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AUTHOR LIST AND AFFILIATIONS

Thomas TRANCART[1*], Nils TEICHERT[1], Jézabel LAMOUREUX[1], Elouana GHARNIT[1], Anthony ACOU[2], Eric DE OLIVEIRA[3], Romain ROY[3], Eric FEUNTEUN[1]

* : Corresponding author

1 : Laboratoire de Biologie des Organismes et Ecosystèmes Aquatiques (BOREA) MNHN, CNRS, IRD, SU, UCN, UA, Station Marine de Dinard – CRESCO, 38 rue du Port Blanc 35800 Dinard, France

2 : Agence Française pour la Biodiversité, UMS AFB-CNRS-MNHN PatriNat, Station Marine du MNHN, Dinard, France

3 : EDF R&D LNHE - Laboratoire National Hydraulique et Environnement, 6 Quai Watier, 78401, Chatou, Cedex, France

ABSTRACT

Very few tidal power plants exist in the world. The first one was built in the Rance estuary (Brittany, France) in 1966 and the second one in South Korea. However, with the increasing demand in renewable energy, other tidal power plant projects are being studied.

These power plants are larger than unidirectional fluvial hydropower plants and strongly modify the natural tidal cycle in estuarine systems. As such, their effect on megafaunal movements might strongly differ from those caused by unidirectional fluvial hydropower plants and should be specifically considered and studied before the development of similar constructions.

In this study, an acoustic telemetry array was deployed to track 25 silver eels released 16 km upstream of the Rance tidal power dam. Only 1/3 of the tagged eels passed the dam and reached the sea. Data suggested that eels interrupted their migration up to 5 km upstream of the dam. We assume that the noise and tidal disturbance generated by the dam could lead to a disruption of a high proportion of silver eels' reproductive migration.

KEYWORDS

Anguilla Anguilla

Escapement

Conservation policy

Acoustic telemetry

Hydropower plant

Turbines

Tidal power plant

1. INTRODUCTION

In France, the proportion of renewable energy raw consumption increased significantly from about 9% in 2005 to 19.1 % in 2020 (Phan et al., 2021). Investments should increase massively in the coming years as the French directive 2009/28/CE set a global target of 33 % by 2030. In comparison to the total energy production in France by year, i.e. 307 TWh, the contribution of marine energy remains very low, with only 0.5 TWh produced. However, this production is made by only one facility: the tidal power plant of Rance. The Rance estuary, in northwestern France, is one of the rare estuaries in the world equipped with a tidal power plant. This plant is the second largest in the world, measuring 750 m long and creating an upstream retention basin of 22 km², which is a natural ria of 20 m maximum depth. The power plant can produce around 500 GWh per year and participate in up to 17 % of the Region's energy production, which provides approximately the supply for a city of c.a. 200,000 inhabitants. This estuary is also an area with a large fish biodiversity (Le Mao, 1985), and the eel population appears quite important across the river basin, although this is not verified (no fisheries and no regular scientific sampling).

As the recruitment rate of European eels has dramatically declined (factor of ten since the late 1970s, (Dekker et al., 2003; ICES, 2021, 2018), since 2014 the species is considered as a critically endangered species by the International Union for Conservation of Nature (Jacoby and Gollock, 2014). In order to restore the European eel stock, the European Union has adopted an eel regulation which mandates, in each member state, the implementation of measures to reduce anthropogenic impact on eels (e.g. reducing commercial fishing activity, taking measures to make rivers passable or temporary switching-off of hydro-electric power turbines, restoring habitats, etc.) (ICES, 2022). Hydroelectric turbines are listed as a major impact on silver eel migration, causing injuries (Bruijs and Durif, 2009), direct mortality (Winter et al., 2006; Bruijs and Durif, 2009), delays to the timing of migration (Behrmann-Godel and Eckmann, 2003), and hinder downstream migration (Durif et al., 2003). A common objective of an escapement to the sea of at least 40 % of the silver eel biomass "relative to the best estimate of escapement that would have existed if no anthropogenic influences had impacted the stock" was also set (UE Regulation No.1100/2007, European Commission, 2007).

The silver eel stage corresponds to the downstream migrants, leaving the watersheds after several years of growth to reach the Sargasso Sea for breeding (Aarestrup et al., 2009; Tesch, 1977). The downstream migration of European silver eels depends on local conditions that act at three different phases. First, temperature, photoperiod and food regime influence the growth and maturation of the eels during their growth phase (yellow eels, Daverat et al., 2012). Second, the increase in temperature and photoperiod during spring stimulates the neuroendocrine system that promotes metamorphosis from yellow to silver eels (Dufour, 2003; van den Thillart et al., 2009. Third, at the end of summer, silver eels are physiologically ready to migrate (Durif et al., 2006), with migratory behaviour being triggered and driven by environmental factors such as strong water discharge along rivers (rainfall, flood events, dam openings, and atmospheric depression) and low light conditions (increased turbidity and moon phases) (Winter et al., 2006; Bultel et al., 2014).

Because of the scarcity of tidal power plants in the world, at the best of our knowledge, no study investigated the silver eel movement or migration in such highly modified estuary. In contrast, numerous studies have focused on direct impacts of turbines on eel migration (e.g. mortalities or injuries) in classical hydropower turbines, *i.e.* dams with turbines on unidirectionnal-water-flow river (see for instance Winter, Jansen, & Bruijs, 2006; Bruijs & Durif, 2009). However, the structure and functioning of tidal power plants remain strongly different from classical hydropower dams for four main reasons. Firstly, their sizes are often more important, i.e. the Rance tidal power plant is 750 m long, with 24 turbines for a 240 MW total instantaneous power and in South-Korea, the Sihwa Lake plant (the most powerful tidal power plant in the world), is 10 km long and 254 MW total power. Fluvial hydropower dams on a large rivers are usually equipped by 4 to 8 turbines, as for instance the Kembs (6 turbines, 170 m long) or Fessenheim (4 turbines, 120 m long) plants in the Rhine River, which are two of the most largest river powerplants in France. Secondly, tidal power plants are bidirectional as they operate during the two tidal ways (ebb and flood tides). Thirdly, these dams maximize the hydraulic potential between high and low tides, which creates artificial tidal rhythms and sharply modifies hydrodynamic regimes (duration of the tides and velocity of the currents). Finally, the turbine rotation speeds are lower than in large rivers hydropower turbines (93 Hz in Rance versus >100 Hz for others). Given these particularities, specific studies on tidal power plants should be implemented to investigate their impacts compared to a classic fluvial hydropower power plant.

Accordingly, this study aimed to investigate the complete silver eel migration based on acoustic telemetry approach, from the top of the estuary to the mouth, via the tidal power plant. In this aim, the escapement of silver eels (number of tagged eels that reached the sea versus the total number of tagged eels that started the migration) and the progression in the estuary will be precisely described.

2. MATERIAL AND METHODS

2.1. Study sites and hydrophone arrays

The study took place in the Rance estuary which opens into the English Channel (48°38'01.5"N 2°02'24.4"W), but is impaired by a large 750 m long hydropower dam (Fig. 1). The overall length of the river is 127 km and the watershed is 1,117 km². Close to the estuary (10 km from tidal limit), the river has a minimum discharge of 0.055 $m^3 \cdot s^{-1}$ to reach 0.55 $m^3 \cdot s^{-1}$ during flooding periods (Guenroc - 1938/2014, barrage de Rophemel - Banque HYDRO, DREAL Bretagne). Fish downstream and upstream movement to cross plant is possible by three ways: 1) a lock on its left bank, 2) a tidal power plant composed of 24 Kaplan turbines (4 blades and a rotation speed of 93 rpm, diameter = 5.35 m), 3) and six sluice gates on its right bank (Fig. 2). The Kaplan turbines, that are the most prevalent in Europe, induce a mortality of 8.7 % for eels in the Rance tidal power plant (Briand et al., 2016). The particularity of tidal barrage is to make use of the potential energy by maximizing the water level difference between high and low tides, creating strong artificial tidal rhythms, both during filling and emptying the basin (double action cycle).

2.2. Acoustic telemetry system

Passive acoustic telemetry affords valuable information about escapement rates, activity periods, swimming distances, speeds, and route choices (Trancart et al., 2018) even if the exact position of the tagged individuals is not known between two successive detection events. Therefore, prior to eel migration period, we deployed 33 hydrophones (Thelma TBR700 and Vemco VR2W) along the Rance estuary from the tidal limit to the mouth of the Rance river, totalising 15.5 km of survey. Each hydrophone was attached about 15 cm from the bottom to a mooring weight of 80 kg. Preliminary range tests indicated that each hydrophone could detect fish within a radius of 200 m in classic water turbidity and current conditions. To maximise the probability of detection, the hydrophone network was designed with seven acoustic arrays (composed of two to six hydrophones), creating six bounded zones (Fig 1). Stations S1 to S5 were located 12.8 km to 1.5 km upstream of the dam whereas stations S6 and S7 were deployed downstream of it. The 33 hydrophones were deployed until mid-May 2020, when eel migration was over.

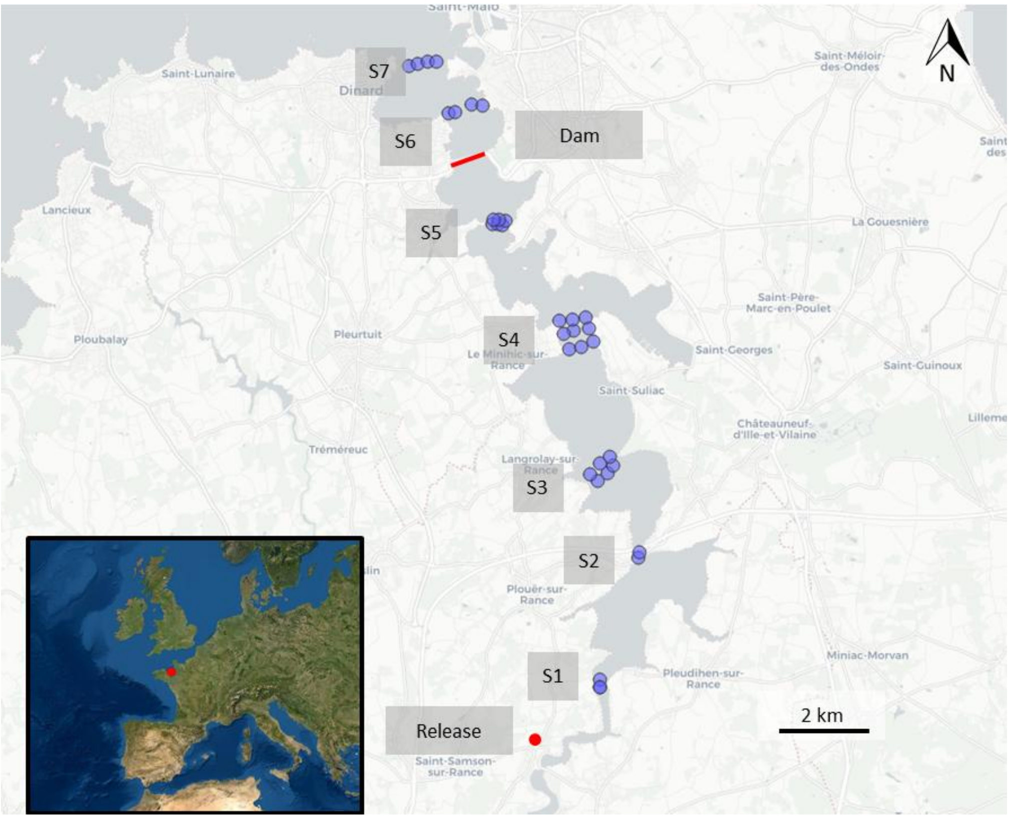

Figure 1 : Study site located in Britany (North-west of France), in the ria of the River Rance. Six bounded zones have been created by acoustic hydrophones' barriers (33 hydrophones, purple points) at seven different locations (S1 to S7) on a linear of 15.5 km. The hydropower dam of the Rance is located between stations 5 and 6 (red line).

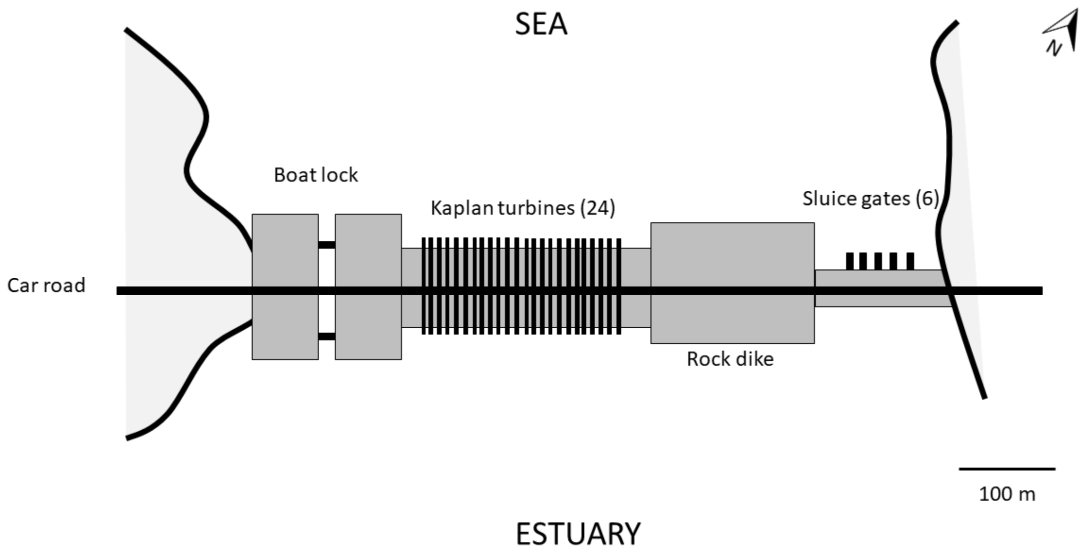

Figure 2: Scheme of the dam on the Rance river.

2.3. Collection and tagging of silver eels

Scientific capture of silver eel in the Rance river being unsuccessful, individuals (n = 25) were captured in fall 2019 by a professional fishery using triple fyke nets in the lake Grand lieu (47°05'31.8"N 1°38'59.0"W), located about 200 km away from the Rance estuary. All eels were transported to the laboratory (200 km) for tagging and maintained in large tanks (2 x 400 l) filled with water from the Grand lieu lake. The same day fish were transported, they were anesthetized with benzocaine (150 mg/L) and tagged with acoustic transmitter (ID-LP9L-69 kHz Thelma Biotel, Trondheim, Norway; transmission interval 30-90 seconds) of 9 mm diameter, 24 mm long and weighing 4 g in air, respecting the 2% transmitter/body mass ratio (Winter, 1996) in internal cavity. Incisions (20 mm long) were located on the ventral face, 10 cm before the anus, closed with absorbable sterile sutures (3–0 Ethicon Monocryltm, Ethicon Ltd., Livingston, UK) and disinfected with bactericidal antiseptic (0.05% chlorhexidine). Once the eels were anesthesied, the durations of anaesthesia were under 5 minutes. Total length (mm), body weight (g) of each individual was recorded as well as pectoral fin length (mm) and average eye diameter (mm) to determine the maturation stage. The mean total length was 728 mm (sd = 74 mm), the mean total weight 802 g (sd = 287 g), and all the tagged eels were classified as silver eels using standard external characteristics of silvering (Acou et al., 2005). All tagged eels were assumed to be females based on body length that represent well known sexually dimorphic features (Tesch, 2003). Eels equipped with transmitters were finally released after one hour of acclimatation in a small brackish tributary of the river Rance (i.e. Le moulin River) on the 21st of November 2019, about 16 km upstream from the dam and 2 km from station 1 (Fig. 1). All fish were handled following the European Union regulations concerning the protection of experimental animals. Accordingly, the research protocol was approved by the Ethics and Animal Experimentation Committee of the MNHN (CEEA – 068, # 2019-68-108) and the French Ministry of research and the tagging was realized by an authorized person only.

2.4. Individual metrics

Following eel release, both date and time of the beginning of the migration were determined by the first detection at the first station. The proportion of downstream migrants was defined as the number of tagged silver eels observed at the first station in comparison to the total number of tagged eels (n = 25). The individual progression of fish in the estuary was investigated by computing the presence of tagged eels at each station and the total number of individual detections at each station. A large number of detections for a given fish at a specific station indicates a slow passage or a stationary phase close to the hydrophone. To remove obvious detection failures, a fish observed at a given station was considered as observed at all the previous stations. These extrapolated data were used to compute the line loss and the escapement rate, but not for temporal estimation. The line loss along the estuary was investigated by computing the percentage of tagged eels observed at each station in comparison to the total number of tagged eels (n = 25). A polynomial model (degree 3) was then fitted, and the derivative was computed to determine the slope breaks, corresponding to stations where the longitudinal progression dropped.

Finally, the escapement success was estimated with several metrics. The final escapement was defined as the total number of tagged eels detected by at least at one station located downstream of the tidal power plant against the total number of tagged eels. The time to cross the estuary was defined by the time difference between the last upstream (station 1) and the first downstream detections (stations 6 or 7). The time to cross the tidal power station was defined by the time difference between the last upstream (station 5) and the first downstream detections (stations 6 or 7). The individual date and time of escapement was then linked with the tidal power plant log to determine the operational status of the dam, i.e. turbines power turn on or off. At the power plant, silver eel may escape to the sea via three different ways: passing through one of the 24 turbines, through the boat lock or the sluice gates. All the opening of the boat lock are summarized in a log book, and linked with the individual time-date of escapement in order to see if the boat lock was a possible escapement way for each tagged eel.

2.5. Array efficiency

The efficiency of the hydrophone array was determined for each station (except the last) as the ratio between the number of eels detected versus the total number of eels that cross the station (i.e. detected and extrapolated).

3. RESULTS

All the tagged silver eels were detected by at least one hydrophone located in the estuary, indicating that they all displayed a migratory behavior (Fig.3). The efficiency of the array was constant and high through the upstream estuary, ranged from 92 to 100 % (S5 – S1). Only the detection in the station 6 (downstream the power plant) was lower (66.7 %, Table 1). Among the 25 tagged eels, 76 % (n = 19) moved before the third day after their release and 100 % before the 12th day. A non-constant line loss was observed along the estuary, i.e. 100% of tagged eels were detected at the first station, 96 % at the second, 92 % at the third, and 72 % at the fourth (Fig. 3). But only 48

% of tagged eels were detected at the fifth station, located just before the tidal power plant. Analysis of the slope of the derivative showed an inflexion point located between stations S4 and S5. Finally, 36 % of silver eels were detected downstream of the tidal power dam, representing an escapement rate of 75 % (ratio between the total number of tagged eels observed at station #5, and the number of eels observed at stations #6 and #7).

Table 1: Efficiency of the detection array

Station	**Efficiency (%)**
S1	100
S2	100
S3	95.6
S4	94.4
S5	91.6
S6	66.7

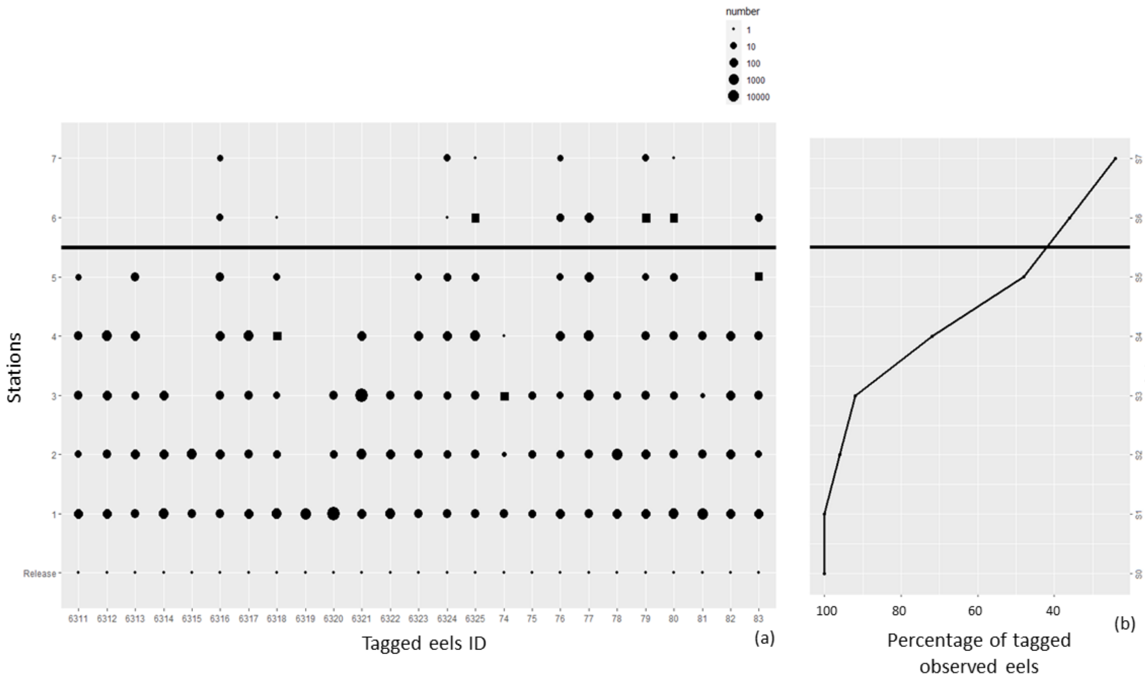

Figure 3-a: Variation of spatial detection evolution of the 25 tagged silver eels within the Rance estuary for each detection station ordered from upstream release site to the sea (S7). The size of the dots indicates the number of records. Black squares indicate extrapolated detections. Figure 3-b: Percentage of tagged observed eels at each stations. The black lines indicate the position of the tidal power plant.

The median time to cross the estuary and the power plant was 6 days with a range from 4.0 to 82.2 days. Among the 9 individuals that crossed the dam, 8 (98%) did it during night-time (between 9 PM and 4 AM) and all the tagged eels crossed the tidal power plant through one of the 24 turbines during ebb-tide periods. None of the date and time of crossing events corresponded to the timing of opening of the boat lock (no boat traffic at night during the study period) or the sluice gates. The median time to pass the dam was 68.4 minutes, ranging from 53 to 122 minutes. Finally, for the 9 escaped eels, no reverse movement from station S5 to upper stations was observed.

No significative difference occurred between the eels that crossed the dam and the eels blocked in the estuary either in the total length (GLM, p = 0.3) or in total weight (GLM, p = 0.55).

4. DISCUSSION

The most striking result of this study is the low apparent escapement of silver eels (36%). The range of silver eels escapement from a hydropower station is very large, with a lot of adapted structures with low impact, as for instance in Behrmann-Godel and Eckmann (2003, 78 % of escapement), in Brown et al. (2009, 90 % of escapement) and Piper et al. (2013, 76 and 65 % in two successive years with 5 different blocking structures). On the other hand, some hydropower structures enable very low escapement down to 23%, as for instance Pedersen et al. (2012) . In the present study, the escapement from the tidal powerplant, defined as the ratio of tagged eels observed in station S5 versus the number of tagged eels observed in stations 6 & 7 was 75 %, as classically reported. On the opposite, the movements in the upper estuary (from release site to station S5) was lower (48 %) and led to a global low escapement rate from the Rance ria (power plant + estuary). Data on eel migration in free-flowing rivers are scarce. For instance, in the Loire river, in a 80 km long study site without dam, 94 % of tagged silver eels escaped to the sea (Bultel et al., 2014). Consequently, regarding the distance between the release site and station S5 (10 km), the number of tagged eels reached this station appeared to be low.

Firstly, a possible explanation to understand the low number of tagged eels is a default in the array efficiency close to the dam. Indeed, it is acknowledged that a noisy environment may reduce acoustic detection capacity. However we showed in preliminary 24h field tests that no significant decrease in detection capacity was observed. Moreover, the array efficiency was evaluated from our data, and the efficiency was high and constant from stations S1 to S5. Only the station S6 showed lower detection efficiency. This result seems consistent, because the station S5 located 1.5 km from the turbines and the hydrophone were placed close to the ground, where the water current is lower due to the friction force. Finally, the low number of tagged eels detected in the station S5 should not be considered as an artefact or a technical biais.

To explain this low number of tagged eels reached the station S5, we speculate that the fish translocation had a limited bias on this result. On Rhine River, an acoustic survey was deployed along a 70 km river with silver eels from four different origin sites (Trancart et al., 2018). Seven kilometers after the release site, the proportion of each origin site of observed tagged eels was similar to the release. Seventy kilometers after the release site, the proportions of observed tagged eels were still unchanged. The only factor that seems to be influenced by the translocation was the time to start the migration, but this study showed that the beginning of the migration was precipitated when the origin site was smaller (size and water flow) than the release site (Trancart et al., 2018 and unpublished data). In the present study, the tagged eels were collected in a lake, without water flow, and released in a small running stream. In our study, the majority of eels started their migration within three days and arrived up to station S4, which suggests a limited effect of translocation because the migration behaviour seemed comparable to observations in other systems (Besson et al., 2016; Trancart et al., 2018, 2020). More recently, Piper et al. (2020) compared the behaviour and the final escapement between natural and translocated eels. Migration patterns and behaviours were broadly similar between the translocated eels and river eels with 86 and 90 % of each group successfully reaching the sea, respectively. Consequently, translocation should not be considered as an important factor explaining the low escapement in the upper part of the estuary.

Another possible cause to explain the low number of tagged eels reached the station S5 could be the tidal distortion in the Rance estuary due to the tidal power dam. As for an important number of aquatic species, it is now clearly established that silver eels use selective tidal-stream transport (Forward and Tankersley, 2001) (downstream movement during ebb tide) in order to reduce energy expenditure (McCleave and Arnold, 1999; Parker and McCleave, 1997; Verhelst et al., 2018) during their downstream migration. In this type of transport, the orientation is ruled by the water current reversal cycle. However, in the Rance Estuary, the dam modifies the natural cycle of tides to produce electricity during long ebb episodes and shorter flood episodes through turbines and valves. Consequently, the flood tide currents are stronger than ebb currents. A strong behavioural disturbance caused by “fake” tidal distortion, leading to disorientation in the estuary should also be considered.

A remaining factor explaining the low number of tagged eels reached the station S5 was the dam effect, with probable high noise and vibration likely perceived by migrating silver eels in a large area upstream the tidal power plant. The noise and vibrations of dam were frequently cited as possible blocking factors on silver eel migration (Trancart et al., 2017; Bolland et al., 2019; van Keeken et al., 2020, 2021), but unfortunately, this factor was never really tested in field conditions. Silver eels face a diversity of structures with contrasted designs. The main problem for this species is generally injury or direct mortality (Bruijs and Durif, 2009; Winter et al., 2006), higher than for other fish because of their length (Larinier and Travade, 2002). In addition to direct mortality, the impacts of hydroelectric complexes are well-known, causing injuries (Bruijs and Durif, 2009), delay in the timing of migration (Behrmann-Godel & Eckmann, 2003; Besson et al., 2016; Trancart et al., 2019), and hindrance or blocking of downstream migration (Durif et al., 2003; Trancart et al., 2020). However, a fundamental difference is the distance from the dam. All the effects previously cited occurred at a very low distance from the structures. In the present study, the main problem was the low proportion of tagged eels observed in front of the tidal power plant. One assumption can be the higher noise generated by the tidal power plant than by classical river hydroelectric structures because of the high number of turbines. In the Rance River, there is 24 Kaplan turbines, while the most important hydropower dams in the main French rivers are a maximum of 6 or 8 turbines. Further acoustic measures should thus be made in the Rance estuary in order to confirm or remove this assumption.

Finally, the last reason to explain the low number of tagged eels observed in station S5 is a possible mortality. It is a recurrent problem in telemetry study to know if the tagged and tracked fish are still alive during the tracking. Eels could die as a consequence of the tagging procedure or natural mortality. For this reason, we considered that eels blocked in the estuary could be dead. Few possible predators are present in estuary, except cormorants, but regarding the mean size of tagged eels (800g – 73 cm), an eventual predation should be very low. Although post-surgery death is possible, but we are confident that the tagging protocol we applied induced low to nil post-surgery mortality as shown in previous studies we performed (Bultel et al., 2014; Trancart et al., 2017).

As discussed previously, a part of the low total escapement (estuary + dam) could be associated to the powerplant crossing. A possible explanation could be a low detection range downstream of the tidal power plant, leading to a mis-detection of escaped individuals. Such imperfect detection is possible since three tagged eels (# 6325, # 79 and # 80, Fig. 3) were recorded at station S7 without being detected at station S6. But among the 16 tagged eels that were considered as blocked (or dead) in the estuary at the end of the study, only 2 were observed for the last time at station 5. For these two eels, although the probability of escapement without been detected in stations 6 and 7 is low, it remains possible. So, it has to be considered that the "maximal" escapement including these two eels remains low (44%).

Finally, Kaplan turbines generally cause eel mortality rates ranging between 20 and 38% (Bruijs & Durif, 2009), but a previous study indicated a mortality of 8.7% for eels through Kaplan turbines in the Rance tidal power plant (Briand et al., 2016). In the present study, there is unfortunately no way to conclude if the tagged eels that passed through the power plant turbines were injured or dead. The two downstream stations were located at 1 km and 2.6 km from the dam. At this small distance, a dead or dying eels could be carried by the high-water flow released from the tidal power plant towards the sea. Nevertheless, for the tagged eels that reached the station 5, the impact of the tidal power plant seemed to be very low: 75% of success rate with a median crossing time of one hour. Two different migration behavior types seemed to occur in this study. First group seemed not to be impacted, and crossed the estuary and the tidal power plant without real difficulty. On the other hand, the second group seemed to be significantly impacted, and failed to escape. No difference was observed between these two groups for total length, total weight and maturation stage, suggesting a possible effect of behavioral traits rather than a control of morphological traits.

5. CONCLUSION

This study clearly highlighted a likely strong impact of tidal power plant on the silver eel migration. This result should be confirmed by another field study with native silver eels and with higher number of tagged eels, in order to remove potential biases. If confirmed, this impact should be taken into consideration in next future, when marine renewable energy will be widespread in our society. The European eel is a sensitive species, but other threatened diadromous fish species such as shads, salmons or lampreys could be impacted in the same manner. More generally this study poses the question of the effects of tidal hydropower dams on the ecological continuity between the estuarine ecosystems and the open sea, and the potential disruption of key ecological functions and services played by estuarine systems for marine species.

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