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Temporary turbine and reservoir level management to improve downstream migration of juvenile salmon through a hydropower complex

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Abstract – Developing management rules to improve downstream migration of salmon smolts in large hydropower plants is essential to limit mortality and migration delay. A 2-year telemetry study was conducted to assess the efficiency of temporary measures to enhance the safety and speed of juvenile salmon passage through the Poutès dam (Allier River, France). 124 smolts were tracked through the reservoir and downstream of the dam, during implementation of turbine modulation and/or shutdown during night and reservoir level lowering. Level lowering significantly reduced median residence time from 3.4 days to 4.4 hours. However, even with high spill during turbine modulation, the risk of smolt being drawn toward the turbines was increased at low reservoir level due to the site's configuration, greater proximity to the surface and weak repulsive effect of the rack. Moreover, results revealed that a substantial proportion of smolts can migrate during daytime and twilight during floods, even at the beginning of the migration period. Thus targeted turbine shutdown has a good potential to protect smolts, but implementation requires studies taking account of site specificities and a flexible approach.

Keywords: Atlantic salmon / downstream migration / migratory delay / operational management / turbine shutdown

Résumé – Gestion temporaire du niveau de retenue et du turbinage d'un aménagement hydroélectrique visant à protéger les smolts de saumon Atlantique. Le développement de règles de gestion pour améliorer la dévalaison des smolts de saumon au niveau des grandes centrales hydroélectriques est essentiel pour réduire les mortalités et les retards de migration. Un suivi par télémétrie a été mené pour tester l'efficacité de mesures temporaires mises en œuvre au barrage de Poutès (rivière Allier, France). Au total, 124 individus ont été suivis depuis l'amont de la retenue jusqu'à l'aval du barrage pendant la mise en œuvre de modulation ou d'arrêt du turbinage et l'abaissement du niveau de la retenue. L'abaissement a significativement diminué le temps de résidence des smolts (médiane de 3.4 jours à niveau haut contre 4.4 heures à niveau bas). En revanche, cela a augmenté le risque d'entraînement vers les turbines en raison de la configuration du site, d'une plus grande proximité de la prise d'eau avec la surface et d'un faible pouvoir répulsif de la grille. De plus, une proportion importante des poissons peut migrer de jour et au crépuscule durant les crues, même en début de période de migration. Les arrêts ciblés de turbinage ont une efficacité potentielle élevée, mais leur mise en œuvre nécessite des études tenant compte des spécificités de chaque site.

Mots clés : Saumon atlantique / dévalaison / retard migratoire / gestion opérationnelle / arrêt de turbinage

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1 Introduction

Atlantic salmon (*Salmo salar*) is a famous anadromous species, with both juveniles (smolts) and adults undertaking long migrations between freshwater and marine habitats. Unfortunately, the species has undergone a general decline. Recruitment of the European stock has diminished almost 3-fold, from 8 to 3 million, since the early 1970s (Friedland *et al.*, 2009). Among other threats, river fragmentation is frequently reported as the main cause of this decline (Lucas and Baras, 2001; Thorstad *et al.*, 2008; Limburg and Waldman, 2009).

When migrating to marine habitats, smolts can encounter hydroelectric facilities and suffer direct or delayed mortality by passing through the turbines (Pracheil *et al.*, 2016; Thorstad *et al.*, 2017). Moreover, dams can also cause migratory delay because reduced flow velocity slows downstream migration and alters flow paths (Hansen *et al.*, 1984; Marschall *et al.*, 2011; Huusko *et al.*, 2018), resulting in erratic movements and difficulty in finding reservoir outlets (Aarestrup *et al.*, 1999; Tétard *et al.*, 2016a; Schwinn *et al.*, 2018). This delay can decrease smolt survival through elevated migration energy costs (Marschall *et al.*, 2011), reduced success of passage (Nyqvist *et al.*, 2017) and extended exposure to predation (Jepsen *et al.*, 1998; Gauld *et al.*, 2013; Schwinn *et al.*, 2017). High rates of predation in lakes or reservoirs were reported in some studies. For example, Jepsen *et al.* (1998) found that 90% of smolts negotiating an artificial lake died, mainly due to fish (56%) and bird predation (31%). Migratory delay can also further lead to desmoltification (McCormick *et al.*, 1999): *i.e.* smolts losing their propensity to migrate or ability to survive in saltwater. Additionally, decreased migration speed can decrease smolt survival when migration timing and optimum environmental conditions in rivers, estuaries and the coastal environment are out of phase (McCormick *et al.*, 1998; Thorstad *et al.*, 2012).

In the context of climate change, the need to restore longitudinal connectivity is even more crucial (Jonsson and Jonsson, 2009; Isaak *et al.*, 2015). The thermal and hydrological regimes of rivers are significantly affected by climate change, which may impact downstream migration of smolts (Arevalo *et al.*, 2020). Earlier migrations are already being observed in many rivers (Jonsson and Jonsson, 2014; Otero *et al.*, 2014; Kuczynski *et al.*, 2017). Therefore, delayed migration may adversely affect the long-term survival of the salmonid populations (Crozier and Hutchings, 2014; Morita, 2019).

Fish-passage solutions now exist, enabling quick and safe downstream migration through hydropower complexes. Recent tests on fine-spaced low-sloping racks associated to 1 or more surface bypasses showed good effectiveness and quick passage (Tomanova *et al.*, 2017, 2018; Nyqvist *et al.*, 2018). However, due to management issues and investment cost, these solutions are presently limited to hydropower plants (HPP) with turbine capacity up to about a hundred $m^3 s^{-1}$ (Larinier *et al.*, 2020).

Implementation of passage solutions in large HPPs is complex and expensive (Larinier and Travade, 2002). Surface bypasses associated to conventional trashracks are usually implemented, but tests generally showed variable and limited efficiency (Ovidio *et al.*, 2017; Tomanova *et al.*, 2018; Larinier *et al.*, 2020). Other solutions, using behavioral systems to guide fish, have been tested (Mueller and Simmons, 2008; Perry *et al.*, 2014; Tétard *et al.*, 2019) but no clear solution easily applicable to diverse locations has been determined (Williams *et al.*, 2012). Consequently, other active solutions, such as trap-and-transport or turbine modulation/shutdown during migration peaks, are sometimes considered to mitigate the impact of dams (Thorstad *et al.*, 2012; Stich *et al.*, 2015; Teichert *et al.*, 2020a). To be effective and acceptable for stakeholders, these mitigation measures need a precise forecast of migration timing, based on calendar dates or using environmental records, to limit the financial impact on hydropower generation (Teichert *et al.*, 2020b). In most cases, these measures are implemented in conjunction with biological monitoring (telemetry, capture, *etc.*).

Most smolts migrate to the ocean in spring (Otero *et al.*, 2014), but in some locations some individuals migrate outside of the peak season, especially in fall (Birnie-Gauvin and Aarestrup, 2019). "Smoltification" is controlled by photoperiod and temperature, with migration onset triggered by temperature and sometimes by discharge (McCormick *et al.*, 1998; Thorstad *et al.*, 2012), especially when river flow peaks occur at the beginning of the migration season (Whalen *et al.*, 1999; Otero *et al.*, 2014; Teichert *et al.*, 2020a). Some studies modeling smolt migration with these environmental variables showed high predictive performance (Sykes *et al.*, 2009; Teichert *et al.*, 2020a), which can give credence to active solution approaches. Nevertheless, whatever the "passage" solution (active or passive), and no matter how effective it may be, some large reservoirs can cause substantial migratory delay of several days or even weeks in some locations (Venditti *et al.*, 2000; Schwinn *et al.*, 2017, 2019; Tétard *et al.*, 2019; Babin *et al.*, 2020). However, barriers, and especially hydropower regulations, typically focus only on passage efficiency and mortality (Marschall *et al.*, 2011) with most managers and developers overlooking the potential for sublethal costs induced by migratory delay (Silva *et al.*, 2018).

Poutès dam is located in the Upper Allier River (France), the main tributary of the Loire River. Although this hydropower dam was equipped with fish passage solutions in the late 1980s, a number of problems remained when the Poutès-Monistrol hydropower complex was relicensed in 2011: migratory delay for upstream and downstream migration, and difficulty for fish in using the fishways (Bach *et al.*, 2000; Tétard *et al.*, 2019). After several years of concerted discussions between stakeholders, it was decided to reconfigure the Poutès dam to meet ecological connectivity requirements for sediment and fish. The project included new fishways and a much lower reservoir level.[1] As a first step, a scientific program helped to assess the initial impact of the Poutès dam on smolt migration before reconfiguration (Tétard *et al.*, 2019). The beginning of construction, which was to start in 2016, was postponed until summer 2019, and temporary measures during smolt migration were needed as early as 2017, pending the start of reconfiguration. These proposed measures were discussed with stakeholders and aimed to improve passage efficiency while minimizing residence time in the reservoir. They consisted in temporarily lowering the reservoir

[1] https://www.nouveau-poutes.fr/vers-le-nouveau-poutes/le-nouveau-poutes/

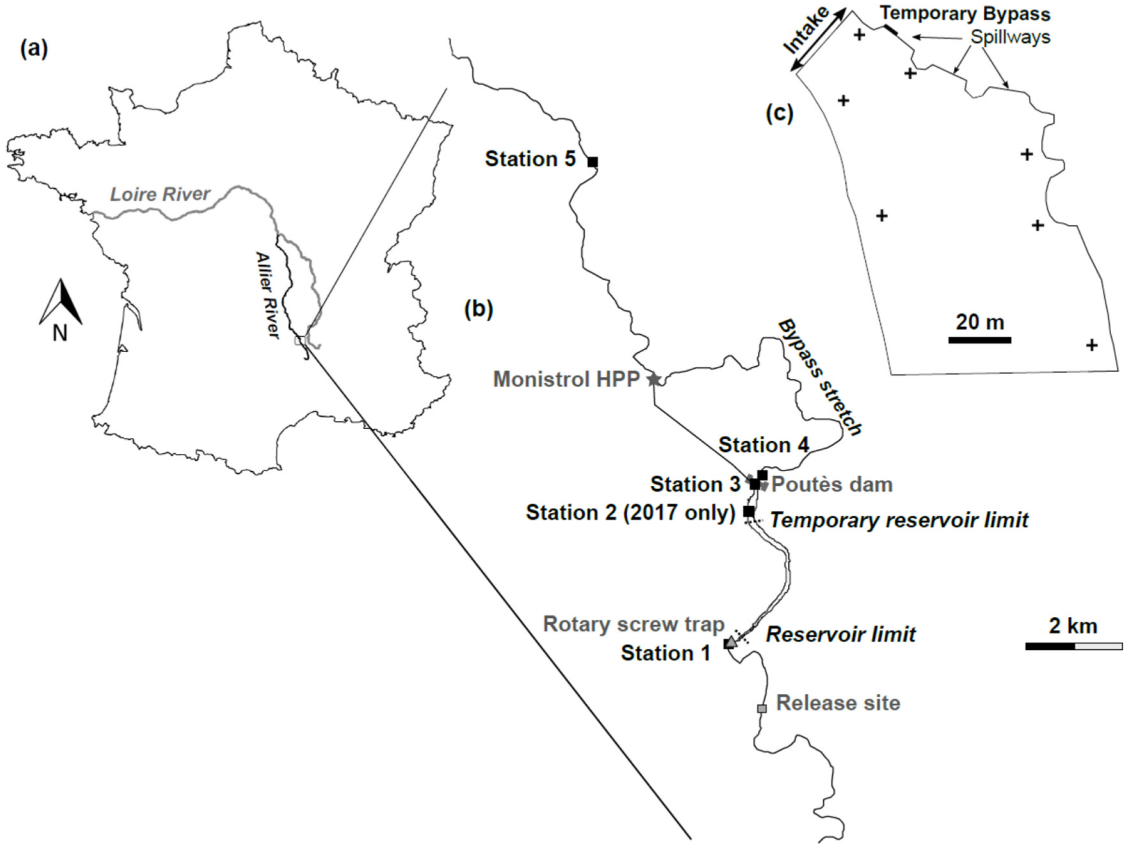

Fig. 1. Geographical location of the study area (a, b) and description of the areas close to the Poutès dam (c). The crosses indicate hydrophone positions in the dam zone for the season 2017.

level to decrease migratory delay, building a temporary bypass, and modulating (in 2017) or stopping (in 2018) turbine operation.

The present study aimed to provide feedback on the successes and failures encountered during the 2 years in which management rules were implemented, based on a telemetry experiment. The temporary measures were discussed with stakeholders and continuously improved during the experiment, through a structured iterative process of "learning by doing". Comprehensive assessment of successive measures implemented at the Poutès dam thus provides feedback to guide management plans in other hydropower sites for solving issues of migratory delay and passage efficiency during smolt migration.

2 Materials and methods

2.1 Study area

The Loire River (Fig. 1) is 1012 km long and has a drainage area of 117,000 km^2. It is the longest river system in Europe in which spawning migration of Atlantic salmon still occurs (Cuinat, 1988). The Allier River, its main tributary, is the main migration axis, with high-quality habitats for salmon reproduction (Baisez *et al.*, 2011). Located 861 km from the estuary, the Poutès dam is a crucial zone for the salmon population, as upstream areas account for about 60% of the potential juvenile production of the Allier River (Minster and Bomassi, 1999). Nevertheless, since the stop of restocking in 2008, it is estimated that only a few thousand of smolts are produced each year in upstream habitats (Bach *et al.*, 2015). This is due to a low transfer rate of adult salmon upstream of Poutès dam so far; this situation should be significantly improved soon with the dam reconfiguration under way. The dam, 18 m high and 85 m wide, bypasses a 10 km river stretch of the Allier River and engenders a reservoir of 2.4 Mm^3 that extends over 3.5 km in normal conditions. The fish assemblage in the impoundment is dominated by roach (*Rutilus rutilus*). Common species like spirlin (*Alburnoides bipunctatus*), eurasian minnow (*Phoxinus phoxinus*), chub (*Squalius cephalus*), perch (*Perca fluviatilis*) and pike (*Esox Lucius*) are also found. The mean annual discharge of the Allier River is 16.6 m^3 s^{-1}, and mean water residence time in the impoundment is 1.67 days. The maximum flow diverted to the powerhouse is 28 m^3 s^{-1}. The powerhouse is equipped with three Francis turbines (#1/2: 16 m^3 s^{-1}; #3: 3 m^3 s^{-1}); Legal minimum flow in the bypass stretch downstream of the dam is 4 or 5 m^3 s^{-1}, depending on the season (Tétard *et al.*, 2019). Three spillways, each 14 m long, discharge floodwater.

An intake protected by a rack (24 m wide, 5.7 m high) is located on the left bank, between 7 and 13 m below the surface (in normal operating conditions), and has a gap-width of 3 cm (Fig. 2). A surface bypass, operating from March to June, is located on the right side of the rack. A gate automatically

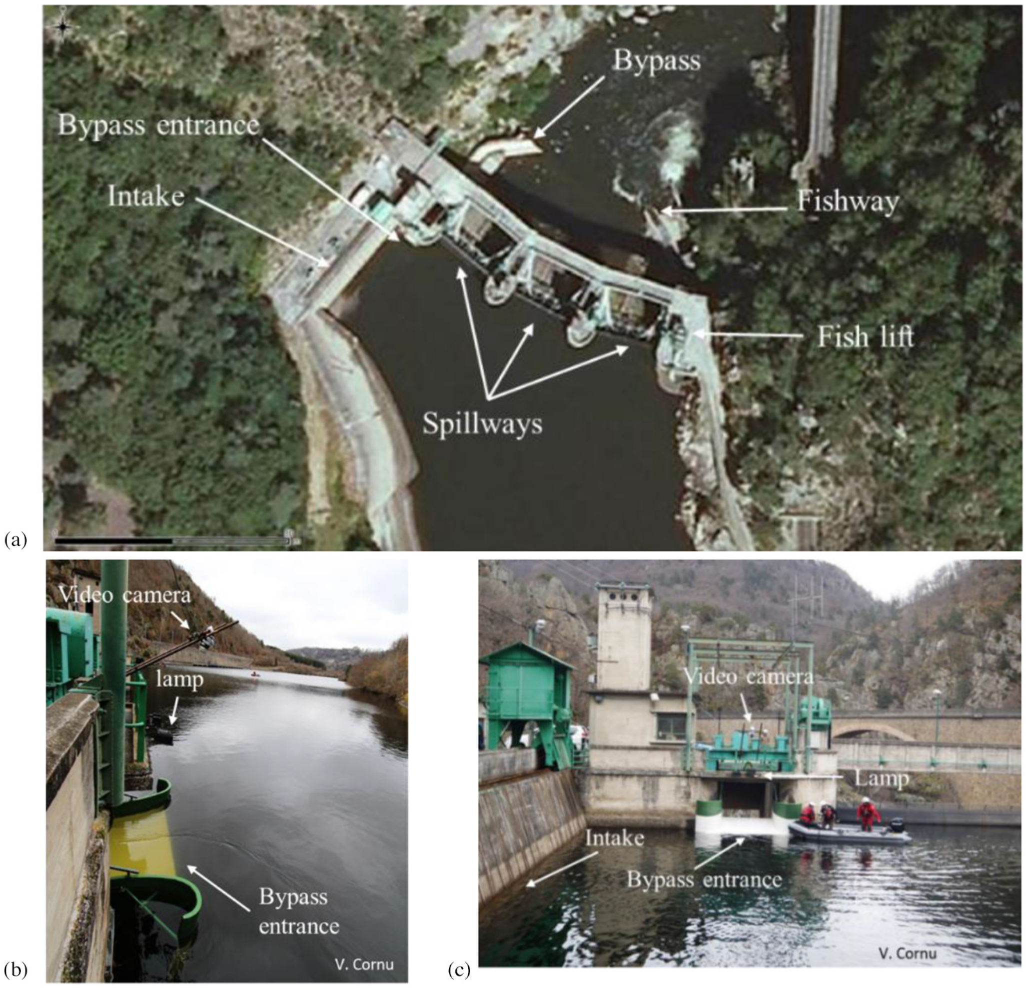

Fig. 2. Aerial view of the Poutès dam (a), side view of the bypass entrance (b) and front view of the intake and bypass entrance (c).

regulates the water level to ensure a continuous flow of 2 m^3 s^{-1}, representing 7.1% of the maximum turbine flow. The bypass is lit by a 50 W mercury vapor lamp positioned 3 m above the entrance to produce a halo of light of approximately 3 m diameter. The efficiency of this initial passage solution and the migratory delay induced by the Poutès reservoir were previously evaluated (Tétard *et al.*, 2016a, 2019), showing passage efficiency of 66% and significant median reservoir residence time of 9.3 days (more than 23.6 days for 25% of smolts).

2.2 Adaptive management for smolt migration

During the 2-year experiment, three kinds of temporary measures were implemented to improve smolt migration speed while preventing turbine entrainment: (1) water level lowering, (2) bypass design, and (3) turbine modulation and/or shutdown. To be adaptive, the management rules were discussed with the stakeholders and improved during the second migration season by feedback on the successes and failures reported during the first season.

2.2.1 First season: 2017

In the first season, the reservoir was lowered on March 1st to 644.7 NGF (lowering of 5.5 m from the normal water level of 650.2 NGF). This measure decreased reservoir volume by 90% (238,706 m^3, down from 2.4 Mm^3) and length by 70% (1,000 m, down from about 3,500 m) (Figs. 1 and 3). Mean water residence time in the impoundment was reduced to about 4 hours.

At this water level, the initial bypass was inoperative, and therefore a new temporary bypass entrance was designed using the left bank spillway (Fig. 3). An extension of metal uprights and wooden parts of about 1 m was fashioned to partly obstruct the weir crest and create a 4.5 m-wide notch that delivered a flow of 5 m^3 s^{-1} with a hydraulic head ≥70 cm over the weir crest. Unlike in normal operating conditions, the temporary bypass was not lit. To prevent abrasion injury, the facing of the spillway in front of the temporary bypass entrance was softened.

To increase passage efficiency, turbine operation was modulated during 20 nights, by implementing different decisions rules depending on river flow to maximize bypass

(a) (b) (c)

Fig. 3. Picture of upstream limit of the temporary Poutès reservoir (a). Top view of temporary bypass (b). Upstream view of intake, usual (non-functional) and temporary bypass entrances (c).

Table 1. Turbine management rules during temporary measures period for the 2017 season.

River flow	Power plant discharge		Bypass discharge	
	$m^3\ s^{-1}$	%	$m^3\ s^{-1}$	%
$\leq 8\ m^3\ s^{-1}$	0	0	[5;8]	100
[$9\ m^3\ s^{-1}$; $11\ m^3\ s^{-1}$]	[1;3]	11–27%	8	73–89%
[$12\ m^3\ s^{-1}$; $40\ m^3\ s^{-1}$]	[4;13]	31–37%	[8;27]	63–69%
$>40\ m^3\ s^{-1}$	28	≤70%	≥12	≥30%

discharge ratio, especially during low-flow periods (Tab. 1). Modulation was set to begin at night (7pm – 7am, local time) when migrating smolts are expected to be found. From March 1st, modulation was triggered either by smolt captures upstream of the reservoir (rotary screw trap located next to Station 1; Fig. 1) or when the river flow exceeded a threshold of 20 $m^3\ s^{-1}$. The measure was continued for 20 nights and the reservoir level was raised after the last night.

2.2.2 Second season: 2018

During the second season, the temporary operating measures were similar to those of 2017, but the stakeholders decided to stop turbine operations completely instead of merely modulating them. Unlike in 2017, the reservoir level was kept low for approximately 1 week after the last night, to carry out maintenance work on the intake.

2.3 Fish catching and tagging

Two rotary screw traps were used to catch wild migrating fish, as in previous studies conducted in this area (Tétard *et al.*, 2016a, 2019). The first one (“Alleyras trap”) was positioned about 1.5 km upstream of the normal Poutès reservoir, and the second (“Chanteuges trap”) about 28.5 km downstream of the dam. The two rotary screw traps can operate until river flow

Table 2. Characteristic of tagged smolts in 2017 and 2018. The number, origin, length, and weight of fish are provided, as well as the reservoir level at the time of release.

Release date	Number	Origin	Reservoir level	Total Length (mm)	Weight (g)
9th March 2017	1	Wild (Alleyras trap)	Low		
18th March 2017	1	Wild (Alleyras trap)	Low	152 ± 30.5	31.8 ± 19.6
24th March 2017	8	Wild (Alleyras trap)	Low		
2nd April 2017	24	Fish farm	Low	164 ± 9.7	40.4 ± 7.4
12th April 2017	20	Fish farm	High		
8th March 2018	25	Wild (Chanteuges trap)	Low	147.4 ± 15.4	26.7 ± 8.5
30th March 2018	45	Fish farm	Low	168.5 ± 7.3	41.8 ± 6.1

reaches a maximum of around 30 m^3 s^{-1} and 50 m^3 s^{-1} for Alleyras and Chanteuges, respectively (CNSS, 2013, 2014). In 2017, the Alleyras trap operated from February 27th to April 10th, and the Chanteuges trap from February 28th to May 31st, and in 2018 from March 3rd to April 12th and from March 1st to May 13th, respectively.

Overall, smolts collected in the Alleyras trap were preferred, to limit fish transport over a long distance (about 30 km from the release site). However, as the number of fish trapped at Alleyras was insufficient, some smolts collected in the Chanteuges trap and some from the National Wild Salmon Conservatory (CNSS) fish farm were used to ensure that a substantial number of fish were tagged, whatever the hydrological conditions (*e.g.*, floods) (Tab. 2).

Traps were checked every morning during the experiment and fish were tagged and released in the evening. Before tagging, fish were anaesthetized in phenoxyethanol solution at 0.3 $ml.l^{-1}$, then measured (TL, mm) and weighed (TW, g). Acoustic tags were then carefully inserted into the body cavity via a lateral incision. Closure used surgical glue. Conventional ethical standards for the care and use of animals were followed. JSAT L-AMT-1.421 tags (10.5 × 5.2 mm wide; 416.7 kHz; Lotek Wireless Inc.®) were used, weighing 0.32 g in air. Transmitters were programmed to emit a unique individually recognizable coded acoustic signal every 5 seconds, resulting in a battery life of approximately 40 days. Weight in air amounted to less than 2% of fish body weight, as recommended by Winter (1996). After recovering from the anesthesia, fish were released 3 km upstream of the reservoir. As capture could occur late in the temporary operating measure period and smolts could delay their migration, they were also tracked under high reservoir level conditions.

2.4 Telemetry array and position calculation

Smolt movements throughout the study area were tracked in 2D using acoustic telemetry. 23 and 16 WHS4000 hydrophones (Lotek Wireless Inc.®) were installed in 2017 and 2018, respectively. Hydrophones were positioned at 5 stations in 2017 and only 4 stations in 2018 (installation limitations). Stations were distributed from upstream to downstream to assess smolt progression within river reaches (Fig. 1).

- Station 1 (3 km from release site, 4 hydrophones) was located upstream and detected smolts in the free-flowing Allier River (about 1.5 km from the normal upstream limit of the Poutès reservoir).
- Station 2 (6.9 km from release site, 4 hydrophones in 2017, but not equipped in 2018) was located at the temporary upstream limit of the Poutès reservoir (about 700 m upstream of the dam).
- Station 3 (7.6 km from release site, 7 hydrophones in 2017 and 4 in 2018) was located in the dam zone and was used to track fish movement up to approximately 80 m upstream of the dam.
- Station 4 (7.9 km from release site, 4 hydrophones) was located 300 m downstream of the dam, in the bypass stretch, to confirm bypass passages.
- Station 5 (21.6 km from release site, 4 hydrophones) was located in the free-flowing Allier River, 4 km downstream of the confluence between the bypass stretch and the tailrace of the powerhouse.

Hydrophones were positioned on 1 m PVC tubes anchored on 25 kg concrete bases and their GPS location (precision: 0.3 m) was recorded with a differential GPS (Leica®). The 2D position was calculated using UMAP V1.3.1 (Lotek Wireless Inc.®) and was post-processed using 0.3 DOP (Dilution of Precision, UMAP parameter) (Tétard *et al.*, 2019).

In 2017, a preliminary survey was conducted in station 3 to assess positioning error (*i.e.*, Euclidian distance between calculated and actual positions of the tag) (Roy *et al.*, 2014). It was conducted on a boat along two trajectories, using a differential GPS device. Median positioning error was 0.7 m.

2.5 Behavioral metrics and data analysis

2.5.1 Residence time in the reservoir

To assess potential migration delay, residence time in the reservoir was calculated as the time difference between 1st detection in the reservoir (station 2) and last detection in the dam zone (station 3). At high reservoir level, the upstream limit of the reservoir was not equipped with hydrophones (Fig. 1), and reservoir entry time was estimated by adding 2.4 hours to the last detection in station 1. This value corresponds to the median travel time between station 1 and the reservoir at high level, as estimated in a previous study (Tétard *et al.*, 2016b). In 2018, the station 2 was not equipped with hydrophones because of installation issues. Therefore, the median travel time between station 1 and station 2 (72 min) calculated in 2017 was used to estimate reservoir entry time. Afterwards, the effect of reservoir level, flow conditions and fish origin on residence time was analyzed using an ANOVA after log-transformation of raw data to normalize the distribution of residuals. Linear regression assumptions were checked.

2.5.2 Attempt and passage at the dam

Attempted passage in the dam zone and back-and-forth movements in the temporary reservoir were computed (back-and-forth movements could only be computed in 2017, when station 2 was operational) for each tagged smolt. For a given individual, successive attempted passages were distinguished by considering a minimal time threshold of 30 min between two consecutive detections (Tétard *et al.*, 2019). The Mann-Whitney test was used to compare number of attempts per smolt between low and high reservoir level.

Successful passages were confirmed when a fish was detected in the bypass stretch downstream of the dam, without crossing turbines. However, some smolts which used the bypass were overlooked in the bypass stretch during high flow periods. In such cases, 2D trajectories in the forebay were used, when possible, to adjust passage rates. When a precise trajectory leading to spillways or bypass was observed, the fish was assigned to the bypass stretch. When the trajectory remained undefined, the fish was considered to have potentially crossed the turbines. Accordingly, passage estimates are conservative, with unknown route considered as a turbine route.

Time of passage was defined as the time of the fish's last position in the forebay before passage. Passage period (twilight or night) was also recorded, according to the angle between the center of the sun and the horizon (when the geometric center of the sun reached −6° and −18° below the horizon, for civil and astronomical twilights, respectively).

Finally, the spatial behavior of smolts in the dam zone was investigated, based on UD (utilization distribution), calculated on the kernel method (Silverman, 1986, Calenge, 2011) according to reservoir level. This approach was only conducted in 2017, because the smaller number of hydrophones in 2018 prevented accurate location of smolts.

2.5.3 Passage efficiency and transfer rates between stations

Transfer rate between stations was defined as the number of fish detected in a given station proportionally to the previous station. As turbine management differed between the two years, transfer rates were calculated per year. To take account of smolt overlooked during high flow, transfer rates were adjusted by adding detections when individuals were detected in downstream stations: for instance, a fish detected at station 4 had necessarily passed stations 1, 2 and 3. For station 5, the transfer rate was calculated by considering only fish that had been detected in station 4, and thus had not crossed the power plant; thus, the transfer rate was reduced, as smolt missed in station 4 but detected in station 5 were not included. Passage efficiency at the dam was calculated as the number of successful passages (detected in station 4 or using trajectory) proportionally to the number of fish detected in station 3. To explore whether the temporary measures influenced passage efficiency, potential differences between low and high reservoir levels were compared on χ^2 test.

2.5.4 Comparison of temporary measures

Some fish were tagged and released throughout the study period, and passages, transfer rates and residence times were compared according to reservoir level (high versus low) and flow conditions (high versus low) during smolt passage. Initiated from March 1st each year, the low reservoir level period ended on April 7th at 8 pm UTC in 2017 and on April 9th at 11pm UTC in 2018. High and low river flow periods were dichotomized according to a 30 $m^3 s^{-1}$ threshold, which is approximately twice the mean inter-annual flow. This threshold allowed: 1) results to be examined when detection efficiency was high in the bypass stretch (fewer missed detections), and 2) the impact of river flow on residence time and transfer rates between stations to be minimized (smolts were expected to show greater migration speed and greater probability of bypass/spillway passage in high flow periods).

All statistical tests were performed using R software (R Development Core Team 2018), implemented with the MASS, maptools, sp, raster, adehabitatHR and rgdal packages.

3 Results

3.1 Management measures and migration dynamics

3.1.1 First season

The reservoir level was lowered on March 1st and began to rise on April 7th, reaching its normal level on April 11th. Turbine modulation was implemented from March 4th, when river flow was 20 $m^3 s^{-1}$, to March 16th, when the local monitoring committee decided to suspend temporary measures until more favorable environmental conditions were met (8 "modulation nights" left). (Fig. 4). On March 24th, a second flood quickly raised the river flow, which reached 108 $m^3 s^{-1}$ on March 25th, resulting in turbine operation modulation being stopped. After the flood, modulation was reiterated for 8 nights until April 7th: *i.e.*, 20 nights over the season (Fig. 4).

During the first season, 54 smolts were tagged and released between March 9th and April 12th 2017 (Tab. 2). Only 10 wild smolts were caught and tagged on March 9th, 18th and 24th. The rotary screw traps were inoperable after this date because of the high river flow. Accordingly, hatchery smolts from the fish farm were used for tracking, because environmental conditions (flood, temperature between 6.5° and 9°C) and smolt abundance in the trap on March 24th suggested the beginning of an important migration episode. A total of 44 hatchery smolts were thus tagged and released on April 2nd at low reservoir level (24 individuals) and on April 12th at high reservoir level (20 individuals). No significant differences between wild and hatchery smolts were reported, either in total length (Mann−Whitney, $p = 0.09$) or in weight (t-test, $p = 0.2$).

Overall, the migration pattern differed between periods of low and high reservoir level (Fig. 4). When reservoir level was low, passage dynamics tended to be similar to that observed upstream of the temporary reservoir (station 1), suggesting that smolts rapidly crossed the dam to reach downstream reaches. Cumulative percentage of passages was usually higher than the

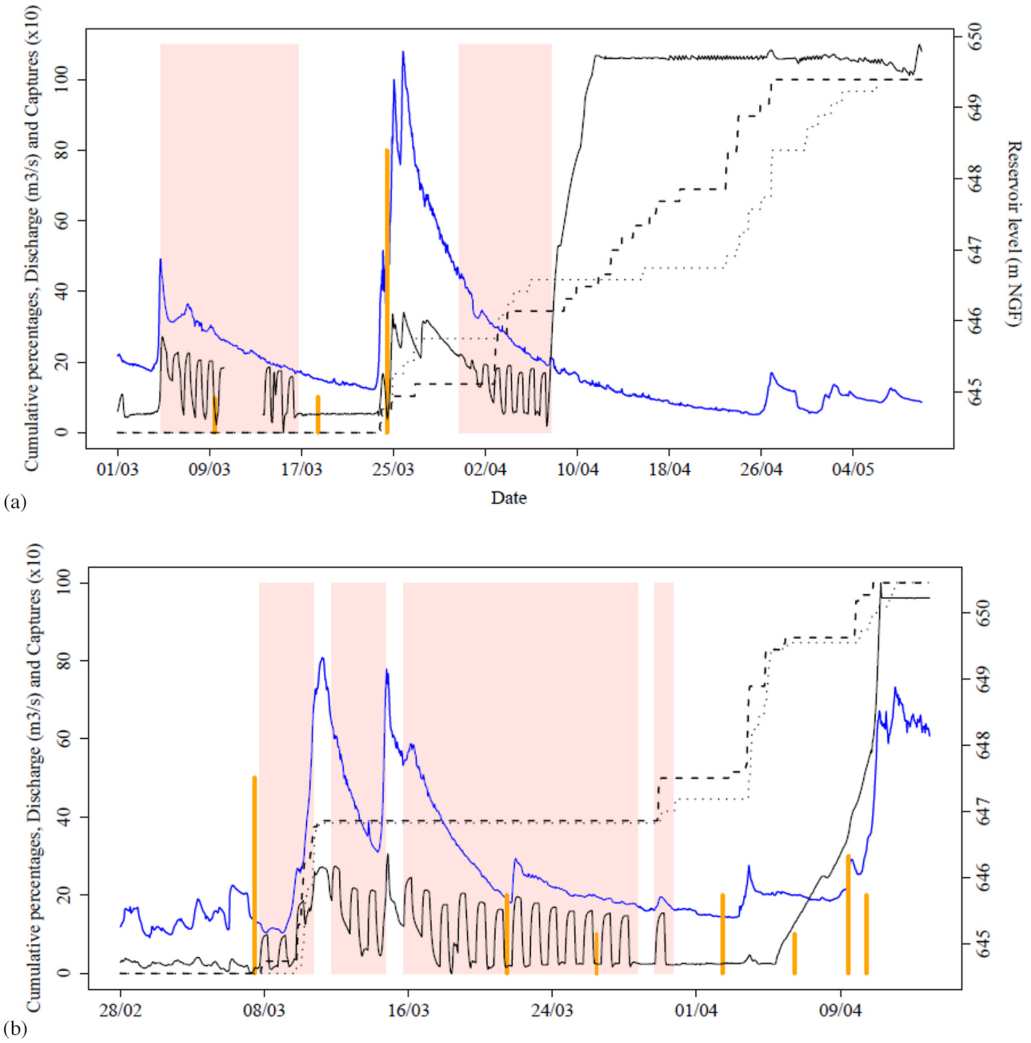

Fig. 4. Changes in hourly river flow (blue), reservoir level (black) and captures at the Alleyras trap (x10, orange) during the study period in 2017 (a) and 2018 (b). The periods of turbine operation modulation are indicated (red rectangle). Cumulative percentages of smolts detected in Station 1 (thick dashed line) and passing the Poutès dam (dotted) are also indicated

percentage of detection in station 1, because of individuals undetected during the flood. After raising the reservoir level, cumulative detections in station 1 greatly increased (from 35% to 69% between April 8th and April 18th), but the percentage of passages remained much lower (Fig. 4). This observation suggests that smolts continued to enter the reservoir but did not manage to exit it.

3.1.2 Second season

The reservoir level was lowered on March 1st and remained low until April 9th. Turbine shutdown was implemented from March 8th, when the first smolts ($N = 8$) were caught in the rotary screw trap, to March 11th, when the flood occurred and turbines were restarted to protect the temporary bypass. Turbines were then stopped from March 12th to March 15th, when a second flood quickly raised river flow to 75 $m^3\ s^{-1}$. Thereafter, the turbines were stopped every night from March 16th to 29th (13 nights) (Fig. 4). It is important to note that turbine shutdown duration changed during the temporary operating measures period, lasting 2 hours less (from 7pm to 5am local time) until March 20th and then prolonged to the planned time slot of 7pm to 7am.

25 wild smolts from the Chanteuges trap were tagged and released on March 8th (Tab. 2). The traps could not operate during the two flood episodes. From March 19th to March 29th, although environmental conditions looked quite favorable for smolt migration, no significant captures were made. As smolt stocks upstream of Poutès were quite low and it was presumed that a large majority had migrated during the two flood episodes (5 smolts caught at the beginning of the first episode), it was decided to tag hatchery smolts to track them during the last remaining night of turbine shutdown. 45 hatchery smolts were tagged and released on March 30th when the turbines had been stopped for the last night (Tab. 2). Wild smolts were smaller (*t*-test, $P < 0.001$) and lighter (Mann-Whitney, $P < 0.001$) than the hatchery smolts.

At low reservoir level, migration dynamics was very similar in stations 1 and 3. All fish of the first release ($N = 25$) migrated during the first flood, and especially during the night

Table 3. Number of smolts and transfer rates between stations in 2017 and 2018. The results are provided for all tagged fish (global) and depending on the local conditions (reservoir level and river flow) when smolts entered in the Poutès reservoir.

		Release site	Station 1	Station 2	Station 3	Station 4	Station 5
Number of smolts (transfer rate%)	Global						
	2017	54 (/)	34 (63%)	33 (97%)	32 (97%)	20 (63%)	15 (75%)
	2018	70 (/)	67 (96%)	/	65 (97%)	43 (66%)	28 (65%)
	Low reservoir level						
	2017		14 (/)	14 (100%)	14 (100%)	7 (50%)	4 (57%)
	2018		57 (/)	/	55 (95%)	38 (69%)	25 (66%)
	Low reservoir level and river flow $\leq$ 30 m^3 s^{-1}						
	2017		6 (/)	6 (100%)	6 (100%)	3 (60%*)	2 (67%)
	2018		36 (/)	/	33 (92%)	23 (70%)	15 (65%)
	High reservoir level						
	2017		20 (/)	19 (95%)	18 (100%)	13 (72%)	11 (85%)
	2018		10 (/)	/	10 (100%)	5 (50%)	3 (60%)
	High reservoir level and river flow $\leq$ 30 m^3 s^{-1}						
	2017		20 (/)	19 (95%)	18 (100%)	13 (72%)	11 (85%)
	2018		2 (/)	/	2 (100%)	0 (0%)	/

* One smolt was detected in station 3 but did not approach the dam.

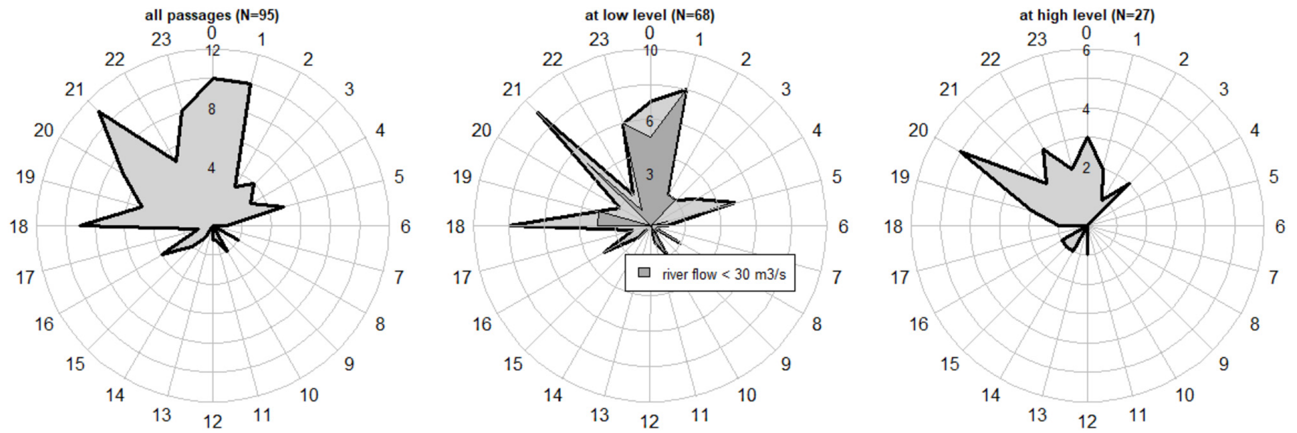

Fig. 5. Radial plots of passages times (UTC) at Poutès according to reservoir level in 2017 and 2018.

of March 11−12th, explaining why only 4 smolts passed the dam when the turbines were stopped. Logically, no movement happened until second release. A majority of detected smolts of the 2nd release (38/42) waited for several days and arrived in Poutès during an increase in river flow on April 4–5th and the flood on April 10−14th. Consequently, only 2 smolts of the 2nd release passed Poutès when the turbines were stopped. Arrivals in station 1 and passages at the dam were slightly dissociated in the last part of the reservoir level raising period (from April 10th to April 13th), although the phenomenon was less pronounced than in 2017.

3.2 Transfer rate, passage efficiency and passage time

During the study, 63% and 96% of smolts were detected in 2017 and 2018, respectively. Overall, transfer rates from station 1 to the dam (station 3) were very high in both years, at 94−97% (Tab. 3). However, passage efficiencies were 63% in 2017 and 66% in 2018. Transfer rates to station 5 were 75% (2017) and 65% (2018).

In the two years, transfer rates to the station 4 ($\chi^2{}_{2017} = 0.36$, $p_{2017} = 0.85$; $\chi^2{}_{2018} = 0.80$, $p_{2018} = 0.37$) did not significantly differ between low and high reservoir levels, indicating that this management measure did not affected the proportion of smolts passing the dam. Similar results were obtained at low river flow, which underlined the constancy of results according to detection efficiency.

The 95 smolt passages (independently of migration route) essentially occurred during twilight or at night, with 81.2% between 6pm and 2am (Fig. 5). However, the proportion of smolts migrating during daytime and twilight was higher when river flow was ≥30 m^3 s^{-1} (Fig. 6, $\chi^2 = 11$, $p < 0.01$) at low reservoir level.

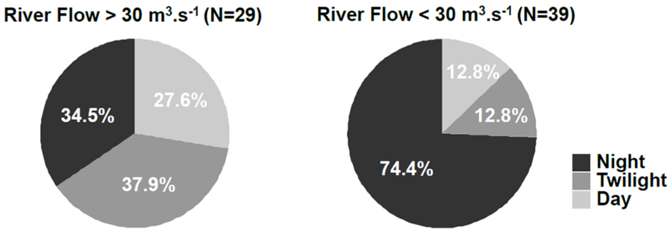

Fig. 6. Distribution of passage periods according to river flow at low reservoir level.

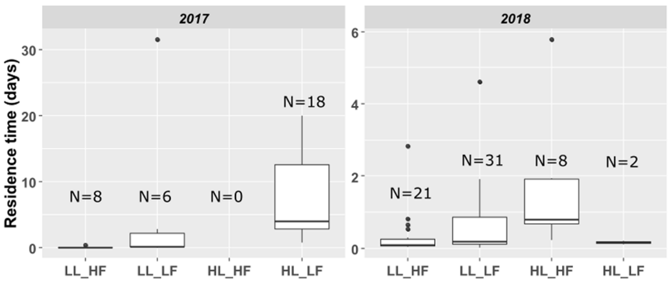

Fig. 7. Residence time according to reservoir level and river flow during smolt entry in 2017 (left) and 2018 (right). LL and HL: low and high level, respectively. LF and HF: low and high flow, respectively. Note that the scale of y-axis differs between the 2 graphs.

Table 4. Analysis of variance table on log-transformed residence time.

	Df	Sum Sq	F value	p (>F)
Reservoir level	1	133.65	64.99	$p < 0.001$
River flow	1	23.57	11.46	$p < 0.01$
Reservoir level: River flow	1	0.04	0.02	0.89
Fish origin	1	0.26	0.13	0.72
Total length	1	0	0	0.1
Residuals	89	2.03		

3.3 Residence time and behavior in the reservoir

3.3.1 Residence time

At low reservoir level, median residence time was 50.8 min in 2017 and 2.1 h in 2018 at high river flow, and slightly longer at low river flow (3.6 h in 2017 and 4.4 h in 2018; Fig. 7). At high reservoir level, the time spent by smolts in the reservoir was substantially longer, at a median 4 days in 2017 at low river flow (no smolts entered the reservoir at high river flow in 2017). In 2018, median residence times at high reservoir level were 19.1 h and 4.4 h at high and low river flow, respectively. Linear model on log-transformed data showed that reservoir level (ANOVA, $F = 64.99$, $p < 0.001$) and flow conditions (ANOVA, $F = 11.46$, $p < 0.01$) were the only variables that significantly influenced the residence time (Tab. 4).

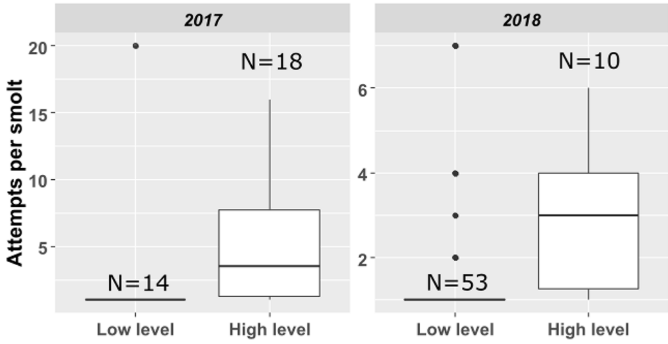

Fig. 8. Number of passage attempts per smolt according to reservoir level in 2017 (left) and 2018 (right). Note that the scale of y-axis differs between the 2 graphs.

3.3.2 Attempts to pass

At low reservoir level, 93% and 87% of smolts passed the dam at the first attempt, in 2017 and 2018, respectively (Fig. 8). At high reservoir level, the median number of attempts per smolt was 3.5 (range, 1−16) in 2017 and 3 (range, 1−6) in 2018. The difference in number of attempts between low and high levels was significant in both years (2017: $W = 50.5$, $p < 0.01$; 2018: $W = 115$, $p < 0.001$).

In 2017, UD maps revealed that detection density peaked in the north-west corner of hydrophone array (Fig. 9). Despite the DOP filter, a few positions lay outside reservoir boundary. At low reservoir level, the probability distribution of smolt relocation was quite concentrated, forming a “channel” directed toward the bypass. The maximum probability density was located just upstream of the bypass, at approximately 11 to 29 meters from the bypass entrance. In contrast, relocations were distributed over the whole dam area at high reservoir level.

4 Discussion

Numerous studies reported migration delay due to hydropower reservoirs and/or tested the efficiency of various fish passage solutions (Tomanova *et al.*, 2018; Schwinn *et al.*, 2019). To our knowledge, our study is the first to assess the impact of temporary measures aiming both to improve passage efficiency and reduce migration delay, with targeted turbine operations and reservoir level lowering.

The study confirmed that lowering the reservoir level and reducing mean water residence time from 1.67 days to 4 hours was a very effective means of reducing the migration delay caused by the reservoir. In 2017, when river flow was less than twice the mean annual flow, operating at low level reduced median residence time from 4 days to 3.6 hours. In low-flow conditions, median residence time at high reservoir level as evaluated in 2015 was 9.3 days (Tétard *et al.*, 2016a). River flow had an important impact whatever the reservoir level, and explained the great difference in residence time between 2017 (mean river flow = 9.6 $m^3\ s^{-1}$) and 2018 (mean river flow = 49.4 $m^3\ s^{-1}$). The causes of the substantial migration delay at high reservoir level were identified in 2015

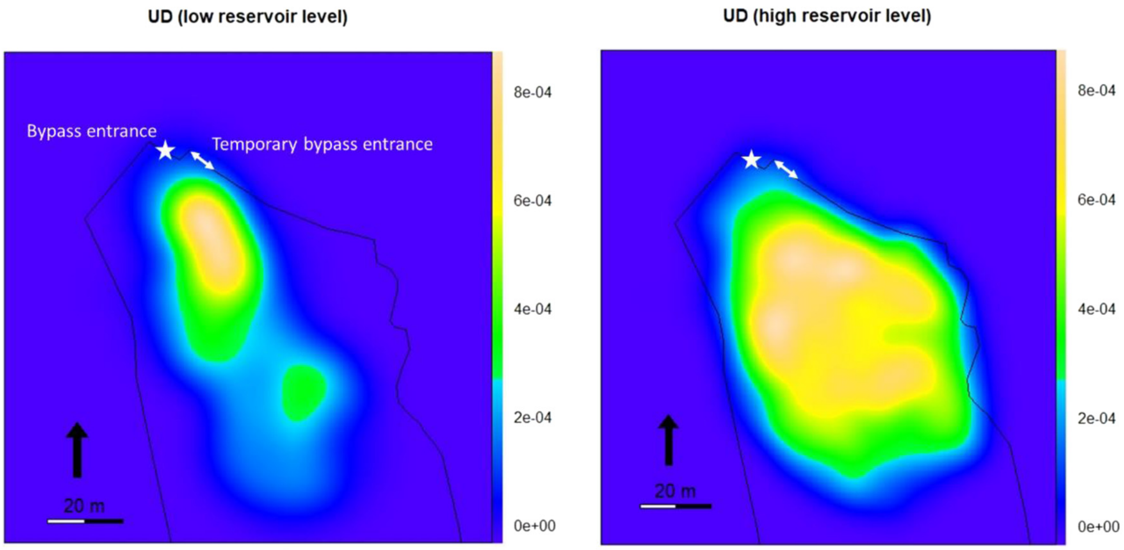

Fig. 9. Probability density of smolt relocation (UD) according to reservoir level in 2017.

as reluctance to enter the bypass and disorientation in the reservoir (Tétard *et al.*, 2016a). Accordingly, the median number of passage attempts in the dam zone before passing downstream was 12, and 64.8% of smolts went back to the upstream end of the reservoir at least once after being detected in the dam area (Tétard *et al.*, 2016a). In contrast, when the reservoir was lowered, no fish went back upstream, and they crossed the dam at the first attempt. Whichever route smolts use, they quickly crossed the reservoir and passed downstream. Although reservoir level modulation appears efficient to mitigate impact on smolt migration, our study did not consider the influence on other biological components, such as benthic fauna or riparian vegetation. Further investigations should thus consider monitoring a larger range of taxa to preserve the functional roles of water reservoir.

To explore whether the temporary reservoir still induced migration delay, the time needed by smolts to travel the same distance was compared with migration speed in a free-flowing stretch. Over a distance of 3.9 km from station 1 to station 2 (at low reservoir level: Fig. 1), median migration speed was 20 km. d^{-1}. This was comparable to other reports, although migration speed is known to vary between rivers and environmental conditions (Imbert *et al.*, 2013; Havn *et al.*, 2018; Huusko *et al.*, 2018). Extrapolating this speed to the temporary reservoir length (from station 2 to station 3: 700 m) would imply 50.4 min to cross the reach (against 4.4 h calculated in the study). Despite uncertainty in estimation, this shows that the temporary reservoir would still induce delay, however short, probably linked to velocity field decrease in the reservoir. One interesting question remains: transition from a situation with substantial delay to an acceptable situation for smolt migration is probably progressive, but how are acceptable hydraulic conditions that prevent detrimental delay to be determined? Studies conducted at Poutès between 2015 and 2018 showed that residence time was more or less of the same order as the mean water residence time. This is essential information for stakeholders discussing remedial measures in other situations.

Results for passage efficiency were less clear. At low reservoir level, average passage efficiency was 65%, whereas it ranged between 50% and 72% at high level between 2015 and 2018 (Tétard *et al.*, 2019). Although it is quite similar regardless of reservoir level, this results from different situations. At high reservoir level, a substantial proportion of smolts come to the dam but never cross it. These smolts are thus liable to be predated in the reservoir or “desmoltify”. In this configuration, focusing only on smolts that pass the dam by whichever route (bypass, spillways or intake), the proportion of smolts using the bypass at high reservoir level was calculated in a radiotracking study in 2004 as close to 90% (Bach *et al.*, 2004). At low reservoir level, almost all smolts detected at the dam passed it, indicating that a higher proportion was led into the intake and hydropower turbines. This seems obvious, as the intake is 7 m below the surface at normal reservoir level but only 1.5 m at low level. Nevertheless, modulating turbine operations should have reduced the risk by reducing the attractiveness of the intake. Due to the high hydrological conditions during the two years of the study, spill ratio (Q spill/Q total) during passage at low reservoir level was substantial, at 20–74% in 2017. This shows that spilling water to divert smolts is not enough if the gap-width of the rack is not sufficiently repulsive, especially when the hydropower plant is approaching maximum capacity. Haraldstad *et al.* (2018) showed that river flow negatively affected fish guidance efficiency in plants with rack gap-width between 50 and 80 mm. High (>90%) fish guidance efficiency was obtained, but only with river flow ≤30% of maximum plant capacity. Moreover, the geometry of the intake and resulting approach flow patterns are undoubtedly of great importance: in the case of Poutès, they may guide smolts toward the intake. Smolts typically follow bulk flow (Coutant and Whitney, 2000) and, even with high spill, it may still guide them toward the intake. This result underlines the importance of (1) stopping fish, (2) guiding them toward bypasses and (3) safely transferring them downstream, and gives credence to design criteria developed for “fish-friendly” intakes

(Courret and Larinier, 2008; Calles *et al.*, 2013; Nyqvist *et al.*, 2018; Tomanova *et al.*, 2018).

As it was concluded that modulation did not improve passage efficiency (compared to that of 2015) after the 2017 experiment, it was decided, in coordination with local stakeholders, to stop the turbines entirely with the same 20-night quota. This strategy did not achieve the expected results on tagged smolts either, due to diurnal migration and turbine restarting during floods.

To be effective, shutdown periods must take account of smolt presence in the vicinity of the dam, in terms both of daily time slots for shutdowns (if turbines are to be restarted) and of numbers of days of shutdown. At low reservoir level, passage times suggested that a time slot from 6pm to 6am UTC would have protected 84% of smolts with turbine shutdown every night of the migration period, and 91% with a 4pm-8am time slot. This measure would have resulted in 97% global survival (or 98.5% with a 4pm-8am time slot) for 65% passage success (see results above) and 50% turbine mortality for smolts arriving outside the shutdown time slot (Larinier and Dartiguelongue, 1989). Accordingly, thanks to the predominantly nocturnal behavior of smolts in Poutès, shutdowns targeting twilight and nights should show good efficiency. However, an important consideration to be kept in mind is that the Poutès dam is located 861 km from the sea, and the smolt downstream migration period begins early and is mainly nocturnal (Tétard *et al.*, 2019). Presence of migrating smolts in the front of an obstacle and the duration of their period of migration depend on local context: *e.g.*, environmental conditions triggering and driving migration, location of juvenile habitats according to dam location, *etc.* However, 40% of the smolts of the first release in 2018 (10/25) migrated between 6am and 6pm. During the first flood peak, after river flow reached 30 $m^3\ s^{-1}$, 38% of smolts migrated during daytime (8/21), with mean river flow 57 $m^3\ s^{-1}$ (for 5 of them, $\geq$66 $m^3\ s^{-1}$). These results indicated that a substantial proportion of smolts can migrate during daytime and twilight during floods, even in locations where smolts are supposedly mainly nocturnal. Consequently, negotiations to set the appropriate shutdown time slot should: (1) carefully consider the presence periods of smolts, either by analyzing biological data when available or with reference to similar contexts (time slots can focus on twilight and night at the beginning then extend over day later in the migration period) and (2) keep a flexible approach, possibly stopping turbines during the day at the beginning of the migration period when floods occur.

The second important item of the negotiation is the shutdown quota to set appropriate measures. When available, phenological models can accurately predict the phenology of smolt migration (Teichert *et al.*, 2020a) and therefore be used to set shutdown quotas. Otherwise, the smolts' migration phenology in several similar contexts can be examined and the quota set in a conservative manner. Finally, the negotiation process will have to find a compromise according to the global survival target set by environmental authorities. The shutdown quota to reach this target will depend on the passage success rate outside of the shutdown period: the greater the success, the fewer shutdown days are needed.

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