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1 **Modelling past migrations to determine efficient management rules favouring silver eel**
2 **escapement from a large regulated Floodplain Lake**

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29 **Abstract**

30 As human activities caused a dramatic decline of European eel population since the 1970s, the
31 European Union has set targets to ensure a 40 % escapement to the sea of the silver eel biomass by
32 considerably reducing anthropogenic impact. Thus, human obstacles to fish migration like dams and
33 hydropower plants should enable efficient management measures ensuring safe passage for eels during
34 the migration. In order to provide a quick and efficient assessment of eel conservation measure applied
35 to the sluice gates of a large floodplain lake, we implemented a novel evaluation method using predictions
36 on past migration seasons when no management measure were applied. For this purpose, we collected
37 acoustic telemetry monitoring data over three migration seasons and fitted a predictive model based
38 on Boosted Regression Trees (BRTs) to describe the influence of environmental parameters on migration.
39 The water level difference over two days proved to be decisive, along with early migration occasions in
40 the season, as an increase of at least 10 cm water level was associated with a sharp increase of migration
41 probability. We then used the BRT model to predict migration occasions at the dam over 8 past seasons
42 and forecast the impact on escapement of management measures if they had been applied. Thanks to
43 this original prospective assessment of dam management measures, we identified an enhanced opening
44 decision rule, capable of increasing the eel escapement for each year of the study. The management
45 measure is particularly efficient during the years with poor hydrological conditions (i.e. droughts), that
46 is the periods with the lowest initial escapement rates. Finally, efficient management measures to
47 increase silver eel escapement were based on increasing the number of gate opening days by only a few
48 days per year (c.a. 15 %). However, the management measure only focused on silver eel migration, so
49 that further investigations should consider the impacts of other threats occurring during the life cycle.
50 This study also provides a highly operational approach for fast evaluation of conservation measures,
51 avoiding lengthy and expensive monitoring campaigns of classical ex-post assessments.

52 **Key words:** eel conservation; reservoir management; predictive model; fish migration

53

54

55 **Introduction**

56 The worldwide fragmentation of river networks represents a major concern for conservation and
57 restoration of continental aquatic ecosystems (Barbarossa et al., 2020). Alteration of river continuity is
58 particularly damaging for diadromous fish that have to migrate in both upstream and downstream
59 directions for achieving their biological cycles (van Puijenbroek, Buijse, Kraak, & Verdonschot, 2019).
60 Among them, the European eel (*Anguilla anguilla*, L. 1758) is highly sensitive to this threat throughout
61 its continental freshwater phase. After spawning and hatching, in the north Atlantic Convergence Zone
62 (Chang, Feunteun, Miyazawa, & Tsukamoto, 2020; Miller et al., 2015), leptocephalus larvae are oriented
63 by marine currents towards European coasts. Early continental stages colonize coastal waters, rivers
64 and lakes, where they grow between 3 and 30 years. After this continental phase, eels undergo
65 morphological and anatomical changes, reaching the silver eel stage, and undertake a long migration
66 back to their breeding areas (Feunteun, 2002; Aarestrup et al. 2008; Righton et al., 2016). At this stage,
67 the disturbances of river continuity greatly affect the downstream migration toward the sea and can
68 cause immediate and / or delayed mortality (Besson et al., 2016; Drouineau et al., 2017; Trancart et al.,
69 2020; Winter, Jansen, & Breukelaar, 2007) or delayed timing of migration (Behrmann-Godel & Eckmann,
70 2003).

71 As recruitment rate of European eel has declined dramatically by a factor of ten since the late
72 1970s (Dekker et al., 2003; ICES, 2018), it is considered since 2014 as a critically endangered species by
73 the International Union for Conservation of Nature (Jacoby & Gollock, 2014). With a view to recovering
74 the European eel stock, the European Union has adopted a regulation which mandates the
75 establishment in each Member State of Eel Management Plans describing measures to reduce
76 anthropogenic impact on eels (e.g. reducing commercial fishing activity, taking measures to make rivers
77 passable or temporary switching-off of hydro-electric power turbines, restoring habitats). A common
78 objective of an escapement to the sea of at least 40 % of the silver eel biomass relative to the best
79 estimate of escapement that would have existed if no anthropogenic influences had impacted the stock
80 was also set (UE Regulation No.1100/2007, Council of the European Union, 2007).

81 Several studies dealt with efficient fisheries management measures (Beaulaton & Briand, 2007)
82 and hydroelectric dams management (Larinier & Travade, 2002; Gosset et al., 2005; Watene & Boubee,
83 2005; Winter, Jansen, & Bruijs, 2006; Trancart et al., 2013). In contrast, few cared about optimizing
84 management of closed (or semi-closed) water systems like lagoons, regulated lakes and reservoirs
85 where fisheries reduction is sometimes necessary but must not supplant the need of a consistent
86 management (Lagarde et al., 2021; Trancart et al., 2018). These ecosystems generally offer suitable
87 growing area where eels are subjected to recreational or professional fisheries (Dekker, 2003). Lakes,

88 lagoons and reservoirs are generally highly productive and are thought to support a large proportion of
89 the spawning stock of European eels (e.g. Allen, Rosell, & Evans, 2006; Tesch, 2003; Westerberg &
90 Sjöberg, 2015). However, the artificial control of water exchanges by sluice gates can also impair the
91 seaward migrating silver eels, so that explicit management rules are required for ensuring silver eel
92 escapement. The selective opening of hydroelectric dam spillway gates which can provide safe
93 downstream passage for migrant eels (Watene & Boubee, 2005) should thus be applied to various
94 human hydraulic structures, raising the necessity to forecast efficiently eel migration peaks. Silver eel
95 migration generally occurs during the night (e.g. Aarestrup et al. 2010) and is triggered by various
96 environmental parameters like discharge, temperature, conductivity, turbidity or lunar phase (e.g.
97 Cullen and McCarthy, 2003; Durif et al., 2003; Sandlund et al., 2017; Vøllestad et al., 1986) which makes
98 possible the development of predictive models (Smith, Fackler, Eyster, Villegas Ortiz, & Welsh, 2017;
99 Teichert, Tétard, Trancart, de Oliveira, et al., 2020; Trancart et al., 2013). Such predictions have already
100 been achieved e.g. for birds whose migration intensities were forecast with a regression model based
101 on meteorological data (Van Belle, Shamoun-Baranes, Van Loon, & Bouten, 2007) and also for silver eels
102 in the case of river catchment and based on commercial fishery data (Durif & Elie, 2008; Trancart et al.,
103 2013; Teichert, Tétard, Trancart, Feunteun, et al., 2020). The accuracy of models used for dams'
104 management is all the more crucial such anthropic barriers are likely to cause a temporary or definitive
105 end to the migration and even a reversion of silver eels to the yellow eel stage (Acou, Laffaille, Legault,
106 & Feunteun, 2008; Durif, Dufour, & Elie, 2005; Feunteun, Acou, Laffaille, & Legault, 2000; Trancart et
107 al., 2018).

108 Furthermore, climate change is likely to structurally change the eel migration patterns owing to its
109 effect on triggering factors of migration (Ficke, Myrick, & Hansen, 2007). For example, extreme
110 temperatures that are an acknowledged consequence of climate change (IPCC, 2018) can inhibit eel
111 migration (Lowe, 1952; Vollestad et al., 1986). Regarding hydrology, extreme precipitations and floods
112 are expected in Europe (Madsen, Lawrence, Lang, Martinkova, & Kjeldsen, 2014) which implies a strong
113 hydrologic variability. As fish are often adapted to a certain level of hydrologic variability, European eel
114 migration patterns could thus be heavily impacted. Consequently, we aimed at proposing a powerful
115 method able to provide still water systems managers with accurate predictions considering the assumed
116 environmental conditions variability in the years to come. Following the example of Teichert, Tétard,
117 Trancart, Feunteun, et al., (2020) in the context of hydropower turbine shutdown, we worked towards
118 offering simple decision rules for sluice gates opening, based on the computed migration predictions.
119 Moreover, as prediction models cannot be directly extrapolated to new locations, we kept in mind the
120 necessity of an tool easy to execute and to transpose together with its transferability to other sites
121 (Teichert, Tétard, Trancart, de Oliveira, et al., 2020).

122 Accordingly, the present study describes a complete approach, including silver eel tagging by
123 acoustic telemetry, to find the more efficient management rules of sluice gates of the Grand-Lieu Lake
124 (western France) thanks to an efficient machine-learning approach, the Boosted Regression Trees. Silver
125 eel migration was monitored over three seasons to develop a predictive model and describe the
126 influence of environmental parameters on migration. Prediction modelling was then used to propose a
127 very effective management measure of sluice gates for conservation managers, able to meet the
128 European target of European eel conservation.

129 **Material and methods**

130 ***Study site***

131 Grand-Lieu Lake is the French largest plain lake in winter located in western France, southwest of
132 Nantes (47°05' N; 1°39' W, Fig. 1a, b). Its surface area ranges from 2 500 ha in summer to 6 300 ha in
133 winter whereas its depth ranges from 0.70–1.20 m in summer to 3.00–3.50 m in winter. The particularly
134 changing shape of the lake is due to its plain location, which leads to the flooding of the surrounding
135 wet meadows in winter. The lake is structured around a 10 km² open water stretch that constitutes the
136 permanently flooded zone with a surrounding region of floating-leaved plants. Large reed beds, willow
137 carrs, and wetland areas then extend in periphery. The lake water system is mainly supplied by the
138 watersheds of the Ognon and the Boulogne rivers (resp. 185 and 470 km²). Downstream discharge is
139 enabled by five channels dug at the northwest extremity of the open water area, which join at the
140 beginning of the Acheneau River (22 km long). Water then flows through the Canal de la Martinière and
141 finally reaches the Loire estuary. A small dam regulates the water level of the lake with five side-by-side
142 sluice gates located at the very beginning of the Acheneau River (Fig. 1c).

143 A management organisation, the SAH Sud Loire (Syndicat d'Aménagement Hydraulique), is in
144 charge of the challenging regulation of the lake water level. Indeed, water level targets, set all along the
145 year through an official decree, have to suit to different and often opposite needs of the various
146 stakeholders. For grassland production, the water level should be as low as possible in order to extend
147 as long as possible the grazing period. Then cattle breeders require low water conditions early in spring,
148 and a high-water level as late as possible in fall. Vegetable producers and farmers located close to the
149 lake use superficial ground waters linked with the lake. Their needs are relatively less important, but can
150 remain significant, especially during low water periods in summer. Professional fishermen activities
151 carried on the lake need high level water and slow decrease when it is rigorously required, and then
152 short low water level periods. Hunters require high water level earliest in fall, in order to increase the
153 size of the attractive areas, high water level during winter and slow water level decrease in spring.

154 Finally, Lake Manager has also to protect a town and (small) urban districts from flooding risks.
155 Accordingly, the high water requirement during autumn and winter to restrict the opening opportunities
156 of sluice gates, which can contribute to delay or impair the success of eel migration.

157 Finally, Grand-Lieu Lake is a wetland habitat recognised for its unique biodiversity and is therefore
158 largely protected by a national nature reserve, completed by a regional one. The site is classified as a
159 wetland of international importance by the Ramsar Convention (1971). As it provides shallow open
160 water habitats, shelters in the dense rivularian vegetation and a diversity of preys (Adam 1997;
161 Carpentier 2003), Grand-Lieu lake is a highly suitable ecosystem for European eels. Seven professional
162 fishermen, each able to use 13 fyke nets, are authorized by environmental authorities to fish eel in the
163 lake, but the silver eel catch is restricted from the 1st October to the 15th January of the migration
164 season.

165 *Collection and tagging of silver eels*

166 For this study, European eels were monitored throughout three different migration seasons (2015-
167 2016, 2016-2017 and 2019-2020) by acoustic telemetry, which implies tagging by transmitter
168 implantation in their general cavity. In 2015-2016, 50 female silver eels were tagged over three sessions
169 (September 25: n = 18, October 16: n = 16, and November 20, 2015: n = 16). In 2016-2017, 52 female
170 silver eels were tagged over two sessions (November 7 and November 29, 2016). In 2019-2020, n = 80
171 silver eels (n = 40 males and n = 40 females) were tagged over three sessions (October 11: n = 20,
172 October 29: n = 22, November 6, 2019: n = 38).

173 The applied experimental protocol was the same for the three considered migration seasons. Silver
174 eels were captured in the fall by professional fishermen and stocked in the lake for one or two days
175 before the tagging operation. Silver eels were selected following the common anatomical
176 characterisation, e.g. eye size, dorsal and ventral colour surfaces and lateral-line differentiation (Acou,
177 Boury, Laffaille, Crivelli, & Feunteun, 2005). To conform to the 2 % tag per body mass rule (Winter,
178 1996), too thin individuals were removed from the tagging process. The size of females remained
179 comparable between the three seasons (727±48, 721±190 and 715±62 mm TL (mean±sd) in 2015, 2016
180 and 2019 respectively) and the males tagged in 2019 measured 404±32 mm LT in average. During the
181 tagging process, eels were maintained anaesthetized thanks to a closed water system containing
182 benzocaine (150 mg/l). The acoustic transmitters (model V9-69 kHz, 3.7 g in air, 25 mm; Vemco®,
183 Bedford, NS, Canada; Thelma® Biotel ID7 for males and ID9 for females) were introduced through a 2-
184 cm mid-ventral incision, which was then closed with independent absorbable sterile sutures (3-0
185 ETHICON MONOCRYLTM, Ethicon Ltd, Livingston, UK). During the operation, sterile instruments were
186 used, and individuals disinfected with a bactericidal antiseptic (0.05 % chlorhexidine). After the

187 operation, the fish recovered in a tank for 1 or 2 hours before being released in the open water area of
188 the lake. For the fish tagging, all institutional and national guides for ethical care and use of laboratory
189 animals were followed.

190 In 2015-2016, a postoperative survey was conducted to assess mortality possibly induced by the
191 operation. Ten supplementary individuals were thus marked during a tagging session and then kept in
192 captivity in a container filled with water from a nearby river. Throughout the 12 weeks of follow-up, no
193 mortality was observed and after the 10 first weeks 9 out of 10 eels had completely healed from the
194 operation. Nevertheless, it should be noted that the captivity conditions were optimal, while the
195 sanitary conditions in the lake may be poorer and more conducive to infections leading to additional
196 mortality.

197 ***Monitoring by acoustic telemetry***

198 The principle of acoustic telemetry is based on the reception by an acoustic receiver of a signal
199 emitted by the transmitter implanted in the fish, which enables the location of this fish close to the
200 acoustic receiver at a given time. Accordingly, acoustic receivers (Vemco® VR2W and Thelma® Biotel
201 TBR700) were deployed just upstream in front of the sluice gates to monitor the presence of the tagged
202 eels at the dam (Fig. 1c). Moreover, three complementary receivers were placed just downstream the
203 dam, along the Acheneau River, to assess for the escapement of tagged eels from the lake. As reported
204 in Trancart et al. (2018), the detection performance of the acoustic receivers in this area was high
205 enough to ensure that no eel could escape through the Acheneau River without being detected. The
206 telemetry acoustic records were then collected from fish release (early fall) period until the end of the
207 migration season (spring).

208 ***Environmental data***

209 As eel migration can be triggered and controlled by many environmental variables (Durif, Elie,
210 Gosset, Rives, & Travade, 2003a; Trancart et al., 2013), forecasting migration requires a steady record
211 of environmental parameters. Considering the variability of environmental and hydrological factors over
212 the years, we used environmental and migration records merged over the three seasons when acoustic
213 telemetry monitoring was achieved (2015-2016, 2016-2017 and 2019-2020). Model development
214 indeed requires data sets with representative inter- and intra- seasonal variability so that cross-
215 validation can be applied effectively (Van Belle et al., 2007). In addition to those three seasons, we
216 gathered environmental data over eight different other seasons of migration from 2009-2010 that were
217 chosen as prediction years to assess impact of different sluice gate opening. Air temperature, rainfall,
218 atmospheric pressure, wind speed and wind direction records were collected from public data of Meteo

219 France's weather station at Nantes Airport (5 km northeast from the lake), whereas discharges of the
220 Ognon and Boulogne rivers were extracted from the Banque Hydro (DREAL Pays de la Loire / HYDRO-
221 MEDDE/DE). Lake water level and daily sluice gates opening chronicles were provided by the SAH Sud
222 Loire. All of those parameters were either directly provided with a daily frequency or, if less, then
223 averaged daily.

224 As silver eel migration is commonly triggered by sharp changes in river discharge or water level
225 (Cullen & McCarthy, 2003; Teichert, Tétard, Trancart, de Oliveira, et al., 2020; Trancart et al., 2018), we
226 processed these variables to get ones that would better fit the movements of eels. Thus, we computed
227 multi-daily differences of the water level (from one to three days lag) to consider the delay in migration
228 events due to the size of the lake. To ensure comparability between the different years of analysis,
229 whose hydrological parameters significantly differed in absolute values, we expressed the inflow of the
230 Boulogne and Ognon rivers as a ratio between the daily flow and its seasonal range (thereafter referred
231 as 'daily flow ratio'). Moreover, we introduced a supplementary variable reflecting the number of
232 favourable occasions for migration since the season beginning, which were defined as days when the
233 water level difference over two days is greater or equal to 12 cm (see result section for threshold
234 details). This last variable aimed at including in the model the fact that the probability of migration
235 decreases as the season goes because several silver eels have probably already had occasions to escape
236 (Teichert, Tétard, Trancart, de Oliveira, et al., 2020).

237 *Development of the migration model*

238 As any statistical learning study, forecasting the migration behaviour of eels requires to determine
239 a response variable that varies as function of a set of predictors. Here, we chose as response variable
240 the presence of eels in front of the dam (days with eel detections from upstream receivers), expressed
241 as a binary presence/absence variable, which reflect the days when eels attempted to escape from the
242 lake for the purpose of migration. The climatic and hydrological variables were used as predictors in a
243 Boosted Regression Trees (BRT) model. The predictive performance of this learning algorithm is
244 regularly assessed as superior to others techniques (Elith et al., 2006; França & Cabral, 2015). Moreover,
245 BRTs are a very flexible tool that is able to select the most significant predictors amongst given ones and
246 to model automatically complex interactions between correlated variables (Elith, Leathwick & Hastie,
247 2008).

248 The analyses were carried out in R 3.5.1 (R Core Team, 2018) with the "gbm" (Ridgeway, 2006) and
249 "dismo" packages (Elith, Leathwick & Hastie, 2008). The algorithm used to model the BRT requires
250 parameters that were set as follows after prior testing of the models' predictive performance (learning
251 rate of 0.001, tree complexity of 3, bag fraction of 0.75 and a Bernoulli error distribution). The number

252 of predictors was then reduced to simplify the model by removing the less significant ones, using
253 “gbm.simplify” function in “dismo” package. Finally, we took advantage of the possibility to force
254 monotone variations for some relevant variables in the BRT model in order to avoid overfitting, that
255 would harm predictions (Teichert, Tétard, Trancart, de Oliveira, et al., 2020). Accordingly, we specified
256 in the model structure that differences in the water level had monotone increasing relationships with
257 eel migration.

258 The model performances were evaluated using the area under the Receiver Operating
259 Characteristic (ROC) curve, which presents the advantage to be independent from the chosen threshold
260 for presence/absence (Fielding & Bell, 1997). The area under the curve (AUC) ranges from 0 to 1, where
261 a score of 1 indicates perfect discrimination, a score of 0.5 implies predictive discrimination that is no
262 better than a random guess, and values < 0.5 indicate performance worse than random (Elith et al.,
263 2006). Usually, an AUC value over 0.8 suggests an excellent discrimination, while a value over 0.9
264 indicates an outstanding discrimination (Hosmer Jr, Lemeshow, & Sturdivant, 2013). We estimated the
265 mean AUC of our model by averaging the results of one hundred cross-validation loops on the data of
266 the three monitoring seasons (fitting fraction: 80 %; validation fraction: 20 %).

267 *Modelling past migrations*

268 After identifying the best model to describe eel presentation at the dam, we computed predictions
269 over the eight complementary seasons (between September and April) without telemetry data (2009-
270 2010; 2010-2011; 2011-2012; 2012-2013; 2013-2014; 2014-2015; 2017-2018 and 2018-2019). As BRT
271 method is based on stochastic processes, we averaged the daily prediction values obtained after running
272 the BRT fitting process one hundred times. In order to move from the computed presence probability
273 (by definition between 0 and 1) to a binary presence/absence predicted variable, we fixed a probability
274 threshold to qualify presence of eels in the front of gates. The choice of a relevant threshold is all the
275 more important that the ensuing results are highly correlated to the prevalence of the considered
276 species. Thus, scarce events can be over-predicted if the classification criterion is badly chosen, which
277 can induce dramatic consequences in conservation ecology (Manel, Williams, & Ormerod, 2001). Here,
278 we considered that it was on the one hand essential to minimize false negatives, i.e. days when an
279 absence is predicted while eels show up at the gates, because the aim of the management measure is
280 to favour escapement of a critically endangered species. On the other hand, the management of the
281 sluice gates obeys to a strict regulation in terms of water level targets (Préfecture de la région des Pays
282 de la Loire, 2015) and we cannot afford to recommend a measure that would overestimate the peaks
283 of migration and consequently the frequency of gates opening, which means also minimizing the
284 number of false positives. Thus, we chose to maximize sensitivity, i.e. capacity to give a positive result

285 when the hypothesis is verified, and specificity, i.e. capacity to give a negative result when the
286 hypothesis is not verified. The commonly used approach to make a trade-off between those two targets
287 is to maximize the Youden's J statistic equal to $J = \text{Sensitivity} + \text{Specificity} - 1$, particularly recommended
288 in ecological presence/absence studies (Allouche, Tsoar, & Kadmon, 2006; Youden, 1950). Considering
289 this statistic, the optimized threshold was then obtained with the package "PresenceAbsence" (Freeman
290 & Moisen, 2008).

291 After having calculated the predicted binary variable of presence at the dam, we derived a
292 potential escapement variable by considering day per day if a presence was forecasted and if the gates
293 were opened enough to enable eel escapement. Indeed, Trancart et al. (2018) showed that the
294 escapement of eels from Grand-Lieu Lake was effective for a cumulative sluice gate opening exceeding
295 75 cm, probably because of noise and current speed increase as the opening narrows, which might
296 dissuade the eels (Bruijs & Durif, 2009). For each season, we thus computed the proportion of days
297 where the gates were opened (>75 cm) while an event of silver eel migration was predicted.

298 ***Determining a relevant management measure***

299 Finally, we used past modelling outcomes to propose a management measure of the sluice gates
300 in order to improve the ratio of gate opening relevant for silver eel escapement. Focusing on missed
301 escapement occasions during the low ratio seasons, we empirically explored relevant gates manoeuvres
302 that could enable more escapement. A compulsory constraint was nevertheless to consider, for the
303 definition of a management measure, only environmental parameters whose updates are immediately
304 available for the local manager, which excludes e.g. the inflow of the Boulogne and Ognon rivers.
305 Moreover, the management measure should be applied without having a too prejudicial effect on the
306 complex multifactorial regulation of the lake water level. Accordingly, we quantified the amount of
307 additional opening of the gates (>75 cm) that would have been conducted if the different management
308 measure had been applied over the last seasons of migration since 2010.

309 **Results**

310 During the three migration seasons, 84 tagged eels successfully escaped from Grand-Lieu lake (17,
311 14, and 53 for the seasons 2015-2016, 2016-2017 and 2019-2020 respectively), which indicated high
312 inter-annual variations in the escapement rates (35, 27 and 66 % for the three seasons). For the last
313 season, the escapement proportion remained similar between male (60 %) and female (72.5 %),
314 revealing absence of sexual differences in the escapement success (Pearson's Chi-squared test, $\text{Chi}^2 =$
315 0.89, $\text{df} = 1$, $P = 0.34$). The escapement of silver eels essentially occurred during the night with 93.3% of

316 eels leaving the lake between 7 PM and 7 AM. Over the three seasons, a total of 47 days was featured
317 by eel detections just upstream of the regulation dam (14, 10 and 23 days for the seasons 2015-2016,
318 2016-2017 and 2019-2020 respectively). This binary variable was thereafter used as a response variable
319 to adjust the predictive migration model. Overall, when the sluice gate opening exceeded 75 cm, most
320 of the eels detected by the receivers located upstream of the dam successfully crossed the gates and
321 were then detected downstream along the Acheneau River (only one eel detected at the dam was
322 thereafter caught by a fisherman in the lake and another one was not detected by the downstream
323 receivers nor by those located in the lake).

324 *Triggering factors and predictive model*

325 The model selection procedure selected four important metrics for explaining the silver eel
326 presentation at the sluice gates: the number of migration occasions since the beginning of the season,
327 the water level difference over two days, the daily flow ratio and the lake's water level. The other
328 environmental variables, including lunar phase, air temperature, rainfall, atmospheric pressure, wind
329 speed and wind direction, as well as other lagged hydrological variables, were not selected in the best
330 BRT model. The AUC score of this final model is 0.911 based on the training data set, indicating a
331 proficient explanatory model. Similarly, the mean AUC obtained from a one hundred-loop cross-
332 validation was 0.808, which demonstrates powerful prediction capacities. Over the three telemetry
333 seasons, the model correctly predicted between 60 and 74% of the observed number of migrating days
334 depending on the season (Fig. 2), and included from 64 to 88% of eels reaching the front of the sluice
335 gates (Table 1). Overall, the BRT model properly identified the main migration peaks associated with
336 changes in hydrological conditions (i.e. increase in water level and river flow), but the model
337 performance was weaker for identifying punctual detections at the beginning of the season (Fig. 2).

338 According to the BRT model, the two most important predictors were the number of migration
339 occasions since the beginning of the season (relative influence: 33.7 %) and the water level difference
340 over two days (relative influence: 27.3 %). The partial plot of the functions fitted for the final model
341 showed that probability of migration steeply dropped when the number of occasions exceeds 10, which
342 reflected that the migration probability drops throughout the season as migration opportunities already
343 occurred (Fig. 3a). In contrast, the migration was favoured when the water level difference over two
344 days was above 10 cm, as the fitted function becomes positive (Fig. 3b). The migration probability also
345 sharply increased when the daily flow ratio is over 0.2 and has a relative influence of 23.2 % (Fig. 3c).
346 Similarly, the daily water level was positively related to the migration probability with a relative influence
347 of 15.9 % (Fig. 3d).

348 ***Past migration predictions and implementation of a management measure***

349 The BRT model was then used to predict the days when favourable environmental conditions
350 occurred for silver eel migration during the eight seasons without monitoring records. The number of
351 predicted days greatly varied between seasons, ranging from 11 to 56 days, essentially because of
352 disparity in hydrological conditions. During these favourable migration days, the sluice gates were
353 opened between 0 and 55 days per season (Fig. 4). Accordingly, the seasonal proportion of efficient
354 continuity (i.e. proportion of favourable migration days with open gates) was high for some of the
355 seasons (e.g. 98.2 % in 2013-2014; 83.9 % in 2014-2015), but remained very low or null for others (e.g.
356 0 % in 2018-2019; 18.2 % in 2011-2012; Fig. 4). These later seasons associated with restricted
357 escapement opportunities corresponded to the drought hydrological years, when managers drastically
358 limit the number of gate opening to store water in lake.

359 To overcome the issue of eel escapement, especially during drought season, a new management
360 rule was proposed to improve eel conservation in the Grand-Lieu Lake based on the findings of this
361 study. After exploring different alternatives, it was chosen to open at least one gate of no less than 75
362 cm when the water level difference over two days exceeds 10 cm. This value reflected the threshold for
363 which the migration probability become positive in the BRT model (Fig. 3b), whereas the extent of gate
364 opening corresponded to the threshold favouring escapement, as determined by Trancart et al. (2018).

365 When applying this management rule, a strictly positive increase in the proportion of efficient
366 continuity was predicted for 9 of the 11 considered seasons (Fig. 4). This increasing ranged between 0
367 and 80.0 %, but notably makes possible to reach more than 40 % even during the drought hydrological
368 years. Interestingly, the management rule would have induced in nine out of eleven seasons less than
369 25 % of additional opening days of the gates (Fig. 5). For the most impacted season in terms of additional
370 openings (2016-2017), the management measure would have induced an increase from 2 to 10 days
371 favourable to escapement in return of almost 43 % of additional gates openings.

372 **Discussion**

373 Several studies investigated the impact of hydroelectric complexes in lotic systems (e.g. Behrmann-
374 Godel and Eckmann, 2003; Bruijs and Durif, 2009; Winter et al., 2006), but few have been focus on
375 management solutions for dams that are not equipped with turbines (Larinier, 2001; Larinier & Travade,
376 2002; Trancart et al., 2020), especially in water reservoirs or lakes (Trancart et al., 2018). However,
377 management measures are critically required for obstacles because of their impact on silver eel, such
378 as migration delay or stop (Trancart et al., 2020). Here, the escapement rate of tagged eels at the dam
379 ranged between 27 and 64 % for the three monitoring seasons. The higher escapement rates were

380 recorded in 2019-2020, when the water level of Grand-Lieu was highest and the sluice gates were
381 frequently opened since the beginning of the migration season. In contrast, at low hydrological
382 conditions, the escapement rate was far below the 40 % threshold expected by the European eel
383 management plan. This observation highlights the critical importance of conservation measures during
384 drought hydrological years, which are expected to be more frequent in a context of global changes
385 (Jacob et al., 2014). In this purpose, our approach successively enabled to characterize the
386 environmental factors triggering the eel migration in the Grand-Lieu Lake and to propose management
387 rules based on past estimates of migration events during which silver eels have a downstream migration
388 behaviour.

389 ***Factors triggering silver eel migration***

390 According to BRT model, the factor having the largest influence in the silver eel migration in the
391 Grand Lieu Lake was the number of migration occasions since the beginning of the season. This
392 parameter was not considered as a migration predictor amongst previous studies on silver eel migration
393 patterns at Grand-Lieu Lake (e.g. Trancart et al., 2018). In the present study, we indeed not only sought
394 to elaborate an explanatory model of environmental predictors' influence on eel downstream migration
395 but also aimed at improving the current management practices of the dam to favour eel escapement
396 and thus complying with European eel management plan. Thus, this improvement had also to consider
397 the constraint on gates management brought by this conservation measure, so that it is acceptable by
398 the local manager (SAH Sud Loire), whose hydraulic management of the lake water level complies with
399 many other stakes. For that reason, we anticipated eventual trades-off in the application of the measure
400 by considering a temporal predictor for the eel presentation to the dam, following the example of
401 Teichert, Tétard, Trancart, de Oliveira, Acou, Carpentier, et al. (2020). The BRT analysis confirmed the
402 preponderance of this parameter, whose partial plot in the BRT fitted function highlights the expected
403 result of a decrease of migration probability when the number of migration occasions since the
404 beginning of migration season (1st September) increases, as the stock of eels available for migration
405 decreases throughout the migration season.

406 Beside this temporal factor, the main hydrological parameter triggering migration was an
407 increasing two-day water level difference. Whereas rainfall and river flow appear the main triggering
408 factors in running rivers (Brujij & Durif, 2009; Cullen & McCarthy, 2003; Drouineau et al., 2017; Vøllestad
409 et al., 1986), our results confirmed that water level difference has a superior explanatory potential in
410 lentic systems (Trancart et al., 2018). In particular, we considered in our preliminary models both the
411 water level variation over one and two days and the latter appeared to have higher relative influence
412 on the response variable. The selection of the two days lag can notably be explained by the large size of

413 Grand-Lieu Lake which induced a delay in the arrival of migrating silver eels at the dam. Although the
414 influence of daily river input of the two main tributaries remained less significant, this predictor also
415 contributed to increase the migration probability. Increasing river input should probably induce higher
416 turbidity in the water reservoir, which is known to stimulate the eel migration behaviour (Trancart,
417 Acou, De Oliveira, & Feunteun, 2013; Verbiest, Breukelaar, Ovidio, Philippart, & Belpaire, 2012). It
418 should also be noted that the lunar cycle, which is generally acknowledged to have a significant influence
419 on eel downstream migration owing to their avoidance of light (Haddingh, Van Aerssen, De Beijer, &
420 Van der Velde, 1999; Lowe, 1952), does not appear amongst the most influential triggering factors, as
421 already identified by Trancart et al. (2018). In contrast, the nocturnal pattern of silver eel migration was
422 clearly observed as most of tagged eels leaved the lake between the nightfall and dawn.

423 Our model correctly identified the main migration occasions associated with favourable
424 environmental conditions, but the early eel detections in front of the dam remained less predictable, as
425 they were not related to hydrological changes. Silver eels were released in several batches at the
426 beginning of the migration season during low hydrological conditions. Accordingly, most of eels
427 remained in the lake until the first favourable environmental conditions occurred, which were
428 associated with an increase of the migration probability. The early detection of eels in the front of dam
429 can thus be related to downstream migration, but it can also be associated with an exploratory
430 behaviour of individuals following the release in the lake.

431 ***Benefits of a simple management rule***

432 Whereas traditional monitoring methods necessary focus on a restricted period (here three
433 seasons), the modelling approach enables to cover a greater range of environmental conditions by
434 extending the hydrological records over a decade. In this study, predicting the past migration
435 opportunities during the eight seasons provided a large overview of the impact of the standard
436 management of sluice gates on silver eel migration in the Grand-Lieu Lake. According to the BRT model,
437 a total of 254 favourable days for eel migration occurred during the eight seasons without monitoring
438 records, but the water gates of the lake were only opened for less 173 days (68.1 %), with huge
439 disparities between seasons, i.e. between 0 and 98.2 % of favourable days with open gates. For these
440 eight seasons, the simple management rule proposed to improve eel conservation could have enabled
441 to increase the number of favourable days with gate open to a total of 200 days (78.2 %) with a range
442 from 42.0 to 98.2 % according to the season. Given the nocturnal behaviour of silver eel, the gate
443 opening operations can focus on the night, as more than 90% of the eels escaped from the night. Such
444 procedure should contribute to restrict the total number of hour when gates remain open and therefore
445 limit the impact on water level in the lake. Our model does not enable to estimate the exact number or

446 proportion of silver eels that would escape but it greatly contributes to improve the efficient continuity
447 during downstream movement. Indeed, eel migration generally occurs in several discontinuous waves
448 gathering a variable number of individuals (Durif & Elie, 2008), so that the absolute escapement rate is
449 complex to predict. Nevertheless, the simple management rule appeared particularly efficient for the
450 seasons with low hydrological conditions, leading to achieve more than the 40 % of efficient
451 connectivity. This performance is all the more engaging considering the drought hazard that could
452 increase in some parts of Europe owing to the global warming (Feyen & Dankers, 2009; Roudier et al.,
453 2016). Here too, learning from an extended period of environmental records is a mean to anticipate
454 impacts of such extreme events for improving eel conservation in the future. Although 40% escapement
455 compiles with the objective of the EU eel management plan, it does not consider the other sources of
456 anthropogenic mortality occurring during the yellow and silver stages. For example, a previous study
457 demonstrated that around 18% of silver eel were caught by commercial fishermen in the Grand-Lieu
458 Lake (Tancart et al. 2018). This observation underlines the importance of simultaneously considering
459 the different threats occurring during the life cycle to develop an integrative management plan for eel
460 conservation in the lake (Feunteun 2002).

461 In summary, the new management rule that we recommend constitutes a simple and efficient tool
462 to ensure eel escapement from large regulated lakes in case of unusually low hydrological conditions.
463 In the Grand-Lieu Lake, the measure would have induced from 7 to 29 days per year of additional
464 opening of sluice gates, which appears not detrimental for the economic activities that depend on the
465 water levels and sluice gate management. It also provides a simple and easily transposable method to
466 implement efficient conservation measure based on a robust model that enables to accurately predict
467 the migration peaks of silver eels based on standard environmental parameters. Although the absolute
468 values in decision rule (i.e. 10 cm water level elevation) and in management measure (70 cm gate
469 opening) are likely specific to the Grand-Lieu Lake, the statistical approach and the concept can be
470 transposed to other reservoir systems where silver eels remain blocked by anthropogenic obstacles.
471 Indeed, ecosystems such as lakes, reservoirs and lagoons, are generally highly productive because of
472 their large surface of open water and can support a significant part of the European eel production.
473 However, the disturbance of connectivity by dam or water gates (even of small size, as in the Grand-
474 Lieu Lake) can critically impair the migration of silver eel. The method of prediction based on BRT
475 provides a robust tool which can be executed rapidly and easily in any other study site after having
476 gathered the training data. Moreover, because it enables a rapid ex-ante assessment, our approach
477 constitutes an innovative way to evaluate conservation measures in ecology. It spares monitoring time
478 before an analysis of the conservation measure can be conducted. Such an approach obviously does not

479 supersede a classical ex-post evaluation but in a view to develop urgently efficient protection measures
480 for endangered species, it represents a highly operational strategy that we suggest leveraging.

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498 **Bibliography**

- 499 Aarestrup, K., Thorstad, E., Koed, A., Svendsen, J., Jepsen, N., Pedersen, M., Økland, F., 2010. Survival
500 and progression rates of large European silver eel *Anguilla anguilla* in late freshwater and early
501 marine phases. *Aquat. Biol.* 9, 263–270. <https://doi.org/10.3354/ab00260>
- 502 Acou, A., Boury, P., Laffaille, P., Crivelli, A. J., & Feunteun, E. (2005). Towards a standardized
503 characterization of the potentially migrating silver European eel (*Anguilla anguilla*, L.). *Archiv Für*
504 *Hydrobiology*, 164, 237–255.
- 505 Acou, A., Laffaille, P., Legault, A., & Feunteun, E. (2008). Migration pattern of silver eel (*Anguilla anguilla*,
506 L.) in an obstructed river system. *Ecology of Freshwater Fish*, 17(3), 432–442.
507 <https://doi.org/10.1111/j.1600-0633.2008.00295.x>
- 508 Adam, G. (1997). L'anguille européenne (*Anguilla anguilla*). Dynamique de la souspopulation du lac de

- 509 Grand-Lieu en relation avec les facteurs environnementaux et anthropiques. Doctoral dissertation,
510 PhD Thesis, University Paul Sabatier of Toulouse.
- 511 Allen, M., Rosell, R., & Evans, D. (2006). Predicting catches for the Lough Neagh (Northern Ireland) eel
512 fishery based on stock inputs, effort and environmental variables. *Fisheries Management and*
513 *Ecology*, 13(4), 251–260.
- 514 Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models:
515 prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, 43(6), 1223–1232.
516 <https://doi.org/https://doi.org/10.1111/j.1365-2664.2006.01214.x>
- 517 Barbarossa, V., Schmitt, R. J. P., Huijbregts, M. A. J., Zarfl, C., King, H., & Schipper, A. M. (2020). Impacts
518 of current and future large dams on the geographic range connectivity of freshwater fish
519 worldwide. *Proceedings of the National Academy of Sciences*, 117(7), 3648 LP – 3655.
520 <https://doi.org/10.1073/pnas.1912776117>
- 521 Beaulaton, L., & Briand, C. (2007). Effect of management measures on glass eel escapement. *ICES*
522 *Journal of Marine Science*, 64(7), 1402–1413. <https://doi.org/10.1093/icesjms/fsm071>
- 523 Behrmann-Godel, J., & Eckmann, R. (2003). A preliminary telemetry study of the migration of silver
524 European eel (*Anguilla anguilla* L.) in the River Mosel, Germany. *Ecology of Freshwater Fish*, 12(3),
525 196–202. <https://doi.org/10.1034/j.1600-0633.2003.00015.x>
- 526 Besson, M. L., Trancart, T., Acou, A., Charrier, F., Mazel, V., Legault, A., & Feunteun, E. (2016). Disrupted
527 downstream migration behaviour of European silver eels (*Anguilla anguilla*, L.) in an obstructed
528 river. *Environmental Biology of Fishes*, 99(10), 779–791. [https://doi.org/10.1007/s10641-016-](https://doi.org/10.1007/s10641-016-0522-9)
529 [0522-9](https://doi.org/10.1007/s10641-016-0522-9)
- 530 Bruijs, M. C. M., & Durif, C. M. F. (2009). Silver eel migration and behaviour. In *Spawning migration of*
531 *the European eel* (pp. 65–95). Springer.
- 532 Carpentier, A. (2003). Réponse numérique et fonctionnelle d'un prédateur aux contraintes spatio
533 temporelles d'utilisation de la ressource: le cas du grand cormoran et du peuplement
534 ichtyologique au lac de Grand-Lieu. Doctoral dissertation, PhD Thesis, University of Rennes,
535 France.
- 536 Chang, Y.-L. K., Feunteun, E., Miyazawa, Y., & Tsukamoto, K. (2020). New clues on the Atlantic eels
537 spawning behavior and area: the Mid-Atlantic Ridge hypothesis. *Scientific Reports*, 10(1), 1–12.
538 <https://doi.org/10.1038/s41598-020-72916-5>
- 539 Council of the European Union. (2007). Council Regulation (EC) No 1100/2007 of 18 September 2007

540 establishing measures for the recovery of the stock of European eel. *Official Journal of the*
541 *European Union*, 248, 17-23.

542 Cullen, P., & McCarthy, T. K. (2003). Hydrometric and meteorological factors affecting the seaward
543 migration of silver eels (*Anguilla anguilla*, L.) in the lower River Shannon. *Environmental Biology of*
544 *Fishes*, 67(4), 349–357. <https://doi.org/10.1023/A:1025878830457>

545 Dekker, W. (2003). On the distribution of the European eel (*Anguilla anguilla*) and its fisheries. *Canadian*
546 *Journal of Fisheries and Aquatic Sciences*, 60(7), 787–799.

547 Dekker, W., Casselman, J. M., Cairns, D. K., Tsukamoto, K., Jellyman, D. J., & Lickers, H. (2003). Worldwide
548 decline of eel resources necessitates immediate action. *Fisheries*, 28(12), 28–30.

549 Drouineau, H., Bau, F., Alric, A., Deligne, N., Gomes, P., & Sagnes, P. (2017). Silver eel downstream
550 migration in fragmented rivers: use of a Bayesian model to track movements triggering and
551 duration. *Aquatic Living Resources*, 30, 5. <https://doi.org/10.1051/alr/2017003>

552 Durif, C., Dufour, S., & Elie, P. (2005). The silvering process of *Anguilla anguilla*: a new classification from
553 the yellow resident to the silver migrating stage. *Journal of Fish Biology*, 66(4), 1025–1043.

554 Durif, C., & Elie, P. (2008). Predicting downstream migration of silver eels in a large river catchment
555 based on commercial fishery data. *Fisheries Management and Ecology*, 15(2), 127–137.
556 <https://doi.org/10.1111/j.1365-2400.2008.00593.x>

557 Durif, C., Elie, P., Gosset, C., Rives, J., & Travade, F. (2003). Behavioral study of downstream migrating
558 eels by radio-telemetry at a small hydroelectric power plant Behavioral Study of Downstream
559 Migrating Eels by Radio-telemetry at a Small Hydroelectric Power Plant. *American Fisheries Society*
560 *Symposium*, 33, 343.

561 Elith, Jane, H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., ... E. Zimmermann, N. (2006).
562 Novel methods improve prediction of species' distributions from occurrence data. *Ecography*,
563 29(2), 129–151. <https://doi.org/10.1111/j.2006.0906-7590.04596.x>

564 Elith, Jane, Leathwick, J. R., & Hastie, T. (2008). A working guide to boosted regression trees. *Journal of*
565 *Animal Ecology*, 77(4), 802–813. <https://doi.org/10.1111/j.1365-2656.2008.01390.x>

566 Feunteun, E. (2002). Management and restoration of European eel population (*Anguilla anguilla*): An
567 impossible bargain. *Ecological Engineering*, 18(5), 575–591.

568 Feunteun, E., Acou, A., Laffaille, P., & Legault, A. (2000). European eel (*Anguilla anguilla*): prediction of
569 spawner escapement from continental population parameters. *Canadian Journal of Fisheries and*

570 *Aquatic Sciences*, 57(8), 1627–1635.

571 Feyen, L., & Dankers, R. (2009). Impact of global warming on streamflow drought in Europe. *Journal of*
572 *Geophysical Research*, 114.

573 Ficke, A. D., Myrick, C. A., & Hansen, L. J. (2007). Potential impacts of global climate change on
574 freshwater fisheries. *Reviews in Fish Biology and Fisheries*, 17, 581–613.

575 Fielding, A. H., & Bell, J. F. (1997). A review of methods for the assessment of prediction errors in
576 conservation presence / absence models. *Environmental Conservation*, 24(1), 38–49.

577 França, S., & Cabral, H. N. (2015). Predicting fish species richness in estuaries: Which modelling
578 technique to use? *Environmental Modelling and Software*, 66, 17–26.
579 <https://doi.org/10.1016/j.envsoft.2014.12.010>

580 Freeman, E. A., & Moisen, G. G. (2008). A comparison of the performance of threshold criteria for binary
581 classification in terms of predicted prevalence and kappa. *Ecological Modelling*, 217(1), 48–58.
582 <https://doi.org/https://doi.org/10.1016/j.ecolmodel.2008.05.015>

583 Gosset, C., Travade, F., Durif, C., Rives, J., & Elie, P. (2005). Tests of two types of bypass for downstream
584 migration of eels at a small hydroelectric power plant. *River Research and Applications*, 21(10),
585 1095–1105. <https://doi.org/10.1002/rra.871>

586 Hadderingh, R. H., Van Aerssen, G. H. F. M., De Beijer, R. F. L. J., & Van der Velde, G. (1999). Reaction of
587 silver eels to artificial light sources and water currents: an experimental deflection study.
588 *Regulated Rivers: Research & Management*, 15, 365–371.

589 Hosmer Jr, D. W., Lemeshow, S., & Sturdivant, R. X. (2013). *Applied logistic regression* (Vol. 398). John
590 Wiley & Sons.

591 ICES. (2018). *Report of the Joint EIFAAC/ICES/GFCM Working Group on Eels (WGEEL)*. Kavala, Greece.

592 IPCC. (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C
593 above pre-industrial levels and related global greenhouse gas emission pathways, in the context
594 of strengthening the global response to the threat of climate change,. In P. R. S. [Masson-Delmotte,
595 V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, T. M. A. Pirani, W. Moufouma-Okia, C. Péan, R.
596 Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, & and T. W. M.
597 Tignor (Eds.).

598 Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., ... Yiou, P. (2014). EURO-
599 CORDEX: New high-resolution climate change projections for European impact research. *Regional*

600 *Environmental Change*, 14(2), 563–578. <https://doi.org/10.1007/s10113-013-0499-2>

601 Jacoby, D., & Gollock, M. (2014). *Anguilla anguilla*.
602 <https://doi.org/http://dx.doi.org/10.2305/IUCN.UK.2014-1.RLTS.T60344A45833138.en>

603 Lagarde, R., Peyre, J., Amilhat, E., Bourrin, F., Prellwitz, F., Simon, G., & Faliex, E. (2021). Movements of
604 Non-Migrant European Eels in an Urbanised Channel Linking a Mediterranean Lagoon to the Sea.
605 *Water*, 13(6), 839.

606 Larinier, M. (2001). *Dams, Fish and Fisheries: Opportunities, Challenges and Conflict Resolution*.

607 Larinier, M., & Travade, F. (2002). Downstream migration : problems and facilities. *Bulletin Français de*
608 *La Pêche et de La Pisciculture*, 364, 181–207.

609 Lowe, R. H. (1952). The influence of light and other factors on the seaward migration of the silver eel
610 (*Anguilla anguilla* L.). *Journal of Animal Ecology*, 21, 275–309.

611 Madsen, H., Lawrence, D., Lang, M., Martinkova, M., & Kjeldsen, T. R. (2014). Review of trend analysis
612 and climate change projections of extreme precipitation and floods in Europe. *Journal of*
613 *Hydrology*, 519, 3634–3650. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2014.11.003>

614 Manel, S., Williams, H. C., & Ormerod, S. J. (2001). Evaluating presence–absence models in ecology: the
615 need to account for prevalence. *Journal of Applied Ecology*, 38(5), 921–931.
616 <https://doi.org/https://doi.org/10.1046/j.1365-2664.2001.00647.x>

617 Miller, M. J., Bonhommeau, S., Munk, P., Castonguay, M., Hanel, R., & McCleave, J. D. (2015). A century
618 of research on the larval distributions of the Atlantic eels: a re-examination of the data. *Biological*
619 *Reviews*, 90(4), 1035–1064. <https://doi.org/10.1111/brv.12144>

620 Préfecture de la région des Pays de la Loire. Arrêté préfectoral du 11 mars 2015 définissant la gestion
621 expérimentale du niveau d’eau du lac de Grand-Lieu (2015).

622 Ridgeway, G. (2006). Generalized Boosted Regression models. Documentation on the R package ‘gbm’.
623 (<http://www.i-pensieri.com/gregr/gbm.shtml>, Ed.).

624 Righton, D., Westerberg, H., Feunteun, E., Økland, F., Gargan, P., Amilhat, E., ... Aarestrup, K. (2016).
625 Empirical observations of the spawning migration of European eels: The long and dangerous road
626 to the Sargasso Sea. *Science Advances*, 2(10). <https://doi.org/10.1126/sciadv.1501694>

627 Roudier, P., Andersson, J. C. M., Donnelly, C., Feyen, L., Greuell, W., & Ludwig, F. (2016). Projections of
628 future floods and hydrological droughts in Europe under a +2°C global warming. *Climatic Change*,
629 135(2), 341–355. <https://doi.org/10.1007/s10584-015-1570-4>

630 Sandlund, O. T., Diserud, O. H., Poole, R., Bergesen, K., Dillane, M., Rogan, G., ... Vøllestad, L. A. (2017).
631 Timing and pattern of annual silver eel migration in two European watersheds are determined by
632 similar cues. *Ecology and Evolution*, 7(15), 5956–5966. <https://doi.org/10.1002/ece3.3099>

633 Smith, D. R., Fackler, P. L., Eyler, S. M., Villegas Ortiz, L., & Welsh, S. A. (2017). Optimization of decision
634 rules for hydroelectric operation to reduce both eel mortality and unnecessary turbine shutdown:
635 A search for a win–win solution. *River Research and Applications*, 33(8), 1279–1285.
636 <https://doi.org/10.1002/rra.3182>

637 Team, R. C. (2018). *R: A language and environment for statistical computing*. Vienna, Austria.

638 Teichert, N., Tétard, S., Trancart, T., de Oliveira, E., Acou, A., Carpentier, A., ... Feunteun, E. (2020).
639 Towards transferability in fish migration models: A generic operational tool for predicting silver eel
640 migration in rivers. *Science of The Total Environment*, 140069.

641 Teichert, N., Tétard, S., Trancart, T., Feunteun, E., Acou, A., & de Oliveira, E. (2020). Resolving the trade-
642 off between silver eel escapement and hydropower generation with simple decision rules for
643 turbine shutdown. *Journal of Environmental Management*, 261.
644 <https://doi.org/10.1016/j.jenvman.2020.110212>

645 Tesch, F. W. (2003). *The Eel* (Blackwell). Oxford, UK.

646 Trancart, T., Acou, A., De Oliveira, E., & Feunteun, E. (2013). Forecasting animal migration using
647 SARIMAX: an efficient means of reducing silver eel mortality caused by turbines. *Endangered*
648 *Species Research*, 21(2), 181–190. <https://doi.org/10.3354/esr00517>

649 Trancart, T., Carpentier, A., Acou, A., Charrier, F., Mazel, V., Danet, V., & Feunteun, É. (2020). When “
650 safe ” dams kill : Analyzing combination of impacts of over fl ow dams on the migration of silver
651 eels. *Ecological Engineering*, 145(2019), 105741. <https://doi.org/10.1016/j.ecoleng.2020.105741>

652 Trancart, T., Feunteun, E., Danet, V., Carpentier, A., Mazel, V., Charrier, F., ... Acou, A. (2018). Migration
653 behaviour and escapement of European silver eels from a large lake and wetland system subject
654 to water level management (Grand-Lieu Lake, France): New insights from regulated acoustic
655 telemetry data. *Ecology of Freshwater Fish*, 27(2), 570–579. <https://doi.org/10.1111/eff.12371>

656 Van Belle, J., Shamoun-Baranes, J., Van Loon, E., & Bouten, W. (2007). An operational model predicting
657 autumn bird migration intensities for flight safety. *Journal of Applied Ecology*, 44(4), 864–874.
658 <https://doi.org/10.1111/j.1365-2664.2007.01322.x>

659 van Puijenbroek, P. J. T. M., Buijse, A. D., Kraak, M. H. S., & Verdonschot, P. F. M. (2019). Species and
660 river specific effects of river fragmentation on European anadromous fish species. *River Research*

661 *and Applications*, 35(1), 68–77. <https://doi.org/https://doi.org/10.1002/rra.3386>

662 Verbiest, H., Breukelaar, A., Ovidio, M., Philippart, J.-C., & Belpaire, C. (2012). Escapement success and
663 patterns of downstream migration of female silver eel *Anguilla anguilla* in the River Meuse.
664 *Ecology of Freshwater Fish*, 21(3), 395–403. <https://doi.org/10.1111/j.1600-0633.2012.00559.x>

665 Vøllestad, L. A., Jonsson, B., Hvidsten, N. A., Næsje, T. F., Haralstad, O., & Ruud-Hansen, J. (1986).
666 Environmental factors regulating the seaward migration of European silver eels (*Anguilla anguilla*).
667 *Canadian Journal of Fisheries and Aquatic Sciences*, 43(10), 1909–1916.

668 Watene, E. M., & Boubee, J. A. T. (2005). Selective opening of hydroelectric dam spillway gates for
669 downstream migrant eels in New Zealand. *Fisheries Management and Ecology*, 12(1), 69–75.
670 <https://doi.org/10.1111/j.1365-2400.2004.00422.x>

671 Westerberg, H., & Sjöberg, N. (2015). Overwintering dormancy behaviour of the European eel (*Anguilla*
672 *anguilla* L.) in a large lake. *Ecology of Freshwater Fish*, 24(4), 532–543.

673 Winter, J. D. (1996). Advances in underwater biotelemetry. (B. R. Murphy & D. W. Willis, Eds.). Bethesda:
674 American Fisheries Society.

675 Winter, H. V., Jansen, H. M., & Breukelaar, A. W. (2007). Silver eel mortality during downstream
676 migration in the River Meuse, from a population perspective. *ICES Journal of Marine Science*, 64(7),
677 1444–1449. <https://doi.org/10.1093/icesjms/fsm128>

678 Winter, H. V., Jansen, H. M., & Bruijs, M. C. M. (2006). Assessing the impact of hydropower and fisheries
679 on downstream migrating silver eel, *Anguilla anguilla*, by telemetry in the River Meuse. *Ecology of*
680 *Freshwater Fish*, 15(2), 221–228. <https://doi.org/10.1111/j.1600-0633.2006.00154.x>

681 Youden, W. J. (1950). Index for rating diagnostic tests. *Cancer*, 3(1), 32–35.
682 [https://doi.org/10.1002/1097-0142\(1950\)3:1<32::aid-cnrcr2820030106>3.0.co;2-3](https://doi.org/10.1002/1097-0142(1950)3:1<32::aid-cnrcr2820030106>3.0.co;2-3)

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684

685 **Table 1:** Number of days with eel presentation at the dam of the Grand-Lieu Lake and percentage
686 of correct prediction from the Boosted Regression Trees (BRT) model for the three telemetry seasons.

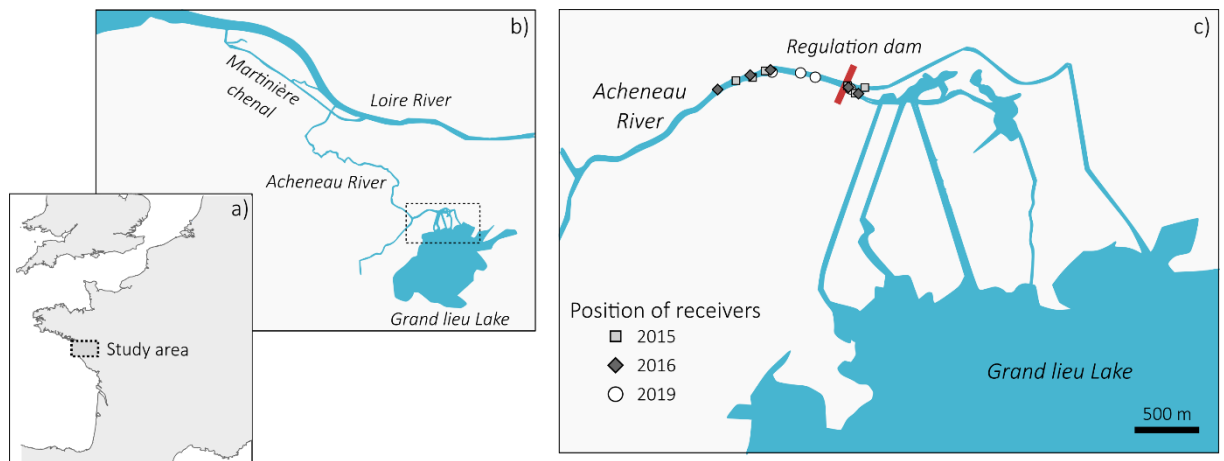
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Season	Number of migration day		Proportion of day predicted	Proportion of eel included
	Observed	Predicted		
2015- 2016	14	9	64%	64%
2016- 2017	10	6	60%	69%
2019- 2020	23	17	74%	88%

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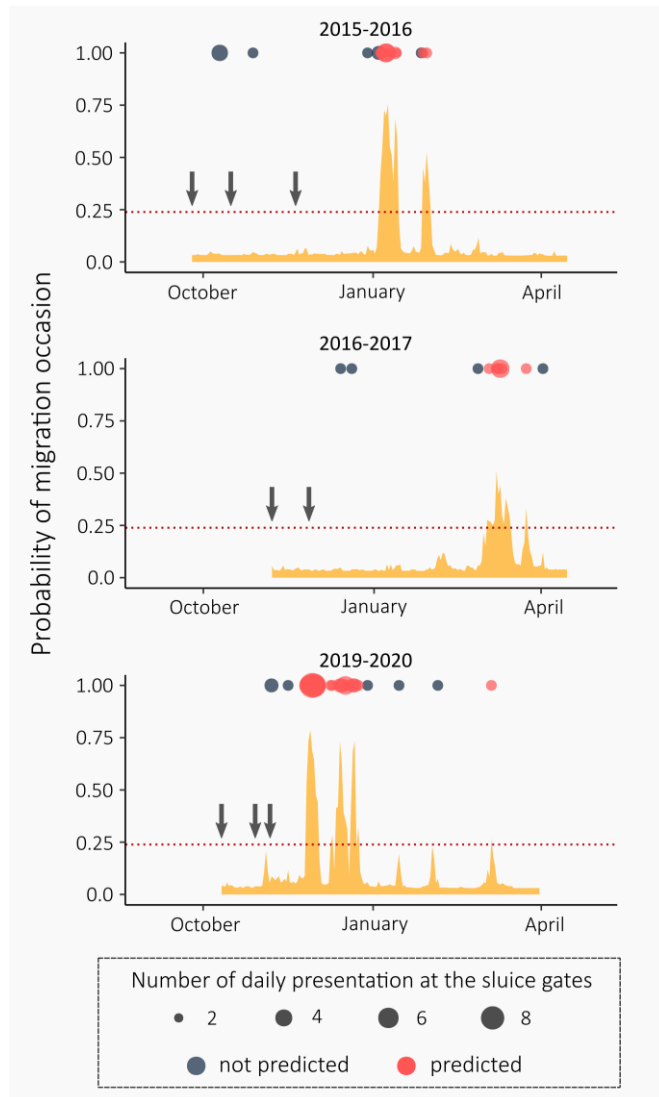


691

692 **Figure 1:** Location of the Grand-Lieu Lake (a) in the western France (b) within the Loire river
693 catchment. The position of acoustic receivers upstream and downstream of the regulation dam is
694 detailed c) for the three telemetry seasons (2015-2016, 2016-2017 and 2019-2020).

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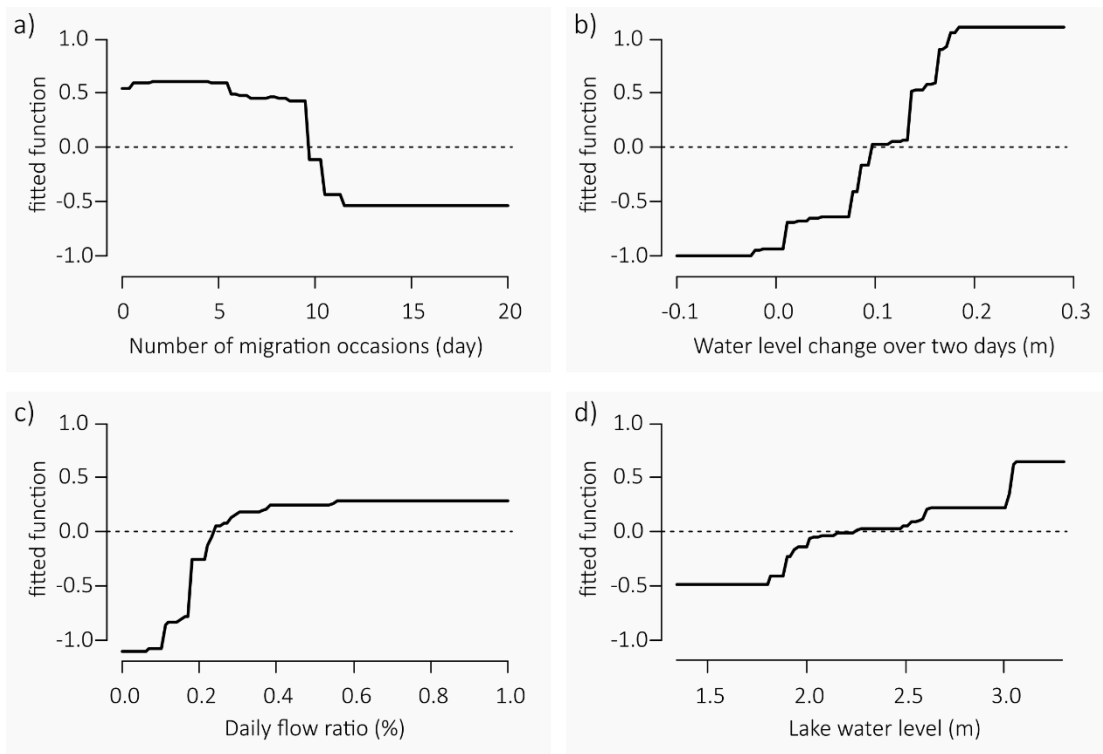
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698 **Figure 2:** Migration probabilities of silver eels predicted from the final Boosted Regression Trees
 699 (BRT) model describing presence of silver eel at the dam of the Grand-Lieu Lake for the three monitored
 700 seasons. The upper dots indicate the observed days with eel detections in front of the dam that were
 701 predicted (red) or not predicted (grey) by the model. The red dashed line indicates the probability
 702 threshold of eel migration defined by the Youden's J statistic. Arrows indicate the dates of eel tagging
 703 sessions.

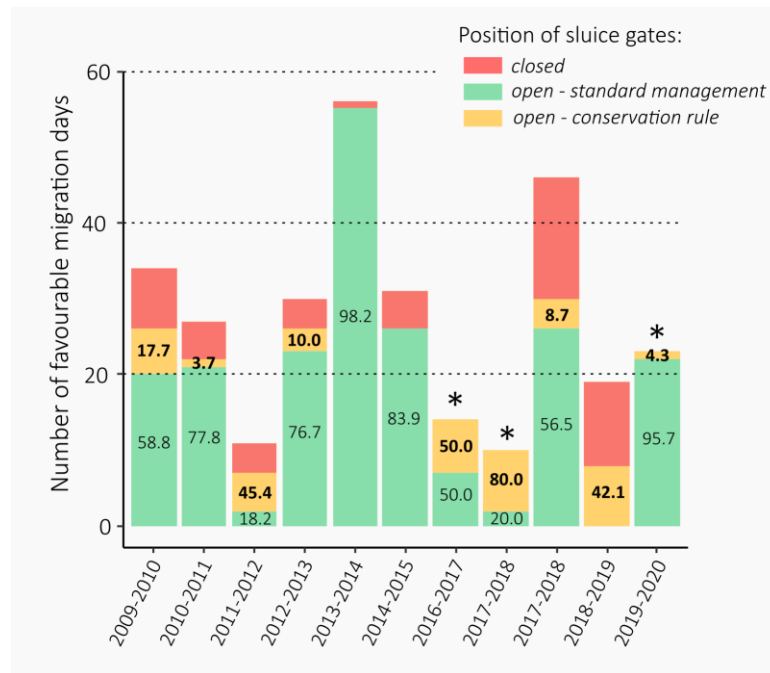
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707 **Figure 3:** Partial plots of the functions fitted for four environmental predictors selected in the final
 708 Boosted Regression Trees (BRT) model describing silver eel presentation at the dam of the Grand-Lieu
 709 Lake.

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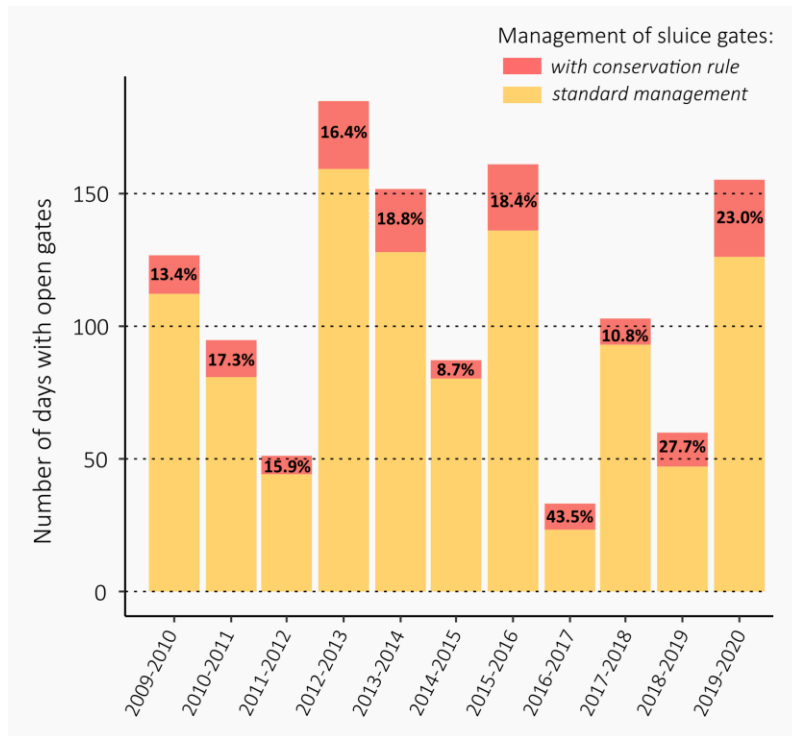


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713 **Figure 4:** Predicted number of days when favourable environmental conditions occurred for silver
 714 eel migration during the eight seasons (between September and April) without monitoring records and
 715 number of migration occasions recorded by telemetry for the three monitored seasons (indicated by
 716 stars). The red and orange bars represent the number of days with favourable migration conditions with
 717 closed gates. The bold digits (orange bars) indicate the expected improvement (i.e. percentage of
 718 migration days with open gates) that would have been induced by the eel conservation measure,
 719 whereas the light digits (green bars) represent the seasonal proportion of efficient continuity for the
 720 standard management.

721

722



723

724 **Figure 5:** Number of days with open sluice gate per migration seasons (between September and
 725 April) in the Grand-Lieu Lake. The bold digits indicate the percentage of additional days with open gates
 726 that would have been induced by the eel conservation rule.

727