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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