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1 **TITLE**

2 A possible strong impact of tidal power plant on silver eels' migration

3

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15

16 **ABSTRACT**

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

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

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

29

30 KEYWORDS

31 *Anguilla Anguilla*

32 Escapement

33 Conservation policy

34 Acoustic telemetry

35 Hydropower plant

36 Turbines

37 Tidal power plant

38

39 1. INTRODUCTION

40 In France, the proportion of renewable energy raw consumption increased significantly from
41 about 9% in 2005 to 19.1 % in 2020 (Phan et al., 2021). Investments should increase massively in the
42 coming years as the French directive 2009/28/CE set a global target of 33 % by 2030. In comparison
43 to the total energy production in France by year, i.e. 307 TWh, the contribution of marine energy
44 remains very low, with only 0.5 TWh produced. However, this production is made by only one facility:
45 the tidal power plant of Rance. The Rance estuary, in northwestern France, is one of the rare
46 estuaries in the world equipped with a tidal power plant. This plant is the second largest in the world,
47 measuring 750 m long and creating an upstream retention basin of 22 km², which is a natural ria of
48 20 m maximum depth. The power plant can produce around 500 GWh per year and participate in up
49 to 17 % of the Region's energy production, which provides approximately the supply for a city of c.a.
50 200,000 inhabitants. This estuary is also an area with a large fish biodiversity (Le Mao, 1985), and the
51 eel population appears quite important across the river basin, although this is not verified (no
52 fisheries and no regular scientific sampling).

53 As the recruitment rate of European eels has dramatically declined (factor of ten since the late
54 1970s, (Dekker et al., 2003; ICES, 2021, 2018), since 2014 the species is considered as a critically
55 endangered species by the International Union for Conservation of Nature (Jacoby and Gollock,
56 2014). In order to restore the European eel stock, the European Union has adopted an eel regulation
57 which mandates, in each member state, the implementation of measures to reduce anthropogenic
58 impact on eels (e.g. reducing commercial fishing activity, taking measures to make rivers passable or
59 temporary switching-off of hydro-electric power turbines, restoring habitats, etc.) (ICES, 2022).
60 Hydroelectric turbines are listed as a major impact on silver eel migration, causing injuries (Bruijs and
61 Durif, 2009), direct mortality (Winter et al., 2006; Bruijs and Durif, 2009), delays to the timing of

62 migration (Behrmann-Godel and Eckmann, 2003), and hinder downstream migration (Durif et al.,
63 2003). A common objective of an escapement to the sea of at least 40 % of the silver eel biomass
64 “relative to the best estimate of escapement that would have existed if no anthropogenic influences
65 had impacted the stock” was also set (UE Regulation No.1100/2007, European Commission, 2007).

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

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

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

101 2. MATERIAL AND METHODS

102 2.1. Study sites and hydrophone arrays

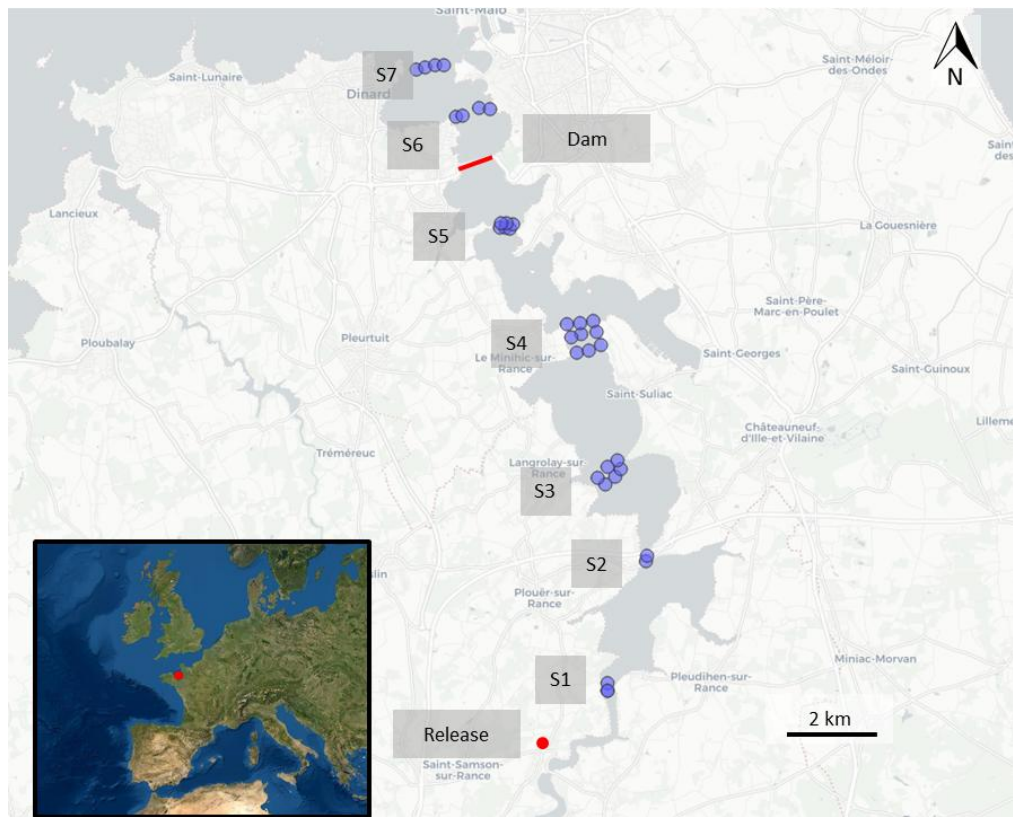
103 The study took place in the Rance estuary which opens into the English Channel (48°38'01.5"N
104 2°02'24.4"W), but is impaired by a large 750 m long hydropower dam (Fig. 1). The overall length of
105 the river is 127 km and the watershed is 1,117 km². Close to the estuary (10 km from tidal limit), the
106 river has a minimum discharge of 0.055 m³·s⁻¹ to reach 0.55 m³·s⁻¹ during flooding periods (Guenroc -
107 1938/2014, barrage de Rophemel - Banque HYDRO, DREAL Bretagne). Fish downstream and
108 upstream movement to cross plant is possible by three ways: 1) a lock on its left bank, 2) a tidal
109 power plant composed of 24 Kaplan turbines (4 blades and a rotation speed of 93 rpm, diameter =
110 5.35 m), 3) and six sluice gates on its right bank (Fig. 2). The Kaplan turbines, that are the most
111 prevalent in Europe, induce a mortality of 8.7 % for eels in the Rance tidal power plant (Briand et al.,
112 2016). The particularity of tidal barrage is to make use of the potential energy by maximizing the
113 water level difference between high and low tides, creating strong artificial tidal rhythms, both
114 during filling and emptying the basin (double action cycle).

115

116 2.2. Acoustic telemetry system

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

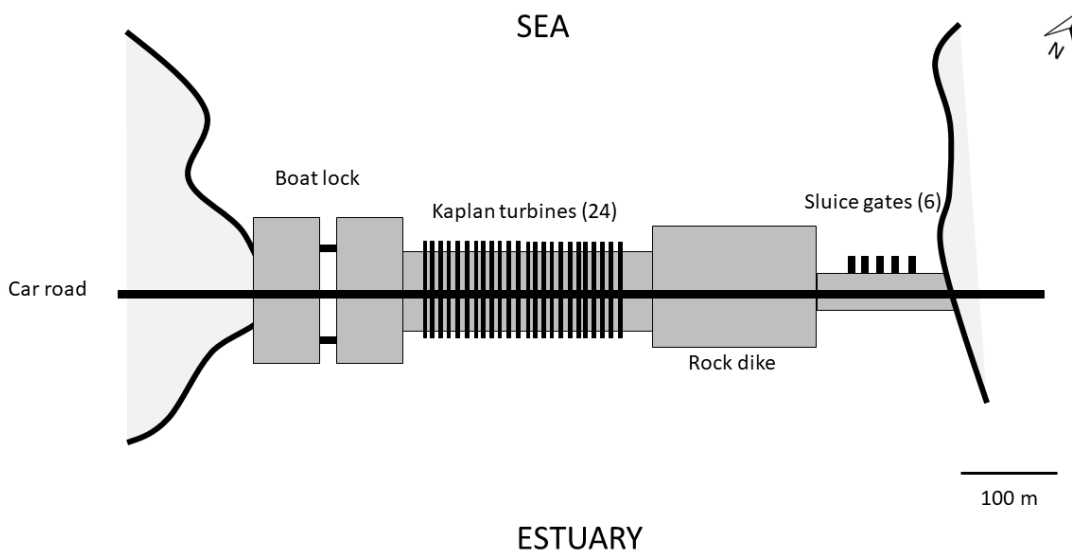
127 upstream of the dam whereas stations S6 and S7 were deployed downstream of it. The 33
 128 hydrophones were deployed until mid-May 2020, when eel migration was over.



129

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

133



134

135

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

136

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 Monocryl™, Ethicon Ltd., Livingston, UK) and disinfected with bactericidal antiseptic (0.05% chlorhexidine). Once the eels were anesthetized, 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

170 a given station was considered as observed at all the previous stations. These extrapolated data were
171 used to compute the line loss and the escapement rate, but not for temporal estimation. The line
172 loss along the estuary was investigated by computing the percentage of tagged eels observed at each
173 station in comparison to the total number of tagged eels ($n = 25$). A polynomial model (degree 3) was
174 then fitted, and the derivative was computed to determine the slope breaks, corresponding to
175 stations where the longitudinal progression dropped.

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

188

189 2.5. Array efficiency

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

193 3. RESULTS

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

201 % of tagged eels were detected at the fifth station, located just before the tidal power plant. Analysis
202 of the slope of the derivative showed an inflexion point located between stations S4 and S5. Finally,
203 36 % of silver eels were detected downstream of the tidal power dam, representing an escapement
204 rate of 75 % (ratio between the total number of tagged eels observed at station #5, and the number
205 of eels observed at stations #6 and #7).

206

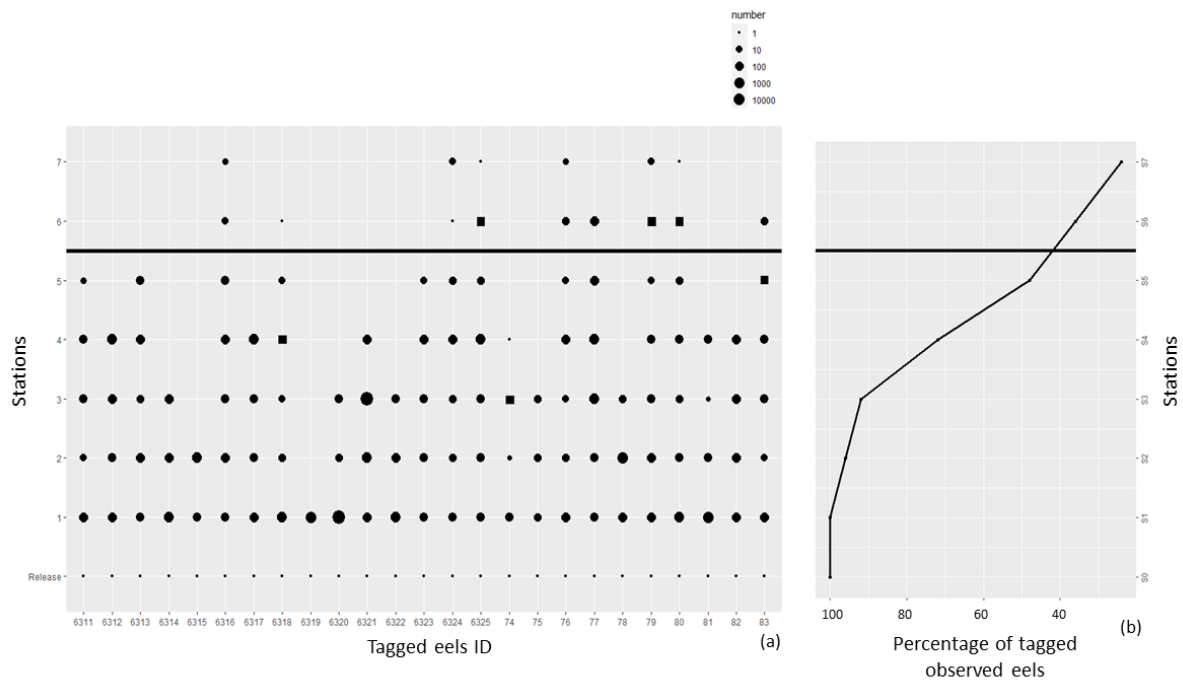
207

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

208

209



210

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

215 The median time to cross the estuary and the power plant was 6 days with a range from 4.0 to
 216 82.2 days. Among the 9 individuals that crossed the dam, 8 (98%) did it during night-time (between 9
 217 PM and 4 AM) and all the tagged eels crossed the tidal power plant through one of the 24 turbines
 218 during ebb-tide periods. None of the date and time of crossing events corresponded to the timing of
 219 opening of the boat lock (no boat traffic at night during the study period) or the sluice gates. The
 220 median time to pass the dam was 68.4 minutes, ranging from 53 to 122 minutes. Finally, for the 9
 221 escaped eels, no reverse movement from station S5 to upper stations was observed.

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

224

225 4. DISCUSSION

226 The most striking result of this study is the low apparent escapement of silver eels (36%). The
 227 range of silver eels escapement from a hydropower station is very large, with a lot of adapted
 228 structures with low impact, as for instance in Behrmann-Godel and Eckmann (2003, 78 % of
 229 escapement), in Brown et al. (2009, 90 % of escapement) and Piper et al. (2013, 76 and 65 % in two
 230 successive years with 5 different blocking structures). On the other hand, some hydropower

231 structures enable very low escapement down to 23%, as for instance Pedersen et al. (2012) . In the
232 present study, the escapement from the tidal powerplant, defined as the ratio of tagged eels
233 observed in station S5 versus the number of tagged eels observed in stations 6 & 7 was 75 %, as
234 classically reported. On the opposite, the movements in the upper estuary (from release site to
235 station S5) was lower (48 %) and led to a global low escapement rate from the Rance ria (power plant
236 + estuary). Data on eel migration in free-flowing rivers are scarce. For instance, in the Loire river, in a
237 80 km long study site without dam, 94 % of tagged silver eels escaped to the sea (Bultel et al., 2014).
238 Consequently, regarding the distance between the release site and station S5 (10 km), the number of
239 tagged eels reached this station appeared to be low.

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

249 To explain this low number of tagged eels reached the station S5, we speculate that the fish
250 translocation had a limited bias on this result. On Rhine River, an acoustic survey was deployed along
251 a 70 km river with silver eels from four different origin sites (Trancart et al., 2018). Seven kilometers
252 after the release site, the proportion of each origin site of observed tagged eels was similar to the
253 release. Seventy kilometers after the release site, the proportions of observed tagged eels were still
254 unchanged. The only factor that seems to be influenced by the translocation was the time to start
255 the migration, but this study showed that the beginning of the migration was precipitated when the
256 origin site was smaller (size and water flow) than the release site (Trancart et al., 2018 and
257 unpublished data). In the present study, the tagged eels were collected in a lake, without water flow,
258 and released in a small running stream. In our study, the majority of eels started their migration
259 within three days and arrived up to station S4, which suggests a limited effect of translocation
260 because the migration behaviour seemed comparable to observations in other systems (Besson et
261 al., 2016; Trancart et al., 2018, 2020). More recently, Piper et al. (2020) compared the behaviour and
262 the final escapement between natural and translocated eels. Migration patterns and behaviours
263 were broadly similar between the translocated eels and river eels with 86 and 90 % of each group

264 successfully reaching the sea, respectively. Consequently, translocation should not be considered as
265 an important factor explaining the low escapement in the upper part of the estuary.

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

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

296 Finally, the last reason to explain the low number of tagged eels observed in station S5 is a
297 possible mortality. It is a recurrent problem in telemetry study to know if the tagged and tracked fish

298 are still alive during the tracking. Eels could die as a consequence of the tagging procedure or natural
299 mortality. For this reason, we considered that eels blocked in the estuary could be dead. Few
300 possible predators are present in estuary, except cormorants, but regarding the mean size of tagged
301 eels (800g – 73 cm), an eventual predation should be very low. Although post-surgery death is
302 possible, but we are confident that the tagging protocol we applied induced low to nil post-surgery
303 mortality as shown in previous studies we performed (Bultel et al., 2014; Trancart et al., 2017).

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

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

326 5. CONCLUSION

327 This study clearly highlighted a likely strong impact of tidal power plant on the silver eel
328 migration. This result should be confirmed by another field study with native silver eels and with
329 higher number of tagged eels, in order to remove potential biases. If confirmed, this impact should

330 be taken into consideration in next future, when marine renewable energy will be widespread in our
331 society. The European eel is a sensitive species, but other threatened diadromous fish species such as
332 shads, salmon or lampreys could be impacted in the same manner. More generally this study poses
333 the question of the effects of tidal hydropower dams on the ecological continuity between the
334 estuarine ecosystems and the open sea, and the potential disruption of key ecological functions and
335 services played by estuarine systems for marine species.

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