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Protecting efficiently sea-migrating salmon smolts from entering hydropower plant turbines with inclined or oriented low bar spacing racks

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ABSTRACT

Restoring the longitudinal connectivity of rivers is becoming a conservation priority in countries with high hydroelectric plant (HEP) development. Newly designed downstream passage solutions for fish are being installed in small and medium-sized HEPs in France, and an accurate evaluation of their functionality is needed. Here we addressed the efficiency of protection systems for the downstream migration of Atlantic salmon smolts at four HEPs (three 26° horizontally inclined racks and one 15° oriented to the flow rack in the bank alignment, all with 20 mm spaced bars). Between 239 and 300 hatchery-reared salmon smolts were PIT-tagged and released in 5–6 groups 100 m upstream of each studied HEP. Their passages through the HEPs were detected with radio frequency identification (RFID) antenna in the bypasses for downstream migration and the fish passes for upstream migration. On average between 82.8% and 92.3% of released smolts successfully passed the HEP through one of the two non-turbine routes. Resulting mean bypass passage efficiency ranged from 80.9 to 87.5% and all fish groups reached over 70% passage efficiency. Excepting one site, 50% of smolts passed through the bypass in less than 23 min after release, and 75% of them in less than 2 h 15 min. Combining our findings with previously estimated fish entrainment rates into the intake channel and turbine-related mortality rates, we assessed the overall fish survivals at the studied dam/HEPs which are between 98.24% and near 100%. Our results confirm recommended design criteria for inclined and oriented racks and the interest of the tested devices for the protection of downstream migrating salmon smolts.

1. Introduction

Despite the impacts related to river fragmentation, hydropeaking or impoundment, the energy production by hydropower is promoted by the European Directive 2009/28/CE (2009), which encourages the use of renewable energy. However, the multiplication of hydroelectric power plants (HEP) along fish migration routes may lead to important cumulative impacts on several endangered migratory species (Marohn et al., 2014; Verbiest et al., 2012). This is the case for the Atlantic salmon (*Salmo salar*) for instance, a declining migratory species in the North Atlantic river basins (Limburg and Waldman, 2009). Contrarily to upstream movements addressed by the development of a wide variety of fish passes, downstream migration issues have been recognized only recently (Larinier and Travade, 2002), calling for further development to prevent the important fish mortality (immediate or delayed) caused by turbine entrainment (Larinier and Dartiguelongue, 1989; Montén, 1985).

A functional downstream fish passage solution must ensure safe and fast passage route for a substantial portion of migrating fish (Nyqvist et al., 2016). Two different kinds of fish protection systems have been tested with varying success: physical (screens) barriers associated with bypass and behavioral (electricity, sound, bubbles…) barriers (see Larinier and Travade, 2002; OTA, 1995 for review). Physical barriers seem however more efficient that the behavioral ones. Several conventional trashracks with modified bar spacing (between 20 and 40 mm) and combined with downstream bypass were evaluated for fish protection (Chanseau et al., 1997; Croze, 2008; Larinier and Travade, 1999; Ovidio et al., 2017), but usually gave low satisfaction due to low (slightly more than 10% in Ovidio et al., 2017 for example) and/or very variable passage efficiency (ranging from 14 to 61% for example at Las Mijeannes study site in France, see Table 5). These studies usually concluded that the passage efficiency is highly dependent on the repulsive effect of the rack (depending on bar spacing) and on the velocity pattern in front of the rack guiding the fish to the bypass entrance. These features were among the main concerns in the following

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developments of fish protection systems. In 2008, Courret and Larinier (2008) proposed two types of fish protection facilities for small and medium sized HEP: (i) horizontally inclined and (ii) oriented to the flow racks, both with narrowly spaced bars, associated to a downstream bypass. Both systems were designed in order to maximize the protection of fish from entering the turbines and to guide them through the safe way (bypass). These authors recommended the following criteria for these protection racks: (1) low bar spacing (≤25 mm for salmon and sea trout smolts protection, ≤15–20 mm for silver eels), (2) a normal velocity (i.e. the velocity near the front of the rack, preventing fish impingement) ≤0.5 m.s^{-1}, (3) an inclination angle relative to the horizontal ≤26° for inclined racks, to guide fish to the top of the rack towards bypass entrance(s); or an orientation of racks to the flow direction ≤45°; and (4) several other criteria for the bypass entrance design, including dimensions, position, spacing and entrance velocity allowing to define the targeted discharge in the bypass, ideally between 2 and 5% of HEP turbine discharge (see Courret et al., 2015; Courret and Larinier, 2008 for more details). Hydraulic studies on both rack types (i.e. inclined and oriented) confirmed satisfactory conditions for energy production (acceptable head loss), good flow directions in front the rack for fish guidance towards the bypass entrances, and no risk for fish impingement against the rack (Raynal et al., 2012, 2015). However, the *in situ* efficiency of these devices to protect downstream migrating fish remains to be tested.

Since 2010, several rack protection systems have been implemented in France following the recommendations from Courret and Larinier (2008) detailed above and making possible *in situ* efficiency studies on downstream migrating fish. Here we present the first efficiency test of these protection systems, supposed to improve the downstream movement protection for Atlantic salmon smolts. We used a radio frequency identification technique (RFID) to study the downstream migration of PIT tagged hatchery reared smolts, released at four different run of river HEPs during their migration period (in April 2015 and 2016). If these recently implemented rack protection systems actually improve the conditions for downstream migration, we should observe high fish passage efficiencies (ratio of all fish passing by the protection system to the total number of fish passing through the HEP), greater than for older systems (Table 5), and short migration time (duration of fish passage). Furthermore, to recognize these protection devices as functional passage solutions, high efficiency levels should be found under different HEP configurations. And finally, an efficient downstream passage solution should significantly increase the overall survival of fish crossing the dam/HEP installations. If the rack configurations proposed by Courret and Larinier (2008) accomplish these requirements and improve the conditions for fish migration, the equipment of other small and medium sized HEPs should greatly benefit downstream migrating endangered fish species.

2. Materiel and methods

2.1. Study sites

The study was conducted at four small and medium sized run of river HEPs in southwestern France. The description of studied racks is summarized in Table 6. The bar thickness and bar spacing were 8 and 20 mm respectively for all studied fish protection racks. All racks were equipped with mechanical debris cleaners.

The Auterrive HEP (43°28′07″N, 0°59′55″W, CAM Energy society), located downstream from an intake channel of 400 m diverted from the Gave d'Oloron River, has a maximum intake capacity of 9.5 m^3·s^{-1} (7.8 m^3·s^{-1} during the study). This HEP is equipped with a 'pool and weir' fish pass for upstream migration (0.5 m^3·s^{-1}) and an inclined rack in front of the turbine with a bypass for downstream migration (Fig. 1, Table 6). The rack is inclined at 26° to the horizontal and has two bypass entrances on the top: one on the right side (0.5 m of width) and the other in the middle (0.7 m) of the rack, both fed with a total discharge of 0.5 m^3 s^{-1} regulated by a flap gate (6.4% of the turbine discharge during the study). The water level upstream of the HEP is not regulated because there is no dam in the river. Therefore, the water depth in the bypass entrances varies between 0.5 and 1.2 m, and the flow velocity between 0.35 and 0.83 m·s^{-1}.

The Trois Villes HEP (43°07′33″N, 0°52′49″W, Société hydroélectrique de Gotein) is situated 550 m from the Saison River and has a maximum intake capacity of 4.1 m^3·s^{-1} (3.9 m^3·s^{-1} during the study). This site is equipped with a Denil fish pass (0.15 m^3·s^{-1}) and an eel pass for upstream migration and an inclined rack in front of the turbine with a bypass for downstream migration (Fig. 1, Table 6). The rack, inclined at 26° to the horizontal, has one bypass entrance (1 m width) on the top left corner of the rack, fed with a discharge of 0.2 m^3·s^{-1} controlled by a broad crested weir (5.1% of the turbine discharge during the study). The water depth in the bypass entrance is 0.5 m and the flow velocity 0.4 m·s^{-1}. The discharge in the intake channel is regulated by a dam in the river and the intake channel section. A motorized bottom gate is installed near the turbine intake on the right bank (Fig. 1), operating when the discharge in the intake channel exceeds the total HEP capacity. In such cases, the motorized bottom gate opens and the exceeding water is evacuated through a canal directly to the tailrace. During the study, this control gate was regularly in function.

The Gotein HEP (43°10′47″N, 0°54′08″W, Société hydroélectrique de Gotein), 7 km downstream from the Trois Villes HEP, is located downstream of an intake channel of 780 m diverted from the Saison River. The turbine discharge during the study was the maximum HEP intake capacity: 6.7 m^3·s^{-1}. This site is also equipped with a Denil fish pass (0.15 m^3·s^{-1}) and an eel pass for upstream migration, and with an inclined rack in front of the turbine with a bypass for downstream migration (Fig. 1, Table 6). The rack, inclined at 26° to the horizontal, has two bypass entrances on the top: one on the right side and another one in the middle (each one of 0.8 m width), both fed with a total discharge of 0.38 m^3·s^{-1} controlled by a broad crested weir (5.7% of intake HEP capacity). The water depth in the entrances is 0.5 m and the flow velocity 0.47 m·s^{-1}. The intake discharge is regulated at the beginning of the intake channel by a dam and a control gate, but in case of discharge excess, the water is evacuated through a spillway situated on the left bank of the intake channel. There was no spillage during the study.

The Halsou HEP (43°22′28″N, 1°25′38″W, Electricité de France EDF), with a maximum intake capacity of 30 m^3·s^{-1} (23.8 m^3·s^{-1} maximum during the study), is located 925 m downstream of an intake channel diverted from the Nive River. This HEP is equipped with a 'pool and weir' fish pass (0.7 m^3·s^{-1}) for upstream migration and an oriented rack in front of the turbines, inclined at 64° to the horizontal and oriented at 15° to the flow. A surface bypass entrance (1.38 m width) is located at the right downstream end of the rack (Fig. 1, Table 6), between the rack and the spillway evacuating the water excess when the turbines shut down. Bypass discharge is regulated by a flap gate to 5% of the turbine discharge. This discharge fluctuates therefore between 1.0 and 1.5 m^3·s^{-1} depending on the HEP turbine discharge, ranging from 20 to 30 m^3·s^{-1}. The minimum depth in the bypass entrance is 0.5 m and the flow velocity varies between 0.7 and 1.4 m.s^{-1}, depending on the discharge and the forebay water level. The Halsou HEP is equipped with a low power mercury vapor lamp located 1.5 m above the bypass entrance to attract the fish. Fish passing through the bypass entrance fall into a reception pool of 1.20 m deep which connects to the spillway canal (Fig. 1). During the study, spillage only occurred a few times. Contrarily to the three previous sites (where wastes on the rack are evacuated through the fish bypass), the mechanical cleaner of Halsou HEP uses a separate canal for the evacuation of vegetal debris.

2.2. Fish tagging and release

To test the efficiency of the protection systems in our four studied HEPs, we used hatchery reared Atlantic salmon smolts (Castels hatchery of MI.GA.DO association). At Auterrive HEP, the fishes were

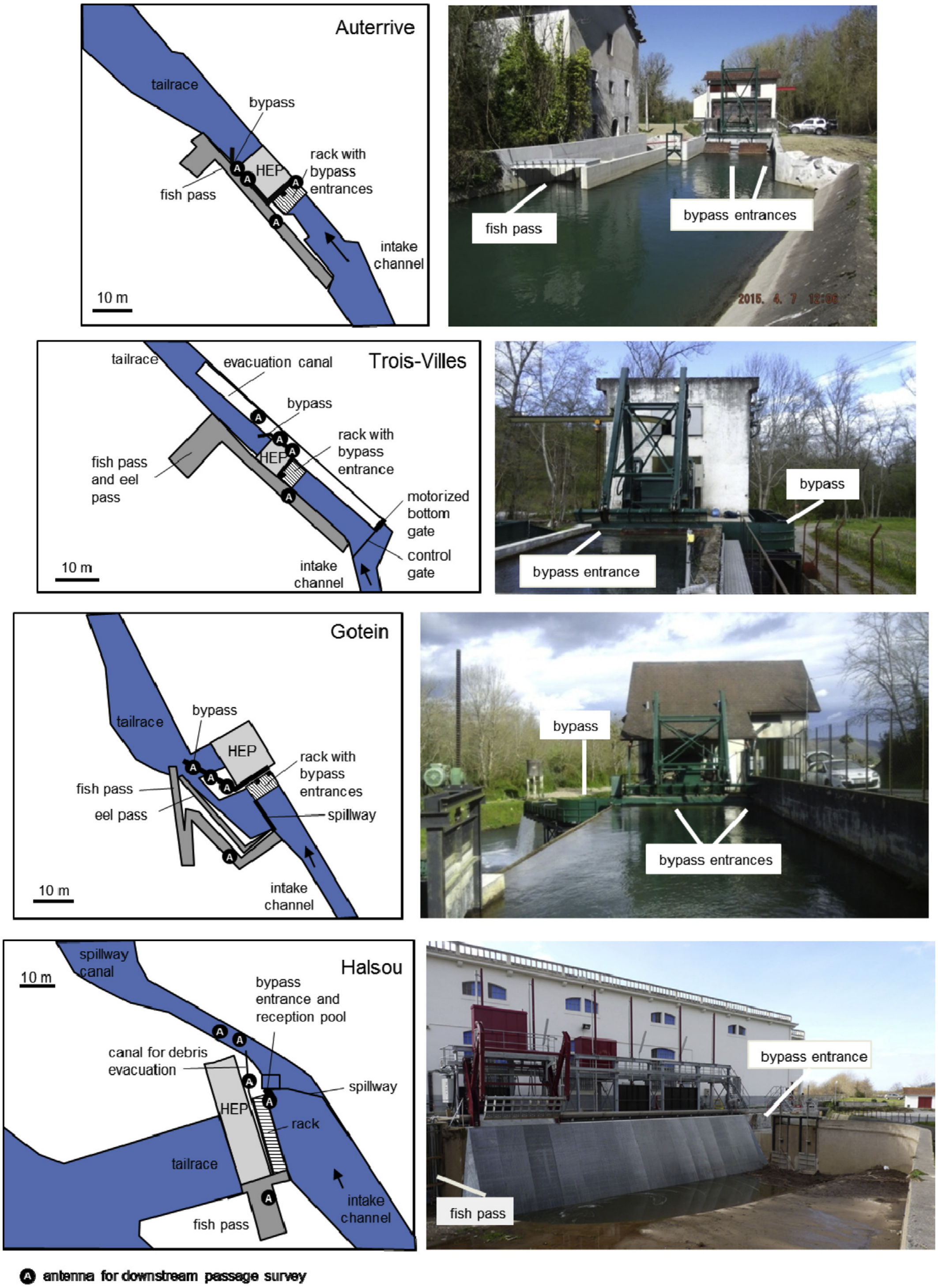

Fig. 1. Schema and photos of the study sites: Auterrive, Trois-Villes and Gotein HEP with inclined racks and Halsou HEP with oriented rack.

tagged in the field several hours before their release. For the three other sites, the fishes were tagged at the fish farm two weeks before their release. The same tagging procedure was always applied. The anaesthetized fish (3 5 min in a bath with clove oil) were first measured (total length) and then tagged with a PIT tag (23 mm) inserted into the body cavity. The surgical procedure lasted a few seconds. After tagging, the fish were kept in a pool with water, where they recovered and could swim normally after a few minutes. Two weeks after the tagging at the fish farm, no fish had rejected its tag.

The study was conducted during the migration period of wild salmon smolts (in April 2015 and 2016) and typical functioning of HEPs during this period (turbine discharge approaching maximum intake capacity). The fish were transported to each site the day before the release and were kept in circular tanks supplied with water from the intake channel. At each site, tagged fish were released in 5 or 6 groups of 37 72 individuals (usually 50) into the intake channel, 100 m upstream of the studied HEP at different times of the day (Table 1). The total length of the tagged fish ranged from 137 to 225 mm, with a mean length of approximately 186 mm at each site. No significant difference in fish length was detected between the released groups (ANOVA test, p value $>$ 0.05). The environmental conditions (temperature and discharge), during and several days after the release of all smolt groups,

Table 1

Released fish groups and proportion of individuals detected (or not) in different ways at the study sites (in bold: total or mean values for each site).

Site/Group	Number of ind.	Time of release	Fish length (mm)			Proportion of released individuals (%)					
			Min	–	Max	undetected	detected in				Overall passage minimum efficiency
							bypass	fish pass	evac. canal	debris canal	
Auterrive											
A 1	37	20:20	160	–	205	8.1	89.2	2.7			91.9
A 2	59	14:48	137	–	210	11.9	84.7	3.4			88.1
A 3	47	21:21	156	–	225	17.0	76.6	6.4			83.0
A 4	49	23:28	166	–	212	24.5	75.5	0			75.5
A 5	47	10:25	158	–	211	14.9	78.7	6.4			85.1
all groups	**239**		**137**	**–**	**225**	**15.5**	**80.9**	**3.8**			**84.7**
Trois-Villes											
TV 1	50	18:28	166	–	205	8	74 (88.1)	2	16		92
TV 2	50	22:20	162	–	210	12	48 (80)	0	40		88
TV 3	50	00:12	165	–	205	6	50 (86.2)	2	42		94
TV 4	50	18:07	161	–	211	4	76 (95)	0	20		96
TV 5	50	22:07	165	–	221	2	66 (97.1)	0	32		98
TV 6	50	23:34	159	–	204	14	52 (78.8)	0	34		86
all groups	**300**		**159**	**–**	**221**	**7.7**	**61 (87.5)**	**0.67**	**30.7**		**92.3**
(in brackets proportions computed when the fish passing through the evacuation canal are ommitted)											
Gotein											
GOT 1	50	19:45	171	–	202	0	100	0			100
GOT 2	50	22:40	158	–	212	22	76	2			78
GOT 3	50	00:40	155	–	211	20	78	2			80
GOT 4	50	18:37	152	–	209	10	88	2			90
GOT 5	50	22:38	150	–	213	28	72	0			72
GOT 6	52	00:17	165	–	220	23.1	71.2	5.8			76.9
all groups	**302**		**150**	**–**	**220**	**17.2**	**80.9**	**2.0**			**82.8**
Halsou											
HAL 1	50	21:13	137	–	210	14	86	0		0	86
HAL 2	50	22:47	167	–	205	14	86	0		0	86
HAL 3	50	18:15	144	–	213	10	90	0		0	90
HAL 4	66	21:42	157	–	212	13.6	78.8	0		7.6	78.8
HAL 5	72	23:05	166	–	210	5.6	94.4	0		0	94.4
all groups	**288**		**137**	**–**	**213**	**11.4**	**87.0**	**0,0**		**1.5**	**87.0**

remained stable at all sites, assuming constant bypass hydraulic attractiveness (bypass discharge representing at least 5% of turbine discharge).

2.3. *Detection of downstream migration*

Downstream movements of tagged fish were detected with several antennas covering all possible migration routes (Fig. 1), except through the turbines and upstream in the intake channel (technically impossible with the RFID technology). At each site, one antenna was placed in the fish pass, and an array of two or three antennas in the bypass (in the spillway canal at Halsou site). The use of two (or three) consecutive antennas allowed a better detection of fish passages through the bypass under high flow velocity conditions. Preliminary tests in Trois Villes, Gotein and Halsou sites, with tagged fish released directly into the bypass, showed a detection efficiency of nearly 100%. In Trois Villes HEP, a supplementary antenna was placed in the evacuation canal. In Halsou, the canal for debris evacuation was also equipped with an antenna because previous observations showed some individuals retained by the rack cleaner. In Auterrive and Halsou sites, an antenna was installed in the bypass entrance for complementary detection of fish approaches near the bypass entrance. The detection ranges varied from 40 to 100 cm upstream and downstream of each antenna. Each antenna was connected to the BASIC or DAMONA decoder (CIPAM society), which automatically stored the information on date, time and ID of tagged fish within the detection range of the antennas. Each decoder can store the data from two antennas which operate simultaneously.

2.4. *Data analysis*

The fish guidance efficiency, that is the percentage of fish successfully guided to the entrance of a particular passageway, is commonly used to evaluate fish protection systems (Bunt et al., 2012; Noonan et al., 2012). Because inclined metal racks could disrupt the efficiency of the RFID technology, the evaluation of this metric could be biased. Indeed, the detection efficiencies from antennas constructed at the bypass entrance in two sites were not satisfactory, preventing the estimation of guidance efficiency at the entrance of the passageway. For this reason, only the data from the antenna arrays installed in the bypass sections (spillway canal at Halsou site) and in the fish passes were used to compute the percentage of successful fish passages through the HEPs.

Two possibilities are left for individuals not detected by the antennas: to cross the rack and enter into the turbines or to swim upstream in the intake channel (and be possibly predated). For an accurate estimation of the fish passage efficiency, we should ideally adjust the number of tested fish by removing upstream migrating individuals. Unfortunately the used RFID technology did not allow detecting them. Following Ovidio et al. (2017), we hypothesized that all undetected fish passed through the turbines, resulting in a minimum passage efficiency estimate. We assume, however, that our minimum passage efficiency estimates are very close to the real passage efficiency because of the predictable behavior of salmon smolts for downstream migration.

Based on this assumption, we computed the proportion of successfully migrating fishes through different possible passage ways: bypass, fish pass and evacuation canal. We present four principal results: i) the bypass passage minimum efficiency, ii) the overall passage minimum efficiency (passages through the bypass + fish pass + evacuation canal), iii) the difference (tested with Student *t* test) in body length between fishes detected in the bypass and those undetected (i.e. those assumed to cross the rack, giving an indication of the rack selectivity), and iv) the migration time needed to safely pass through the HEP by the bypass (computed as the time between the fish release in the intake channel and its last detection in the bypass or spillway canal).

To estimate the overall fish passage survival through dam/HEP installations with and without tested protection systems, we followed the schematic diagram from Baudoin et al. (2015), and accounted for i) the rate of fish passing directly through the dam (considered as safe way), ii) the rate of fish entrainment from the river into the intake channels and the HEP, iii) the proportion of them passing through a safe way at the HEP level (through the bypass, fish pass or evacuation canal) and iv) the proportion of fish passing though the turbine and their mortality rate. The first two parameters can be estimated knowing the dam configuration and the discharge partitioning between the dam and the intake channel. These two rates were computed for each of our studied sites by Anonymous (2002a) and Voegtlé (2010) with more than 10 years of discharge data recorded during the migration period of salmon smolts. The third parameter was determined in our study, and the fourth parameter was computed using mortality rate related to turbines of our sites published in previous studies (Anonymous, 2002a,b; Voegtlé, 2010). Then the overall fish survival for each site was computed by summing fish proportions passing over the dam and those safely crossing the HEP.

3. Results

At Auterrive site, on average 80.9% (from 75.5 to 89.2% depending on the group) of smolts migrated through the bypass, and 3.8% (0 6.4%) passed through the fish pass (Table 1), resulting in a total of 84.7% (75.5 91.9%) of released smolts that successfully crossed this HEP using these two migration passes. At Trois Villes site, on average 92.3% of fish (ranging from 88 to 98%) crossed the HEP through a safe way. Important proportions of individuals (from 16 to 42%) were sucked into the evacuation canal when control gate regulating exceeding water opened. These proportions were always higher for groups released during the night. Consequently, the proportions of fish swimming through the bypass (between 48 and 74%, 61% on average) were smaller compared with the other sites. Nevertheless, when computing the bypass passage efficiency excluding the individuals passing through the control gate, we obtain comparable values ranging from 80 to 97.1%, with an average bypass passage minimum efficiency of 87.5%. At Gotein site, the bypass passage minimum efficiency ranged from 71.2 to 100% (80.9% on average). Curiously, the groups released in the evening achieved higher passage efficiencies (13 22% greater). Including passages in the fish pass, the overall passage minimum efficiency at this site was 82.8% on average (from 72 to 100%). Finally, at Halsou site we obtained similar results to the other sites. Bypass passage minimum efficiency was 87% on average and ranged from 86% to 94.4% for the released groups. 5 individuals were detected in the debris

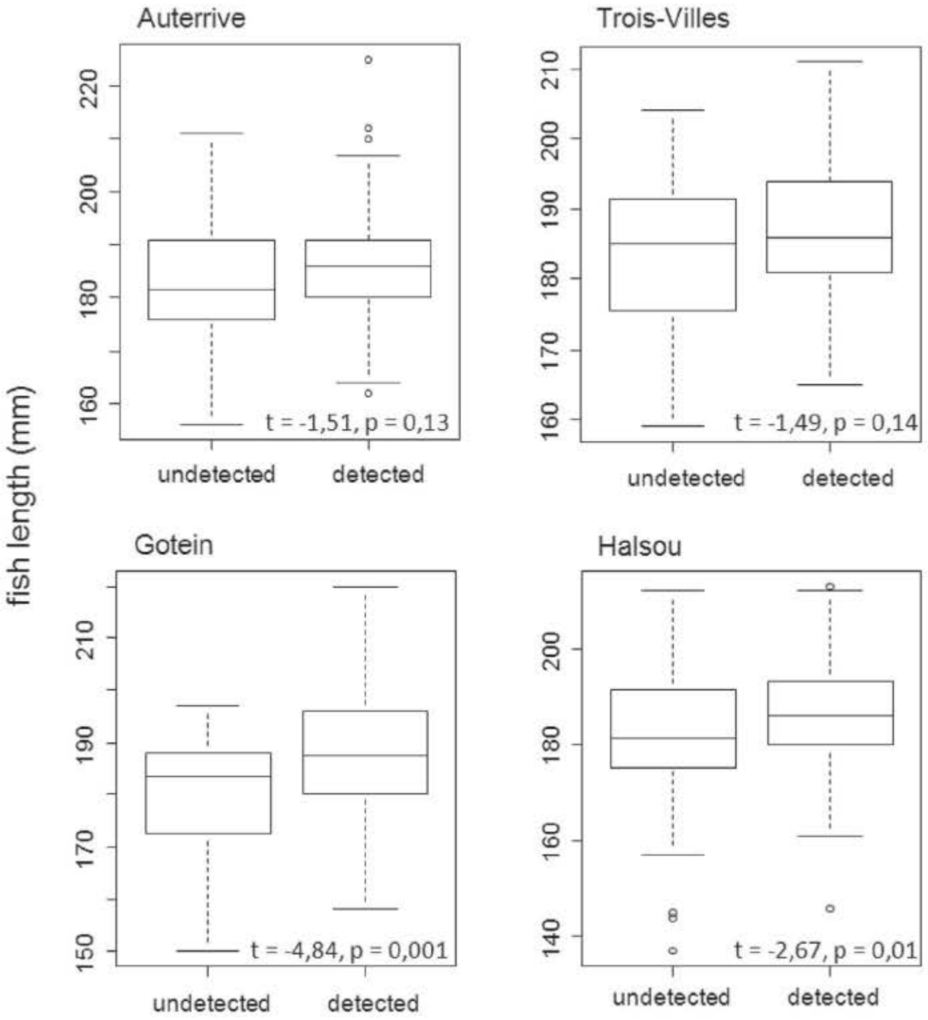

Fig. 2. Comparison of the length between undetected fishes (presumably passed through the rack) and fishes detected in the bypass (tested with Student *t*-test).

Table 2
Fish migration times through the bypass.

Site/Group	Min.	1Quartile	Median	3Quartile	Max.
Auterrive					
A 1	0:11:03	0:14:59	0:18:47	0:23:12	0:58:55
A 2	0:07:47	0:13:53	0:18:29	0:31:51	46:13:00
A 3	0:12:49	0:15:05	0:20:04	0:39:47	5:46:54
A 4	0:11:50	0:15:33	0:21:36	0:54:26	47:00:00
A 5	0:12:43	2:28:12	3:17:00	6:37:06	54:18:34
all groups	**0:07:47**	**0:15:33**	**0:22:24**	**1:51:50**	**54:18:34**
Trois-Villes					
TV 1	1:08:10	3:21:13	4:24:06	7:00:07	9:45:10
TV 2	0:12:11	0:21:43	0:54:07	1:42:09	4:06:33
TV 3	0:07:12	0:11:23	0:28:17	1:21:26	5:00:13
TV 4	0:06:41	0:46:15	1:11:41	3:49:30	40:58:52
TV 5	0:04:25	0:17:55	0:24:41	0:49:04	3:08:22
TV 6	0:08:55	0:18:03	0:37:32	1:06:16	16:35:00
all groups	**0:04:25**	**0:24:41**	**1:02:01**	**3:15:39**	**40:58:52**
Gotein					
GOT 1	0:06:35	0:14:48	0:51:29	1:57:16	187:33:21
GOT 2	0:08:17	0:13:51	0:20:32	0:41:12	6:05:32
GOT 3	0:03:25	0:07:02	0:11:53	0:19:57	1:31:24
GOT 4	0:05:31	0:18:17	0:37:19	1:25:03	44:48:44
GOT 5	0:03:47	0:10:56	0:19:45	0:53:25	52:22:36
GOT 6	0:05:55	0:13:00	0:18:27	0:35:38	108:06:54
all groups	**0:03:25**	**0:12:05**	**0:19:59**	**1:08:13**	**187:33:21**
Halsou					
HAL 1	0:01:09	0:04:09	0:11:15	0:25:45	4:54:00
HAL 2	0:01:06	0:02:30	0:21:12	1:41:06	22:30:00
HAL 3	0:50:12	2:18:12	2:57:06	3:14:00	82j 12:30:56
HAL 4	0:01:06	0:02:54	0:10:30	0:23:20	33j 23:23:35
HAL 5	0:01:20	0:05:06	0:14:06	0:46:20	6j 23:26:53
all groups	**0:01:06**	**0:04:37**	**0:17:35**	**2:14:37**	**82j 12:30:56**

evacuation canal but were omitted from the efficiency evaluations (debris canal was not considered as a safe way for fish although our observations confirmed an apparent integrity of fishes), and no passage was detected in the fish pass.

At all four sites, the mean length of undetected fish was always smaller than the mean length of fish detected in the bypass section: 183.3 < 186.1 mm at Auterrive site; 183.4 < 186.5 mm at Trois Villes site; 180.1 < 188 mm at Gotein site and 180.8 < 186.2 mm at Halsou site (Fig. 2). However, this difference was statistically significant only in two cases: at Gotein ($t = -4.84$, $p = 0.001$) and at Halsou site ($t = -2.67$, $p = 0.01$).

At Auterrive and Halsou sites (equipped with an antenna in the bypass entrance), first individuals approaching the bypass entrances were detected in a few minutes after their release. However, many of these detections were repeated, spaced by several seconds, minutes or hours, revealing hesitations of some individuals. First migrations through the bypass were detected in less than 13 min after the fish release for nearly all groups and all sites (Table 2). Excepting for Trois Villes site (where migration times were longer), 50% of the smolts passed through the bypass in less than 23 min after release and 75% of them in less than 2 h 15 min. Longer fish migration times were generally observed for day releases: median migration times for day releases ranged between 37 min and 4 h 24 min, while median migration times for night releases ranged from 10 to 54 min. Despite some exceptionally long delays, all migrating fish successfully crossed the HEP in less than 2 days.

Table 4
Three different evaluations of bypass passage minimum efficiency using i) all dataset, ii) a subset of individuals less than 200 mm length, and iii) a subset of individuals less than 190 mm length.

Site	Bypass passage minimum efficiency (%)					
	all individuals		ind. ≤ 200 mm		ind. ≤ 190 mm	
	mean	min–max	mean	min–max	mean	min–max
Auterrive	80.9	75.5–89.2	78.9	74.4–85.3	78.5	71.4–86.4
Trois-Villes	87.5	78.8–97.1	87.2	78.6–96.9	87.7	79.2–96.4
Gotein	80.9	71.2–100.0	78.8	68.9–100.0	76.9	65.7–100.0
Halsou	87.0	78.8–94.4	86.9	78.3–94.0	85.7	75.0–95.5

In three of the four studied sites the overall fish survival through the dam/HEP installations was lower without fish protection devices (93.1% at Trois Villes, 92.7% at Gotein and 86.4% at Halsou site) than with them (above 98% for all; Table 3). The Auterrive site, with nearly 100% fish survival with or without protection device (Table 3), is a special case because of the absence of dam in the river and a low turbine discharge compared to the river discharge during salmon smolt migration period, resulting in a very low fish entrainment into the intake channel.

4. Discussion

Our observed minimum passage efficiency through the bypass ranged from 80.9% to 87.5% on average depending on the studied site (Table 1). As stated in Section 2.4, the used RFID technology did not allow the detection of fish passing through the turbine and we assumed that all undetected fish passed through this way resulting in a minimum passage efficiency estimate, the real efficiency being certainly higher. Although our passage efficiency estimates are acceptable, an additional step is needed to confirm or adjust the passage efficiency values observed here with direct estimates of passages through the turbines.

We observed some variability among the released groups (ranging from 71.2 to 100%), but the bypass passage efficiency was never below 70%. In comparison with previous efficiency studies of other rack types (different bar spacing, inclination or orientation, summarized in Table 5), our results belong to the highest bypass passage efficiencies recorded so far.

Table 3
Overall fish survival estimations at the studied sites (dam + HEP passages with and without protection system) based on the entrainment rates of downstream migrating fish into the intake channel, the proportion of them passing through the turbines and the resulting turbine mortality.

Site	Dam		HEP	HEP without protection system		HEP with protection system	
	Proportion (%) of fish passing over the HEP dam in the river[2]	Fish entrainment rate (%) into the intake channel[2]	Turbine mortality rate[2] (%)	Proportion (%) of fish passing through the turbine[3]	Overall fish survival (dam + HEP, %)	Proportion (%) of fish passing through the turbine[4]	Overall fish survival (dam + HEP, %)
Auterrive[1]	97.6	2.4	5.2	2.3	99.9	0.4	99.98
Trois-Villes	8.4	91.6	11	62.8	93.1	7.0	99.2
Gotein	32.4	67.6	11	66.2	92.7	11.6	98.7
Halsou	9.6	90.4	15	90.4	86.4	11.8	98.2

[1] Site without dam in the river.
[2] Following Anonymous, 2002a, 2002b;Voegtlé, 2010.
[3] Computed using fish entrainment rate into the intake channel minus fish passing through the fish pass and the evacuation canal (proportions in Table 2).
[4] Computed using mean entrainment rate to the turbine (= proportion of undetected fish in Table 2).

Our results show some individual based variability in migration time. The first HEP passages were detected in less than 10 min after fish release in the intake channel, and 75% of the individuals detected in the bypass section successfully passed the HEP in a few hours (Table 2). The groups released in the evening or in the morning had migration times much longer than those released at night. Hansen and Jonsson (1985) already observed this difference in migration time between day and night for salmon smolts. Studying the downstream migration of wild salmon smolts at the Nive River (Halsou site), Larinier and Boyer Bernard (1991) showed lower migration activity between 9 and 13 h and between 16 and 18 h, while migration peaked during the night, between 22 h and midnight. This daily variation in fish activity certainly explains the observed differences in migration time. If we only account for groups released at night, we found that 75% of the individuals detected in the bypass section successfully crossed the HEP in less than 1 h in 11 of 16 released groups, in less than 2 h in four other groups and in 3 h 50 min for the remaining group. Individuals with extremely long migration times were rare exceptions that might be either immature for downstream migration or individuals that, after losing their successful congeners, remained disoriented in the intake channel. Overall our findings clearly show short migration times for the tested protection systems as the great majority of fish cross the HEP installations in a few hours.

These high efficiency levels (Table 1) and short migration times (Table 2) were relatively stable among sites and tested groups of individuals. Also, at the level of the dam/HEP equipped with the tested fish protection systems, always more than 88% of the fish passed through a non turbine route, resulting in an overall fish survival always exceeding 98% (Table 3). These results seem satisfactory and confirm the interest of inclined and oriented racks with narrowly spaced bars for safe fish downstream migration through HEP sites.

The fish guidance efficiency, commonly used to evaluate fish protection systems (Bunt et al., 2012; Noonan et al., 2012), could not be measured during our study (see 2.4 Section) and this parameter remains to be evaluated in future studies. Although we did not explicitly evaluate the fish guidance efficiency of the studied racks, the rapid detection of individuals observed near the bypass entrances and in the bypass section (Table 2) could suggest a good guidance of fish. If we omit time, our observed minimum bypass efficiency, between 80.9% and 87.5%, could be used as a proxy of the guidance efficiency. Nevertheless, the guidance of the studied racks is still improvable as we observed some fishes approaching the entrances but not entering immediately. The antennas installed in the bypass entrance in the Auterrive and Halsou sites also detected some individuals never detected afterwards in the bypass sections. It seems therefore that some fish hesitated and spent time upstream the rack before finally entering either the bypass, other ways (fish pass, evacuation canal) or probably passing through the rack and turbines. The velocity acceleration and higher hydraulic turbulence in the bypass entrances might explain fish hesitation (Haro et al., 1998) and should be considered as key points for bypass passage attractiveness.

The efficiency of a fishway depends not only on its general design criteria but also on its implementation in a particular site (i.e. accounting for flow directions and turbulences close to the rack) and on the functioning of the HEP (i.e. the variability in turbine discharge for electricity production). With the majority of passages occurring through the bypass (Table 1), our study shows first that fish passes were not useful for downstream migration because their upstream entrances were not positioned close to the racks. At Auterrive site, we observed a preferential incoming flow on the right bank (unexpected when the rack was designing) leading to a water recirculation zone at the top of the rack along the left bank. Fish individuals spent time in this zone, with no bypass entrance, probably at the expense of the system attractiveness and efficiency (as stated by Larinier and Travade, 1999). Based on this finding and in addition to other general criteria (Courret and Larinier, 2008), particular attention should be paid on the positioning of the bypass entrances to adapt them to the site specific flow organization.

Because of the vulnerable status of salmon populations in many French rivers, we opted for using hatchery reared fishes rather than individuals from wild populations. Previous studies found no difference in downstream passage behavior and success between wild and hatchery reared smolts (Larinier and Travade, 1999; Nyqvist et al., 2016). However, wild salmon smolts being usually smaller than hatchery ones, the potential effect of body size remains open. In a previous downstream migration survey at Halsou site (Gosset and Travade, 1999), body length of wild salmon smolts ranged from 112 to 280 mm with mean values between 162 and 170 mm depending on the year, while our individuals ranged from 137 to 225 mm, with *c.* 186 mm mean length. From our findings, a repellent rack effect as a function of fish size cannot be fully discarded (Fig. 2), suggesting that our results may not be relevant for wild salmon populations. However, our results are only marginally affected by body size. Indeed, if we estimate the bypass passage minimum efficiencies only with individuals less than 200 mm or even 190 mm, to get closer to wild salmon smolts body size, the passage efficiencies only slightly decrease in three of the studied sites, and mean efficiencies are never below 75% (Table 4), suggesting that our results and main conclusions can reasonably be applied to wild populations of salmon smolts.

More than 88% of fish passing through a non turbine route (Table 3) and more than 98% of juvenile fish survival values exceed, for instance, regional goals established for each dam along the Columbia River (USA) to allow for salmon stocks recovery: passage of at least 80% of juvenile migrants through a non turbine route and 95% juvenile fish survival (Ferguson et al., 1998). At first sight, one could believe that fish survival values estimated without protection systems, ranging from 86% to 93% at Trois Villes, Gotein and Halsou sites (Table 3), do not significantly impact downstream migrating fish. It could seem true for a single HEP, but cascades of them are usually placed along a river course, greatly increasing the overall impact. For example, the overall survival of fish crossing our three HEP installations without protection systems (Trois Villes, Gotein and Halsou), if cumulated together, would achieve only 74.6%, but the fish survival increases to 96.1% if the tested protection systems are included. This example shows clearly the ecological gain we can obtain if such fish protection devices are implemented at the catchment scale.

5. Conclusions

We can conclude that the fish protection racks tested here significantly improve the conditions for downstream migration as they result in high and stable efficiency levels and short migration times, allowing to recognize them as functional downstream fish passage solutions for wild Atlantic salmon populations. Further studies are however needed, including other downstream migrating species (e.g. eels) and more HEPs with higher turbine discharge.

Declaration of interest

None.

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Appendix

See Tables 5 and 6.

Table 5
Summary of results about bypass passage efficiencies from present and previous studies (in bold, mean efficiencies higher than 80%).

Reference	Site (River)	Max intake capacity Q_{HEP} ($m^3 \cdot s^{-1}$)	Protection rack			Bypass		Bypass passage efficiency		
			bar spacing (mm)	inclination to the horizontal	orientation to the flow	Nb of entrances	Discharge (proportion of Q_{HEP} %)	Mean	Max	Min
present study	**Auterrive (Gave d'Oloron)**	**9.5**	**20**	**26**	**90**	**2**	**5.3**	**80.7**	**89.2**	**75.5**
present study	**Trois-Villes (Saison)**	**4.1**	**20**	**26**	**90**	**1**	**4.9**	**87.5**	**97.1**	**78.8**
present study	**Gotein (Saison)**	**6.7**	**20**	**26**	**90**	**2**	**5.7**	**80.9**	**100**	**71.2**
Calles (n.d.)	**Övre Finsjö**	**14**	**18**	**35**	**90**	**2**		**84**	**–**	**–**
Croze (2008)	Guilhot (Ariège)	27	32	45	90	1	6–8	75	96.1	64
Croze (2008)	las Rives (Ariège)	39	40	45	90	1	1.9	49	62	37.3
Croze (2008)	Las Mijeannes (Ariège)	40	30	45	90	1	2.25	32	61.2	14
Travade et al. (1999)	**St Cricq (Gave d'Ossau)**	**19**	**25**	**55**	**90**	**2**	**1.5–4.2**	**80**	**100**	**62.6**
Chanseau et al. (1999)	Bedous (gave d'Aspe)	28	30	> 60	90	1	1.6–4.3	55	74.3	38.4
Travade et al. (1996)	Soeix (Gave d'Aspe)	34.8	35	> 60	90	1	2–5.2	59	89	42
Croze (2008)	Crampagna (Ariège)	24	30	75	90	1	1.4	65.6	80.4	50
Chanseau et al. (2002)	Castetarbe (Gave de Pau)	40	25	75	90	3	3–6	33	–	–
Croze et al. (1999)	Camon (Garonne)	85	40	79	90	1	2.4–3.6	73	85	57
Bosc et al. (2016)	Camon (Garonne)	85	20	79	90	1	3.3	37.1	66	4
Bosc et al. (2016)	Pointis (Garonne)	60	20	79	90	2	5	54	76	36
Nettles and Gloss (1987)	Wadham (Boquet River)	4.25	25	90	90	1	10.6–24	50	–	–
Simmons (n.d.)	**Lower Saranac HEP (Saranac)**	**31.6**	**25**	**90**	**45**	**1**	**2.8–4.3**	**90**	**100**	**80**
Environmental Research and Consulting (1996)	Upper Greenwich (Batten Kill)	21.5	25	90	45	1	2.6	64	–	–
Nettles and Gloss (1987)	**Wadham (Boquet River)**	**4.25**	**25**	**90**	**36**	**1**	**10.6–24**	**100**	**–**	**–**
Heiß (2015)	**Herting HEP (Atran)**	**40**	**15**	**90**	**30**	**1**	**0.75**	**89.5**	**–**	**–**
Chanseau et al. (2002)	**Baigts (Gave de Pau)**	**90**	**30**	**76**	**30**	**2**	**2–13.5**	**92.5**	**–**	**–**
Larinier & Boyer-Bernard (1991)	**Halsou (Nive)**	**30**	**30**	**64**	**25**	**1**	**0.9**	**94.5**	**100**	**87.5**
Gosset et al. (1998)	Halsou (Nive)	30	30	64	25	1	1.5–2	56	78	32
present study	**Halsou (Nive)**	**30**	**20**	**64**	**15**	**1**	**5**	**87**	**94.4**	**78.8**
Charles Ritzi Associates (1993)	**Hillsborough Mills Dam (Souhegam)**	**6.8**	**25**	**90**	**~10**	**1**	**12.5–16.6**	**97**	**–**	**–**
Bach et al. (2004) in Tétard et al. (2016)	Poutès (Allier)	28	30	> 60	~20*	1	2.5	58	–	–
Tétard et al. (2016)	Poutès (Allier)	28	30	> 60	~20*	1	7.1	66	–	–
Ovidio et al. (2017)	Lorcé (Amblève)	26	41	90	0	1	0.7	15.3	22	6

– the information is not available in the publication.

* Particular situation: rack orientation is not useful for fish guidance.

Table 6

Detailed characteristics of the study sites and their fish protection systems.

Site (River)	HEP			Fish protection rack					Bypass					
	intake canal length (m)	intake capacity Q_{HEP}* ($m^3 \cdot s^{-1}$)	flow velocity upstream the rack* ($m \cdot s^{-1}$)	inclination to the horizontal (°)	orientation to the flow (°)	submerged surface (m^2)	normal flow velocity* ($m \cdot s^{-1}$)	bar spacing (mm)	discharge ($m^3 \cdot s^{-1}$)	(% of Q_{HEP})*	number of entrances	Width (m)	Entrance depth (m)	Velocity ($m \cdot s^{-1}$)
Auterrive (Gave d'Oloron)	400	7.8 (9.5)	0.36–0.45 (0.44–0.55)	26°	90°	32.5	0.24 (0.29)	20	0.5	6.4% (5.3%)	2	0.5 + 0.7	0.5–1.2	0.35–0.83
Trois-Villes (Saison)	550	3.9 (4.1)	0.37 (0.38)	26°	90°	24.8	0.16 (0.16)	20	0.2	5.1% (4.9%)	1	1.0	0.5	0.4
Gotein (Saison)	780	6.7 (6.7)	0.40 (0.40)	26°	90°	27.5	0.24 (0.24)	20	0.38	5.7% (5.7%)	2	0.8 + 0.8	0.5	0.47
Halsou (Nive)	925	20–23.8 (30)	0.6–0.72 (0.91)	64°	15°	76	0.26–0.31 (0.39)	20	1–1.5	5% (5%)	1	1.38	≥0.5	0.7–1.4

* Mean value during the study (limit or target value fixed by French authorities).

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