values were available for each fish passage event. Excepting Guilhot HPP, there was no (or very limited) spilling over the dams in 2017. All flushing gates remained closed. In contrast, continuous water spilling over dams was observed in 2018 at all three sites. Flushing gates (near of HPP intakes, see Fig. 3) were frequently opened to evacuate water and sediments during flood events (always when river discharge exceeds approx. 100–120 m^3 s^{-1}). The openings of the flushing gates during floods were not recorded and discharges passing through were unknown. Consequently, high Q_{riv} values were underestimated.

2.6. Radio signals analysis

The numerous radio antennas recorded large numbers of radio signals that were subsequently inspected in detail, interpreted and converted into passage history records. The same procedure applied by Skalski et al. (2002) was used here to check the data and eliminate spurious radio signals. In summary, three criteria were used to identify valid detections: (i) the power level of the received signal, (ii) the number of signals received per unit time, and (iii) the consistency of spatial and temporal detections of the radio signals within the antenna arrays at each site. For each antenna, a minimum power threshold was specified during their calibration session, above which a signal was considered as a valid fish passage. For each site and each fish individual, multiple signals received over time and from different antennas were evaluated to determine their consistency with possible smolt movement patterns. Unclear or illogical records were excluded from the dataset (e.g. a false parasitic signal or a fish detected after bird predation). When a fish passed through the HPP turbine and stopped the migration after there (fish damaged or dead), any signal recorded *a posteriori* was eliminated.

2.7. Assessing FDPS success

Two main metrics were computed 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) successfully passing through the bypass (antennas A and P). Accordingly, FDPS failures may occur if the fish turned back upstream (with no more passage attempts) or if the fish passed through the protection rack into the turbines. Passage time (P_t) was computed as the time between the fish detection at the entrance of the HPP intake gate (first detection with antenna E) and its maximum detection signal in the bypass (antenna P) or in the intake channel (antenna C), depending on the passage way. Because these two metrics did not follow normality assumptions (Shapiro and Kolmogorov–Smirnov tests), Kruskal–Wallis or Wilcoxon tests were used to detect differences in P_{eff} and P_t among sites or years. Within each site, a Wilcoxon test was performed to analyse if P_t varied according to passage way (bypass vs turbine).

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 and without hesitation can be mediated by the bypass discharge ratio $Q_{bp\%}$ (ratio between Q_{bp} and Q_{HPP} in %), the fish total length (*TL*), and HPP specificities (*Site* as factor). To build binary response variables, bypass/turbine passages were coded as 1/0 and P_t was set to 1 if lower than or equal to 5 min (i.e. considered as passage without hesitation), and to 0 if P_t was longer (passage with some hesitation). We consider this duration as short enough to ensure successful migration, although a longer time to pass is not necessarily problematic. River discharge (Q_{riv}) was not included in the models because it is highly related to $Q_{bp\%}$ (increasing river level increases bypass discharge). These logistic models were performed using the *glm* function from R (R Core Team, 2019), and the graphics with the ggeffects (Lüdecke et al., 2020) and cowplot (Wilke, 2020) packages.

3. Results

3.1. Fish movements vs hydrological conditions

Different general patterns of fish movements were observed between 2017 and 2018, likely resulting from the contrasting hydrological conditions. In 2017, year with lower discharge levels (Figs. 4), 49% of fish individuals passed through the whole studied river section (i.e. the three

HPP complexes) within one week after release. This rate increased to 72% in 2018, year with higher discharge levels. Fish displacements were also quicker in 2018, where 75% of migrating individuals passed through the studied section within 2 h 48 min in average (min – max: 1 h–4 days), while 3 days and 2 h in average were necessary in 2017 (min – max: 4 h–6 days).

In 2017, higher proportions of migrating fish were detected at the entrance of the HPP intakes (antenna E) compared to 2018 (Fig. 5), with 91% at Las Rives and Las Mijeannes, and 85% at Guilhot. Because of the higher discharge levels and consequently increased water spilling over dams, these proportions were lower in 2018, but still remained important at Las Rives and Las Mijeannes (66% and 84% respectively). Only at Guilhot, the majority of fish crossed the HPP over the dam (antenna R) and only 33% entered into the HPP intake (antenna E). However, for all sites and years we obtained enough individuals entering the HPP intakes, to perform robust efficiency analyses (102, 114 and 53 individuals were detected at Las Rives, Las Mijeannes and Guilhot HPP intakes, respectively).

3.2. Efficiency of FDPS

After the fish individuals entered the HPP intake, no comeback was observed at any site and year. The passage efficiency (P_{eff}) of each tested fish group was never below 70%, and was in average (±SE) always higher than 87% at all sites (Fig. 6, cf. details in Supplementary Material): 88.1 ± 5% at Las Rives, 87.9 ± 3.9% at Las Mijeannes and 98.2 ± 1.8% at Guilhot HPP. No significant P_{eff} differences were detected among sites (Kruskal-Wallis test; $\chi^2 = 5.4$, p = 0.07), and years (Wilcoxon test; W = 2.8, $p = 0.1$), although the P_{eff} values were usually higher in 2018 (94.7 ± 2.5%) than in 2017 (86.7 ± 4%, Fig. 6).

Passage times (P_t) through the bypass were generally very short at all three sites (Table 2). After passing the intake gate (antenna E), 75% of fish individuals continued their migration through the bypass (antenna A and P) in less than 3, 2 and 4 min at Las Rives, Las Mijeannes and Guilhot sites respectively. A significant difference in P_t was observed among sites (Kruskal-Wallis test; $\chi^2 = 8.2$, p = 0.016) and pairwise comparisons confirmed that P_t was shorter at Las Mijeannes than at Las Rives (Wilcoxon test; W = 5177, $p = 0.02$) and Guilhot HPP (W = 1969, $p = 0.01$). Even if statistically significant, these differences were altogether marginal regarding migrating times (i.e. a few minutes). No significant difference in P_t was observed between years (W = 7868, $p = 0.1$), although the better hydrological conditions in 2018 may explain the observed difference in maximum P_t (~11 h in 2018 and ~26 h in 2017; Table 2). Concerning the fish individuals that passed through the racks and entered the turbines (antenna C), P_t was generally longer (Table 2), although the difference was significant only for Las Rives HPP (W = 202, $p < 0.001$ for Las Rives, W = 521, $p = 0.08$ for Las Mijeannes, no test was performed for Guilhot HPP due to the low number of fish entering the turbines).

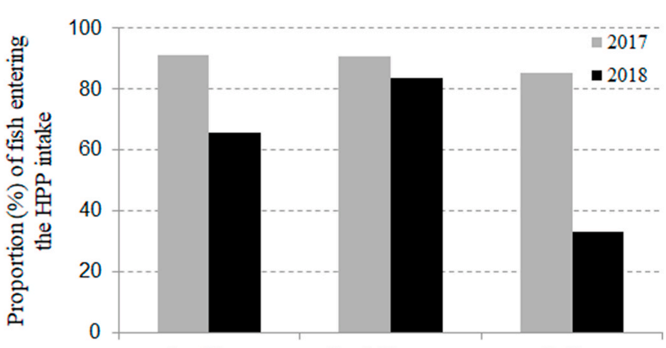

Fig. 5. Proportion of fish detected at the entrance of studied HPP intakes (antenna E) each year (100% - all detected fish crossing the HPP complex).

3.3. Key parameters influencing FDPS success

Among the three tested variables, only $Q_{bp\%}$ explained a significant part of the variability in the probability of bypass passage, with no significant contribution of fish length and Site to the model (Table 3). The bypass passage probability increased with increasing $Q_{bp\%}$ (Fig. 7) reaching 85% with a $Q_{bp\%}$ of 3% (i.e. the minimum set by French authorities), and more than 92% when the $Q_{bp\%}$ exceeded 5%. The probability of bypass passage also slightly increased with increasing fish length (Fig. 8), although this relationship was not significant (Table 3). Although the logistic regression did not capture a large portion of the variability in P_{eff} (pseudo-$R^2 = 0.08$), our results clearly show that the unexplained variability is mostly limited to low $Q_{bp\%}$ values (i.e. under 3%; Fig. 7). Similar results were observed when analysing the probability of bypass passage without hesitation (passage within the first 5 min), with a significant effect of $Q_{bp\%}$ and *Site* (Table 3; pseudo-$R^2 = 0.09$), showing that the probability of bypass passage without hesitation increased with increasing $Q_{bp\%}$ and was higher at Las Rives site (Fig. 7).

4. Discussion

Our first objective was to evaluate the efficiency of horizontally inclined (26°) low bar spacing racks with several entrances to the bypass, which is one of the two currently recommended FDPS in France. This FDPS on HPPs with intake discharge capacities between 32 and 47 $m^3 s^{-1}$ demonstrated successful and rapid fish guidance through the bypass, indicating that no significant delay is added to the fish migration by the FDPS. Our results show high efficiency, with low variability among years and sites and under varying discharge conditions, broadening previous similar findings on smaller HPPs (Tomanova et al., 2018). Comparing current FDPS performances with former passage devices (Croze, 2008), located just upstream from the power plants and evaluated under similar $Q_{bp\%}$ conditions (Fig. 8), shows marked differences in passage efficiency for all three sites (with P_{eff} average gains of 48.6% at Las Rives, 55.4% at Las Mijeannes and 27.4% at Guilhot HPP). The case of Las Rives especially highlights the performance of reduced bar spacing and rack inclination, doubling P_{eff} values even under slightly lower bypass water discharge. The numerical comparison with results obtained from smaller HPPs (Tomanova et al., 2018) shows that the high performances of inclined racks are not affected by intra- and inter-site variability (always more that 80% in average, with minimum values never below 70%; Fig. 8). A further comparison with previous efficiency studies of protection racks with different bar spacing and inclination/orientation summarized by Tomanova et al. (2018), showing a range of efficiencies from 4 to 100%, place our results among the highest bypass passage efficiencies. These findings clearly validate the FDPS tested here as an efficient tool to protect downstream migrating salmon smolts at HPPs projects with discharge capacities up to 50 $m^3 s^{-1}$.

According to Havn et al. (2018) and Persson et al. (2019), higher river discharge conditions positively influence fish migration rate and speed. In line with this importance of flood-like events for salmon smolt downstream migration, our findings also show that the FDPS efficiency and passage time are significantly influenced by bypass discharge ratio $Q_{bp\%}$. The importance of bypass inflow on bypass efficiency has already been reported by Klopries et al. (2018) reviewing efficiency studies of surface bypasses under variable FDPS configurations. Setting a threshold for $Q_{bp\%}$ to guarantee efficient downstream migration remains however an open question. Larinier and Travade (2002) suggested that satisfactory bypass discharges should vary from 2 to 10% of turbine discharge and should be adjusted for each site according to other parameters influencing bypass efficiency (e.g. bypass location, hydraulic conditions, guiding structures, trashrack bar spacing). Accordingly, these authors suggested that "the less favourable the other parameters, the greater the discharge would be needed in the bypass". For horizontally inclined low bar spacing racks, Courret et al. (2015) recommended $Q_{bp\%.}$ between 5 and 6% for HPP with $Q_{HPP} < 50$ $m^3 s^{-1}$, and between 2 and 3% for HPP

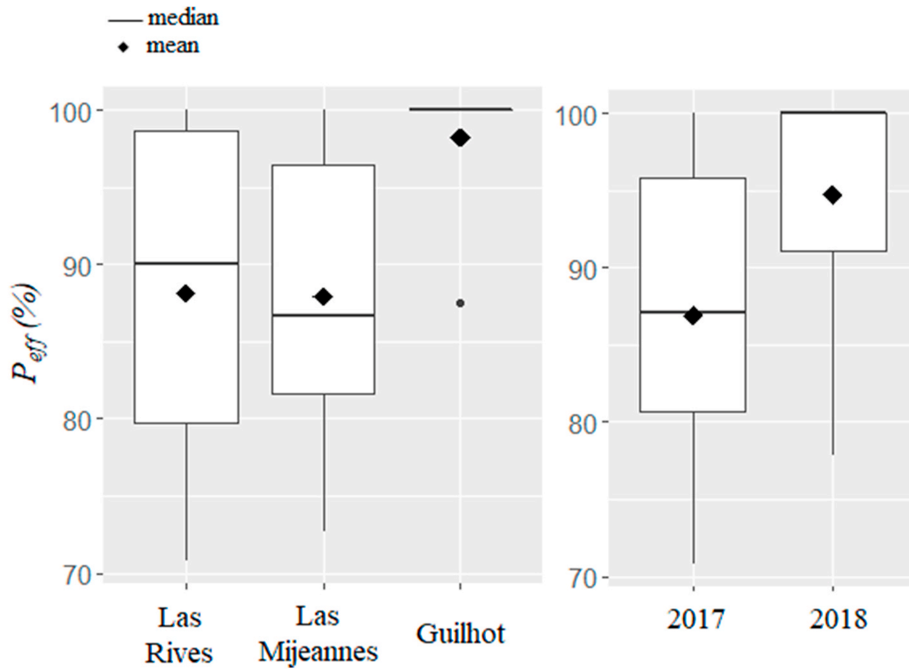

Fig. 6. Box-and-whisker plots of passage efficiency (P_{eff} in %) resulting from pulling all released fish groups, at each site (years pulled together) and each year (sites pulled together). See A1 in Supplementary materials for details on P_{eff} of each released fish group (the median P_{eff} for Guilhot is 100% because all but one fish group reached the maximum efficiency).

Table 2
Fish passage time *Pt* through the bypass or the turbine by site and year.

	Nb of passages	P_t (minutes)					
		Min	25th percentile	Median	75th percentile	90th percentile	Max
Bypass passage							
Las Rives	88	1	1	2	3	5	100
Las Mijeannes	100	1	1	1	2	9	647
Guilhot	51	1	1	2	4	23	1579
2017	106	1	1	2	3	16	1579
2018	133	1	1	1	2	6	647
Turbine passage							
Las Rives	14	1	4	9	27	116	511
Las Mijeannes	14	1	1	2	19	26	40
Guilhot	2	3	–	–	–	–	603

Table 3
Results of the logistic regressions fitted to predict the probability of bypass passage and the probability of bypass passage without hesitation ($Q_{bp\%}$ - bypass discharge expressed as a proportion of exploited HPP discharge, *TL* – fish total length).

Bypass passage					Bypass passage without hesitation				
	Estimate	Std. Error	z-value	p		Estimate	Std. Error	z-value	p
Intercept	−7.53	4.86	−1.55	0.12	Intercept	9.97	5.18	1.93	0.05
$Q_{bp\%}$	0.39	0.16	2.43	0.02	$Q_{bp\%}$	0.42	0.14	3.04	0.002
TL	0.05	0.03	1.65	0.10	*TL*	−0.05	0.03	−1.76	0.08
Las Mijeannes	−0.24	0.43	−0.56	0.58	Las Mijeannes	−1.09	0.50	−2.18	0.03
Guilhot	0.99	0.79	1.25	0.21	Guilhot	−1.59	0.54	−2.93	0.003

with $Q_{HPP} > 50$ m^3 s^{-1}. Setting $Q_{bp\%}$ to 3% of turbine discharge, our study showed for these FDPS ~85% of bypass passage success for smolts and ~80% without hesitation (<5 min) (Fig. 7). Although satisfactory, the probability of bypass passage was further improved with higher $Q_{bp\%}$, exceeding 92% with 5% $Q_{bp\%}$ (90% without hesitation) and stabilizing after. Below the 3% $Q_{bp\%}$ value, lower probabilities were observed and, more importantly, the passage through the bypass and without hesitation revealed greater uncertainty with larger confidence intervals. In light of these findings, setting a threshold to 3% for $Q_{bp\%}$ seems a good compromise between the amount of flow used and the FDPS efficiency obtained in medium-sized HPPs. Other site characteristics such as bypass entrance dimensions, their spacing and entrance water velocity should however be considered for current and future projects to set the best adapted $Q_{bp\%}$ value (for more details see Courret et al., 2015). For instance, our results showed higher probability of bypass passage without hesitation at Las Rives HPP (Fig. 7), which may relate to larger

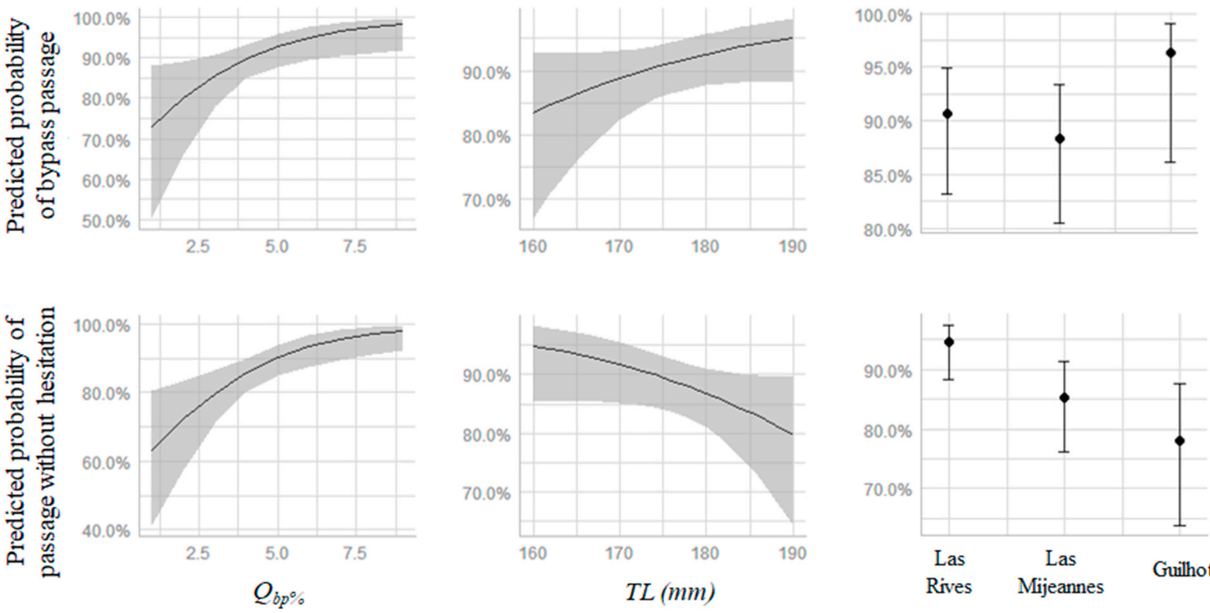

Fig. 7. Predicted probabilities (mean and confidence interval) of bypass passage and bypass passage without hesitation in relation to bypass discharge ratio ($Q_{bp\%}$, expressed as a proportion of exploited HPP discharge), fish total length (*TL*), and studied site.

Rack inclination (°)	70	64	60	26	26	26	26	26	26
Bar space (mm)	40	30	32	20	20	20	20	20	20
$Q_{bp\%}$ mean	4.2	2.5	7.1	3.6	5.1	5.0	5.3	4.9	5.7
min-max	3.1-6.5	1.6-3.4	5.0-12.0	2.6-6.9	2.3-9.1	1.9-8.5	-	-	-

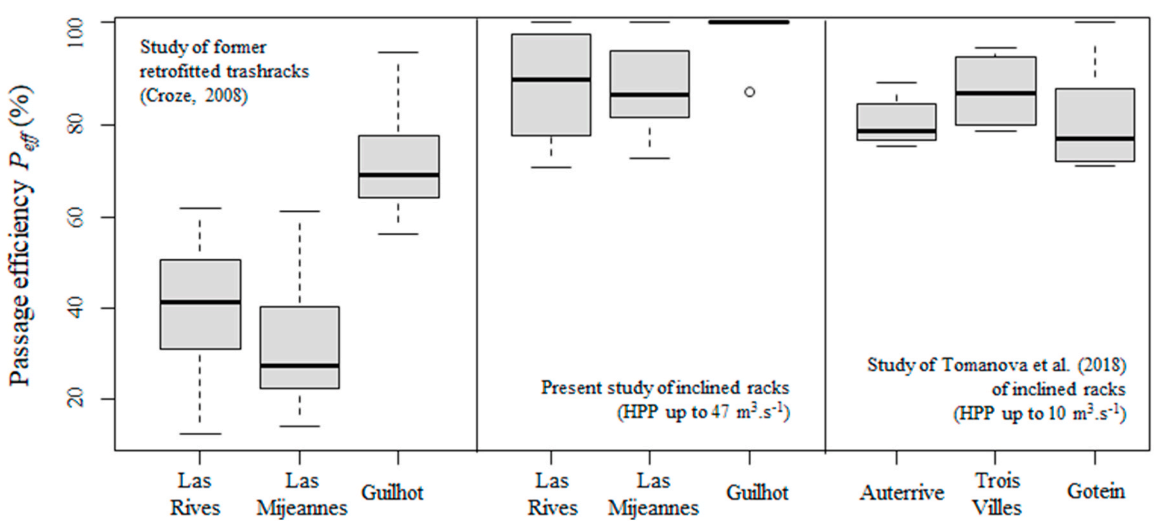

Fig. 8. Comparison of the passage efficiency (P_{eff}) between the previous and current devices, i.e. retrofitted trashracks (data from Croze, 2008) and horizontally inclined racks on the three studied sites (Wilcoxon tests revealed significant differences with $p < 0.001$ in all pairwise comparisons), and with three other horizontally inclined racks studied by Tomanova et al. (2018) in smaller HPPs. Both cited studies applied RFID technology (Radio Frequency Identification) and assessed P_{eff} using the number of released fish instead of the number of fish actually passing through the HPP, as we did here, potentially inducing a very minor underestimation of P_{eff} values in both studies.

bypass entrances (covering in total 20% of the rack width) and obstruction of the upper part of the rack, generating flow deceleration and transversal currents between bypass entrances (Fig. 2) resulting in a better guidance of fish to the bypass entrance. At Las Mijeannes and Guilhot sites the bypass entrances cover ~10% of the rack width and transversal currents are absent or very low, requiring further fish effort to displace over the intake width to find an entrance.

Our test was performed on juveniles and the results cannot be directly projected to adults without further research, although previous works point on that direction (Nyqvist et al, 2017, 2018; Scruton et al., 2007). For instance, studies conducted on the Herting HPP (Ätran River) in Sweden have already proved that the installation of low bar spaced (15 mm) racks angled to the flow was all the more beneficial for downstream migration of kelts (bypass P_{eff} = 100%, all fish passing through the bypass on their first visit to the intake channel, Nyqvist et al., 2017) than for smolts (bypass P_{eff} between 70 and 95%, Nyqvist et al., 2018). Other species of conservation interest, i.e. silver eels, might also benefit from the FDPS studied here, although further specific studies would be needed to confirm their efficiency.

The installation of new FDPS represents some investment costs. For existing HPP, the lower investment needed for retrofitting old HPP trashracks with bypass(es) to improve downstream fish migration may seem economically more relevant. However, low or highly variable fish migration efficiencies are frequently reported for retrofitted trashracks (Ovidio et al., 2017; and studies reviewed in Tomanova et al., 2018). To achieve satisfying levels of passage efficiency with retrofitted trashracks, larger amounts of discharge has to be allocated to the bypass. For instance, Haraldstad et al. (2018) studied two retrofitted near vertical trashracks with 50 and 80 mm of bar spacing and found that the bypass discharge must be at least 6.7% of river discharge (whole river discharge flows through the HPP and bypass) to attract 70–90% of migrating salmon smolts to the bypass. Even accounting for the slightly different way of computing the Q_{bp} ratio, with ~3% bypass discharge (yielding ~85% of passage efficiency in our case), Haraldstad et al. reported efficiencies from ~30 to ~70%. These efficiencies were highly dependent on river discharge; the lowest values were observed during high river discharge events (the salmon preferred period for migration) producing too high water velocities just upstream the rack. Compared to the retrofitted racks tested by Haraldstad et al. the horizontally inclined low bar spacing racks yield higher and more stable efficiency values, independently on river discharge and with lower allocated bypass discharge (between 3 and 5% of HPP discharge). Implementing inclined racks offers a clear benefit for fish migration and lower impact on energy production (through lower discharge diversion to the bypass) than retrofitted old devices, somehow compensating their higher investment and maintenance cost. Moreover, in the case of HPP located on a diversion channel, if the FDPS is installed upstream of the intake channel, as in our studied sites (Fig. 3), bypass discharge can be merged with the minimum ecological flow necessarily delivered to the bypassed river section, reducing even more the loss for energy production (compared to a FDPS installed just upstream the power plants). This solution however impairs the installation of an upstream migration device at the HPP tailrace. An upstream passage solution can still be constructed at the HPP dam but with a risk of lower fish attraction due to reduced discharge in the river bypassed section.

5. Conclusion

Human needs are often detrimental to organisms and ecosystems health, and workable compromises are essential to ensure long-term sustainability. From both ecological and economical sides, the best FDPS should let safely pass 100% of downstream migrating fish with the less discharge loss for energy production. Here we showed that very good efficiency results can be obtained with horizontally inclined (26°) low bar spacing racks that successfully re-establish downstream salmon migration with low impact on energy production. The tested FDPS represents an efficient tool contributing to mitigate HPP ecological impacts.

Credit author statement

Sylvie Tomanova: Conceptualization, Methodology, Supervision, Investigation, Data curation, Formal analysis, Writing – review & editing. Dominique Courret: Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing. Sylvain Richard: Conceptualization, Methodology, Investigation, Writing – original draft. Pablo A. Tedesco: Formal analysis, Supervision, Writing – review & editing. Vincent Mataix: Conceptualization, Funding acquisition. Aurélien Frey: Methodology, Investigation, Data curation, Formal analysis. Thierry Lagarrigue: Methodology, Data curation, Supervision. Ludovic Chatellier: Conceptualization, Methodology, Data curation, Writing – original draft, Funding acquisition. Stéphane Tétard: Conceptualization, Methodology, Writing – original draft, Supervision, Funding acquisition.

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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112012.

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