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1 **Resolving the trade-off between silver eel escapement and hydropower generation with simple**
2 **decision rules for turbine shutdown**

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18 **Highlights**

- 19 • Turbine shutdown can reduce silver eels mortalities when crossing hydropower plants
- 20 • A trade-off between silver eel conservation and hydropower production is required
- 21 • Stakeholders need simple decision rules to maximise eel escapement
- 22 • Compromise alternatives are identified with multiple-criteria decision analysis
- 23 • Outputs provide quantitative elements to guide negotiations between stakeholders

24 **Abstract**

25 Hydropower plants are commonly reported as a major cause of the worldwide decline of freshwater
26 eels (*Anguillidae*), so that management solutions are urgently needed to mitigate their impacts. Where
27 downstream passage solutions are complex to develop, turbine shutdown appears as an effective
28 management solution to protect silver eels during their river migration toward spawning areas.
29 However, the definition of operational decision rules for turbine shutdown is challenging due to the
30 duality between the benefit for eel conservation and the concomitant cost in term of hydropower
31 production. Here, we proposed a decision framework for turbine shutdown based on simple
32 hydrological criteria to guide negotiations between stakeholders toward a trade-off between silver eel
33 escapement and hydropower generation. Eel migration was assumed to be triggered by a minimum
34 river flow associated with a minimum discharge pulse, so that threshold values can be directly
35 implemented as decision rules for turbine shutdown. To estimate relevant thresholds, a generic
36 methodological framework was developed to generate alternative decision rules from data collected
37 at hydropower plants, which can include telemetry surveys and estimates of eel abundance. A
38 multiple-criteria decision analysis was then conducted to rank alternatives and to determine the best
39 compromise between promoting silver eel escapement and limiting turbine shutdown duration.
40 Graphic outputs can help stakeholders to understand the competitive interests between eel
41 conservation and hydropower production, while visually identifying a range of consensual alternatives
42 to support negotiations in the choice of operational thresholds. The method was illustrated for three
43 river systems in Europe featured by distinct hydrological conditions and can be applied in other areas,
44 providing that eel monitoring surveys and flow data are available.

45 **Keywords:** *Anguilla anguilla*; turbine shutdown; conservation policy; multiple-criteria decision; decision
46 rules

47 1. Introduction

48 The widespread fragmentation of river ecosystems across the globe is a crucial issue for freshwater
49 biodiversity management (Nilsson et al., 2005). Among other anthropogenic impacts, the alteration of
50 ecological connectivity within and between river networks contributes to obstruct lateral and
51 longitudinal dispersal of aquatic organisms, resulting in decline or loss of freshwater populations (e.g.
52 Gehrke, Gilligan and Barwick, 2002; Hall, Jordaan and Frisk, 2011). Diadromous fish are particularly
53 sensitive to this threat because effective migrations in both upstream and downstream directions are
54 essential requirements for their biological cycles (van Puijenbroek et al., 2019). While every obstacle
55 affects accessibility of catchments during upstream migration, hydropower turbines are source of
56 immediate and/or delayed mortality during the downstream movements (Besson et al., 2016;
57 Drouineau et al., 2017; Larinier, 2001). The impacts of hydroelectric dams on silver freshwater eels
58 (*Anguillidae*) during the downstream migration was reported in various rivers catchment (Eyler et al.,
59 2016; Pedersen et al., 2012; Trancart et al., 2018b; Verbiest et al., 2012; Winter et al., 2007) and
60 management solutions are urgently needed to enhance escapement success (Dekker, 2016; Feunteun,
61 2002). For example, fisheries and hydroelectric power stations were reported as the main causes of
62 mortality for European eel in the River Meuse, leading a sharp decline in escapement rate at the basin
63 scale (Verbiest et al., 2012; Winter et al., 2006). Nevertheless, the turbine-related mortality appears
64 highly site-specific depending on the local configuration of hydropower dam and its location within the
65 river catchment (Boubée and Williams, 2006; Jansen et al., 2007; Mateo et al., 2017).

66 Facing to the critical decline of European eel, *Anguilla anguilla* (L.), since the 1960-70s (Dekker, 2016),
67 the European authorities proposed a recovery plan targeting the escapement of 40% of silver eel that
68 should be produced in un-impacted rivers or eel management units (EU, 2007). To meet this objective,
69 several mitigation measures have been implemented in hydropower plants, such as building of
70 physical or behavioural barriers associated with bypass(es) aiming to divert fish toward non-lethal
71 ways (Gosset et al., 2005; Larinier and Travade, 2002). However, effective downstream passage
72 solutions are complex to develop, especially for large installations (Larinier and Travade, 2002). In
73 these locations, other active solutions can consist of trapping silver eels upstream of the plant and
74 releasing them downstream (Mccarthy et al., 2014) or operating turbine shutdowns when migration
75 events can be predicted (Eyler et al., 2016; Trancart et al., 2013). Such management actions provide
76 effective outcomes and can be implemented without significant modification of the dam structure,
77 but they require to reliably predict the timing of eel migration to limit the impact on hydropower
78 production (Drouineau et al., 2017; Durif and Elie, 2008; Smith et al., 2017). Silver eels generally show
79 a nocturnal behaviour and the migration dynamic is discontinuous within the season (Sandlund et al.,
80 2017; Stein et al., 2016; Tesch, 2003). Therefore, predictive models to forecast migration activity are

81 valuable tools to propose periods of turbine shutdowns to implement a real time management
82 strategy (Smith et al., 2017; Trancart et al., 2013).

83 In Europe, silver eel downstream migration usually occurs at earlier period in the north of the
84 European eel range, and typically peaked during autumn and early winter (Righton et al., 2016;
85 Vøllestad et al., 1986), but can extend to early spring (Aarestrup et al., 2008; Stein et al., 2016;
86 Trancart et al., 2018b). Within this period, eel movements are generally gathered in several
87 discontinuous waves of migration (Durif and Elie, 2008) that have been correlated with several
88 environmental factors, including river discharge (Bultel et al., 2014; Cullen and McCarthy, 2003; Durif
89 et al., 2003; Vøllestad et al., 1986), water level (Sandlund et al., 2017; Trancart et al., 2018a), rainfall
90 (Stein et al., 2016; Trancart et al., 2013), water turbidity and conductivity (Verbiest et al., 2012), pH
91 (Durif et al., 2008), wind direction (Cullen and McCarthy, 2003), atmospheric pressure (Acou et al.,
92 2008; Cullen and McCarthy, 2003), temperature (Durif and Elie, 2008; Stein et al., 2016) or lunar phase
93 (Acou et al., 2008; Sandlund et al., 2017; Smith et al., 2017). The role of these exogenous factors for
94 triggering eel migration varies depending on typology of aquatic systems where fish are settled and
95 environmental conditions (Trancart et al., 2018a). In lotic environments, migration peaks generally
96 coincides with rainfall events associated with sharp flow pulses along rivers, which in turn impacts
97 water velocity, turbidity and conductivity (Cullen and McCarthy, 2003; Drouineau et al., 2017; Stein et
98 al., 2016). The specific effects of these factors is challenging to disentangle due to their strong inter-
99 correlation. Nevertheless, rainfall and river discharge are easier to monitor and predict than physico-
100 chemical parameters, making them useful surrogate variables in any model aimed at quantifying silver
101 eel activity (Trancart et al., 2013). Moreover, Drouineau *et al.*, (2017) demonstrated that silver eel
102 were most sensitive/influenced by variation in river discharge than river discharge itself in the Dronne
103 River. Such a result is consistent with the peaks of migration activity commonly observed during the
104 rising river flow phase (Behrmann-Godel and Eckmann, 2003; Vøllestad et al., 1986), which coincides
105 with high turbidity levels.

106 Overall, the definition of operational decision rules for turbine shutdown is challenging due to the
107 duality between the expected benefit for eel conservation and the concomitant cost in term of
108 hydropower generation (Drouineau et al., 2018). Stakeholders usually plan monitoring surveys of silver
109 eel on hydropower dams to evaluate the ecological impact and acquire knowledge on the local
110 phenology of fish migration (Eyler et al., 2016; Smith et al., 2017). On the basis of these data, decision
111 makers have to resolve the trade-off involving the escapement rate of silver eels and the modalities of
112 turbine shutdown operations (e.g. triggering criteria, extent of shutdown periods ; Smith et al., 2017;
113 Trancart et al., 2013). Therefore, analytical tools and methods applied can play an essential role in the
114 successful negotiation between stakeholders to develop efficient management strategy (McShane et

115 al., 2011). To be operational, simple and comprehensive decision rules should be preferred to ensure
116 that all stakeholders can fully interpret, assess and subsequently implement the conservation policy.
117 According to this principle, simple decision criteria are already implemented in turbine management
118 strategies for several European hydropower plants. The shutdown policies are commonly based on
119 calendar dates and river flow conditions, which are assumed the primary triggers of eel movements. In
120 such cases, hydropower turbines are switch off from nightfall to dawn during the migration period
121 when river discharge or variation in river discharge exceed given threshold values defined by expert
122 judgments. Although this expert-based approach provides promising results, analytical tools are still
123 lacking to define robust and optimal threshold values for the decision criteria based on the monitoring
124 data collected at hydropower plants.

125 In this paper, we proposed a simple decision framework for turbine shutdown based on hydrological
126 criteria, with the operational aim at orienting stakeholders in the opportunity to resolve the trade-off
127 between silver eel escapement and hydropower generation. In this approach, silver eel activity was
128 assumed to be chiefly triggered by changes in river discharge parameters within a favorable calendar
129 period of migration. A generic methodological framework was developed to help managers in defining
130 parsimonious threshold decision criteria using outputs of the monitoring surveys conducted in
131 hydropower plants, such as telemetric survey or daily abundance estimates. The method was
132 illustrated using telemetry and trap data collected in three river sites characterized by different size
133 and river hydrological conditions.

134 **2. Materials and methods**

135 ***2.1. Proposal of decision scheme***

136 The implementation of mitigation measures requires predicting eel migration event based on
137 environmental data recorded during the previous days and/or planned for the coming days. This
138 prediction must be obtained a few hours before stopping the turbines to give managers enough time
139 to plan the shutdown (Drouineau et al., 2017). In accordance with this requirement and the nocturnal
140 activity of eel, an operational decision can be taken at 12AM for stopping the turbine at nightfall. In
141 the present study, we thus considered a time step of 24 hours ranging from 12AM of the day d-1 to
142 12AM of the d-day. This time step is consistent with the nocturnal ecological rhythm of eel and was
143 thereafter referred as a 'day' in the manuscript for simplification purposes.

144 In the present study, the downstream migration of silver eel was assumed to be triggered by a sharp
145 increase in river flow (e.g. Behrmann-Godel and Eckmann, 2003; Cullen and McCarthy, 2003) within a

146 favorable temporal window of migration (Fig. 1). To capture this pattern, four parameters were
147 considered: the migration period (onset and end dates), the river discharge (Q , $m^3.s^{-1}$), the discharge
148 difference compared to one or more previous days (ΔQ , %), and the delayed response of eel to
149 hydrological cues (N_{delay} , day). The migration period was defined as the calendar dates during which
150 silver eels are expected migrate downstream to reach the marine spawning areas. Environmental
151 authorities generally fix this period in conservation policies. In Europe, the downstream migration
152 generally extends from autumn to early spring, but varies between localities (e.g. Righton et al., 2016;
153 Vøllestad et al., 1986). Turbine shutdowns can be operated during this temporal window to enhance
154 escapement and survival of silver eels. Within this period, the migration peaks can be identified using
155 environmental data. Given the non-linear response of eel to hydrological cues, we assumed that a
156 migration event can be predicted when the river flow conditions exceed both specific threshold values
157 in river discharge (Q threshold) and in delta discharge (ΔQ threshold). This basic threshold model
158 intuitively supposes that a minimum water flow associated with a minimum discharge pulse is
159 required to stimulate the downstream migration. The values of delta discharge reflect the intensity of
160 the flow pulse, as estimated by the relative difference in flow conditions of the d -day compared to the
161 mean discharge of a moving reference period (from $d-1$ to $d-N_{day}$). Depending on the local hydrology,
162 the extent of reference period (N_{day}) can be adjusted to correspond to the mean duration of a flow
163 pulse, generally around 2-6 days. Once favorable hydrologic cues are encountered, silver eels are
164 expected to engage their downstream migration. Nevertheless, some eels can still remain in migration
165 for a few days after the flow peak, while the river flow is stabilizing or decreasing. To consider this
166 situation, we introduced the possibility to repeat the turbine shutdown for several days (N_{delay}) after
167 detecting a discharge pulse that triggered fish migration.

168 ***2.2. Performances of cut-off alternatives***

169 To be efficient and parsimonious, the decision scheme parameters should be defined by a trade-off
170 between the escapement rate of silver eels and the total duration of turbine shutdown. This objective
171 is achievable by evaluating performances of a series of cut-off alternatives for the parameters involved
172 in the decision scheme, and then identifying the optimal thresholds (Q and ΔQ) and number of
173 days (N_{delay}). Moreover, the evaluation must be possible using the different types of emigration data
174 collected in hydropower plants during the monitoring surveys, which may commonly involve count
175 data (e.g. Wolf trap, camera records) or telemetry data.

176 Here, cut-off alternatives were produced by generating unique combinations of values for Q
177 threshold, ΔQ threshold and N_{delay} . More precisely, 40 values evenly distributed between zero and
178 the 95th percentile were generated for Q and ΔQ thresholds, as well as values ranging from 0 to 3

179 days for N_{delay} . This results in 6 400 alternatives. When telemetry data are available, the time slot of
180 daily shutdown can also be considered to determine an optimal window, instead of stopping
181 arbitrarily the hydropower production from nightfall to dawn. In such a case, different time slots were
182 generated as extra alternatives based on the hourly distribution of eel observations. Time slots were
183 incremented by adding one hour successively, starting from the distribution mode until a duration of
184 18 hours was reached. In combination with the previous parameters, a total of 108 800 alternatives
185 was generated. No alternatives were generated according to the migration period because the dates
186 of onset and end are usually determined and fixed *a priori* by environmental authorities on the basis
187 of historical data or expert knowledge. Nevertheless, this period can differ between locations
188 depending the biogeographic regions or local environmental conditions (Durif and Elie, 2008; Righton
189 et al., 2016).

190 Performance of alternatives was then evaluated based on four metrics calculated from monitoring
191 data (e.g. fish trap, telemetry) collected in study sites: i) escapement rate, ii) sensitivity, iii) specificity
192 and iv) cumulative shutdown duration. The rate of escapement over the study period corresponds to
193 the proportion of silver eel caught or detected when the hydropower turbines would have been
194 stopped according to the decision scheme. It is calculated according to the following formula: $Resc_i =$
195 $Nesc_i/Ntot$, where $Resc_i$ is the rate of escapement of the alternative i , $Nesc_i$ is the number of eels
196 included in the conservation measure of the alternative i , and $Ntot$ is the total number of eels in the
197 dataset. When derived from telemetry data, the escapement rate can also consider the time slot of
198 turbine shutdown to search for an optimum solution. However, such an hourly scale is not possible for
199 trap data that are usually collected on a daily basis. Sensitivity and specificity were used as measures
200 of the congruence between the shutdown decisions and the occurrence of downstream migration
201 events. The sensitivity (Sen) measures the proportion of day with actual moving eels for which the
202 decision scheme advocates to stop the turbines. For each alternative i , it is calculated according to the
203 formula: $Sen_i = TP_i / (TP_i + FN_i)$, where TP (true positive) is the number of days with observed
204 migration associated with turbine shutdown, and FN (false negative) is the number of days with
205 observed migration but turbines are on. On the other hand, the specificity (Spe) measures the
206 proportion of day without actual migration that are correctly predicted as such by the decision
207 scheme. For each alternative i , it is calculated according to the formula: $Spe_i = TN_i / (TN_i + FP_i)$,
208 where TN (true negative) is the number of days without both migration and turbine shutdown, and
209 FP (false positive) is the number of days with turbine shutdown whereas eels are not migrating.
210 Therefore, increasing values in sensitivity provides higher conservative value for eel management,
211 whereas increasing values of specificity reduce the hydropower production loss. The cumulative
212 duration of shutdown evaluates the amount of hydropower that would not have been generated over

213 the studied period due to the application of the decision scheme. For trap data that have a daily basis,
214 it corresponds to the total number of nights where the turbines would have been stopped (N_{stop}). For
215 telemetry data, the turbine shutdown duration can be calculated at the hourly scale (H_{stop}) thanks to
216 a higher temporal resolution.

217 ***2.3. Ranking alternatives for decision making***

218 The selection of cut-off alternatives that maximize silver eel escapement while limiting turbine
219 shutdown was performed using a Technique for Order of Preference by Similarity to Ideal Solution
220 (TOPSIS). This multi-criteria decision analysis method is suitable to rank a serial of alternatives on the
221 basis of “cost” criteria and/or “benefit” criteria that are monotonically increasing or decreasing
222 (Hwang and Yoon, 1981). Based on a scoring process, this technique ranks the alternatives according
223 to their relative distance to positive and negative ideal solutions, which represent the conditions
224 obtained when the criteria have extreme values (Huang et al., 2011; Zavadskas et al., 2006). In the
225 present case, the alternatives were ranked as a function of four criteria: escapement rate, sensitivity,
226 specificity and cumulative shutdown duration. Therefore, the positive ideal solution corresponds to
227 the alternative where eel escapement, sensitivity and specificity are maximised whereas shutdown
228 duration is minimised. This case reflects a hypothetical decision scheme that targets the exact
229 migration days that ensures 100% escapement of eel in a minimum of days. On the other hand, the
230 negative ideal solution corresponds to an alternative where turbine shutdown is operated the days
231 without migration, leading to the excessive shutdown duration and minimal values in sensitivity,
232 specificity and escapement rate.

233 Depending on the types of monitoring survey, the cost criteria was either the total number of
234 shutdown nights (N_{stop}) for fish trap data or the total number of shutdown hours (H_{stop}) for
235 telemetry data. Before the TOPSIS analysis, a vector normalization procedure was conducted to
236 transform criteria into a common scale and comparable units (Hwang and Yoon, 1981). An equal
237 weight was assigned to each criteria as no assumption was formulated on their relative importance in
238 the decision process. Finally, the TOPSIS score was used to identify the compromise alternative that
239 provides an optimal trade-off between eel conservation strategy and hydropower production.
240 However, focusing on a unique alternative can be unsatisfactory for selecting the threshold values
241 implied in decision scheme, because the final choice generally results from negotiation between
242 stakeholders (Smith et al., 2017). Accordingly, graphic outputs providing the range of cut-off values
243 (i.e. Q threshold, ΔQ threshold, N_{delay} and time slot) were proposed to evaluate the implications of
244 the different alternatives in terms of TOPSIS score, escapement rate, sensitivity, specificity and
245 shutdown duration. Moreover, when quantified objectives are defined (e.g. minimal escapement rate

246 or maximum number of shutdown days), the TOPSIS ranking can be used to determine the optimal
247 alternative among those that fulfilling the target condition.

248 To be operational and transposable to various river systems, the analyses were conducted using the R
249 free software environment (R Core Team 2018, version 3.5.1) and three generic functions were
250 coded to conduct the analysis (available in Appendix A). The *“fun.sim.eel”* function generates and
251 calculates the performance of cut-off alternatives using either fish trap data or telemetry data,
252 associated with a time series of daily river discharge. The function *“topsis.eel”* performs the TOPSIS
253 analysis based on the matrix of alternatives and the function *“plot.topsis.eel”* identify the preferred
254 alternative and produces graphic outcomes. For each function, different options are proposed to
255 refine the analysis according to operator requirement. The R package *“lubridate”* (Grolemund and
256 Wickham, 2011) was used to manipulate the time formats. TOPSIS analysis was conducted with the
257 package *“MCDM”* (Blanca and Ceballos, 2016) and graphic visualisation requires the package
258 *“SDMTools”* (VanDerWal et al., 2014).

259 ***2.4. Illustrative applications on actual data***

260 Three data sets were used to illustrate and evaluate the applicability of the decision framework in
261 contrasted river systems. The first example was based on telemetry data collected in a large river
262 system, the Meuse River (950 km long, 36 000 km²), whereas the second and third examples were
263 based on fish trap data collected in the Dordogne River (475 km long, 24 500 km²) and in the Scorff
264 River (78 km long, 490 km²). This large range of hydrological conditions was selected to be
265 representative of the different river systems inhabited by the eel in the European regions. Moreover,
266 the method transferability was illustrated by the use of various monitoring techniques commonly
267 implemented in hydropower plants.

268 The Meuse River is extensively used for hydropower generation and silver eel migration was
269 monitored at six power plants located in Wallonia (Sonny et al., 2018), between Namur and the
270 Belgium-Dutch border (*c.a.* 100 km river section). Silver eels (n=150) were captured by a professional
271 fishery in the Rhine River (Deutschland, 7 October 2017) and implanted with acoustic transmitters
272 (LOTEK JSAT L-AMT-8.2). In agreement with the environmental authorities, the eels were then
273 released in the Meuse river (11 October 2017) at different sites, from 0.5 to 2.5 km upstream of the
274 hydropower plants. Between October 2017 and March 2018, the passages of tagged fish at sites were
275 recorded in using a network of 76 acoustic receivers (LOTEK WHS 4250 D) distributed along the
276 hydropower facilities (between 21 and 9 receivers depending on the plant) to ensure high detection
277 capacity. Accordingly, several receivers were placed on each site to cover all the possible pathways,
278 i.e. dam, turbines or navigation locks. After excluding the first 8 days following the fish release to avoid

279 any bias related to manipulation stress (Trancart et al., 2018b), 403 eel passages were recorded at the
280 six plants during the study period. The eel passages were used to illustrate the decision scheme, in
281 combination with measures of river discharge recorded in the middle of the river section. River flow
282 data were provided by the Public Service of Wallonia (Direction générale opérationnelle de la Mobilité
283 et des Voies hydrauliques, Boulevard du Nord 8-5000 Namur) at the Amay station. For the TOPSIS
284 analysis, cut-off alternatives were generated using a large period of migration extending from October
285 1 to February 28 to be conservative. The relative difference in river discharge was calculated using a 5
286 days moving reference period ($N_{day}=5$). As telemetry data were used, the time slot of turbine
287 shutdown was included in the decision process.

288 In the Dordogne River, migrating eels were caught during the night between September 2009 and
289 March 2015 with a stow net (20 m length, 6 m width, 3 m height) by an experimental fishery located
290 upstream of the Mauzac plant (44.862383 N, 0.802087 E). The net had a similar design as stow nets
291 used by professional fishermen like for example in the Loire River (Durif and Elie, 2008). It was located
292 in the inlet canal of the hydropower plant to ensure high capture rates of silver eels, which were
293 assumed representative of local migration dynamic. Indeed, the high discharge capacity of this inlet
294 canal compared to mean river flow during eel migration allows to divert a preponderant part of river
295 flow and therefore, eels. Silver eels were collected daily during the eel migration period (Frey et al.,
296 2014). The five first migration seasons from 2009 to 2013 were used to generate cut-off alternatives,
297 whereas the migration season 2014 was used to evaluate the performances of the best compromise
298 alternative. Similarly to the Meuse River, the migration period was fixed between the October 1st and
299 February 28th and a 5 days moving reference period was used ($N_{day}=5$). River discharge records were
300 provided by Electricité de France.

301 For the Scorff River, fish trap data were previously used by Trancart *et al.* (2013) to forecast eel
302 migration using SARIMAX models in small rivers. Although no hydropower plants were implanted in
303 this river, the data were used as illustrative example. Briefly, silver eels were collected between
304 September 2000 and May 2011 using a fish trap located in the main stem of the river. As for the
305 Dordogne River, the trap was checked daily during the eel migration period and silver eels were
306 counted. The river discharge records were obtained from the Direction Régionale de l'Environnement,
307 de l'Aménagement et du Logement de Bretagne (site: J5102210, DREAL Bretagne/HYDRO-MEDDE/DE).
308 The cut-off alternatives were generated using the nine first migration seasons (i.e. from September
309 2000 to May 2009) and the two later season (i.e. from September 2009 to May 2011) were used as
310 independent evaluation periods. The same migration period was used, but the moving reference
311 period was fixed to 3 days to consider the smaller size of the river system. When using trap surveys,

312 such as for the Dordogne and Scorff Rivers, the performance metrics are calculated at a daily scale and
313 thus did not consider the influence of the time slots on eel escapement.

314 **3. Results**

315 ***3.1. Application 1: Meuse telemetry survey***

316 Among the 151 days of the study period, downstream movements were recorded for 45 non-
317 consecutive days mainly distributed over four waves of migration (Fig. 2). The river discharge ranged
318 between $16.8 \text{ m}^3\cdot\text{s}^{-1}$ and $1121.5 \text{ m}^3\cdot\text{s}^{-1}$, with a median value of $208.7 \text{ m}^3\cdot\text{s}^{-1}$. Overall, the river flow
319 progressively increased from mid-November to February because of several flow pulses that usually
320 coincided with the peaks of eel activity (Fig. 2). The performances of cut-off alternatives generated
321 from the decision scheme were evaluated using the four metrics: escapement rate, sensitivity,
322 specificity and shutdown duration (Fig. 3). Overall, the escapement rate and the sensitivity dropped
323 for threshold values in river discharge over than $100\text{-}200 \text{ m}^3\cdot\text{s}^{-1}$ and in delta discharge over than 15-
324 25%, which suggests that a large number of eels are migrating during lower flow conditions. On the
325 contrary, the specificity showed an inverse trend with decreasing values for the lower thresholds. Such
326 an observation is consistent with the peaks of eel activity recorded during pulses of river discharge
327 and indicates that unnecessary shutdowns are frequently operated when the thresholds values are
328 undervalued. A similar trend was observed for the number of shutdown days because the probability
329 to meet the target flow conditions mechanically decreases with the threshold values.

330 The four performance metrics were combined in the TOPSIS analysis to determine the cut-off
331 alternatives yielding the best compromise for ensuring eel survival and hydroelectric production (Fig.
332 3). The highest TOPSIS score was obtained for an alternative where the thresholds were fixed at 137.0
333 $\text{m}^3\cdot\text{s}^{-1}$ for river discharge and 20.7% for delta discharge, with systematic shutdown repetition for the
334 day following the flow pulse ($N_{\text{delay}} = 1$). The time slot of daily shutdown advocated by this alternative
335 spread from 6PM to 6AM. Such decision rules clearly identified the four main peaks of eel activity
336 recorded during the study period (Fig. 2) and would have allowed 59.0% eel escapement for 26
337 shutdown days. As complementary purposes, the TOPSIS ranking was used to identify the best
338 alternatives ensuring 0.8 escapement rate. Such an objective can be reachable with only 35 days
339 where turbines are stopped between 4PM and 9AM. Indeed, as telemetry surveys were used, the time
340 slot of shutdown is a key parameter to determine the optimal alternative because of its great
341 influence on the rate of silver eel escapement (Fig. 4).

342 ***3.2. Application 2: Dordogne trap survey***

343 During the study period, the river discharge of the Dordogne River ranged between 27.9 m³.s⁻¹ and
344 913.4 m³.s⁻¹, with a median value of 191.5 m³.s⁻¹. Similarly to the Meuse River, the migrating eels were
345 essentially recorded during pulses of river discharge. A total of 1733 silver eels were collected in the
346 trap with an important variability between the migration seasons (2009: n = 214; 2010: n = 118; 2011:
347 n = 98; 2012: n = 861; 2013: n = 47; 2014: n = 395). The migration waves occurred over nine to 35
348 non-consecutive days depending on the season.

349 The TOPSIS analysis was conducted to rank the cut-off alternatives generated from data collected
350 between 2009 and 2013 (Fig. 5). According to this analysis, the best compromise alternative was
351 associated to thresholds fixed at 102.2 m³.s⁻¹ for river discharge and 23.3% for delta discharge, with no
352 systematic shutdown repetition for the following days ($N_{\text{delay}} = 0$). This alternative would have led to
353 stop the turbines for 118 nights between October 2009 and February 2014 (2009: 23 nights; 2010: 23
354 nights; 2011: 16 nights; 2012: 27 nights; 2013: 29 nights). For this period, the sensitivity and specificity
355 values associated to the compromise alternative were 0.47 and 0.89 respectively, and 79.8% of silver
356 eels were caught during the days when shutdowns would have been recommended. These results
357 indicates that the best alternative well discriminated the main waves of migration, but does not
358 advocate turbine shutdowns during low migration days (i.e. relatively low sensitivity value). Applying
359 the compromise alternative to the independent period (i.e. season 2014) provided comparable
360 outcomes. For this season, the sensitivity and specificity values were 0.51 and 0.97 respectively and
361 the percentage of eel escapement reached 89.1% (Fig. 5b). Overall, although the peaks of flows were
362 less marked than on the Meuse River, the decision scheme clearly identified the main migration waves
363 of the Dordogne River, resulting in 36 nights of shutdowns recommended for 2014.

364 ***3.3. Application 3: Scorff trap survey***

365 From September 2000 to May 2011, the river discharge of the Scorff River ranged between 0.36 m³.s⁻¹
366 and 91.7 m³.s⁻¹, with a median value of 3.16 m³.s⁻¹. Over this 10 years period, 95 migration days were
367 recorded during which 531 silver eels were collected. The annual migrations generally occurred in
368 non-consecutive waves, with the largest number of eels caught in 2002 (n=180) and the minimum in
369 2001 (n=4).

370 The best compromise alternative determined for the Scorff River would have recommended to
371 shutdown when the river discharge was over 1.2 m³.s⁻¹ and values of delta discharge exceed 19.2%,
372 without shutdown repetition during the following days (Fig. 6a). This alternative would have led to
373 stop the turbines for 251 nights between October 2000 and February 2009, with a minimum of 22
374 shutdown nights in 2005 and a maximum of 34 nights in 2006. The sensitivity and specificity values for
375 this period were 0.60 and 0.84 respectively, and 81.1% of silver eels were collected during the days

376 when shutdowns would have been recommended. The compromise alternative was applied to two
377 independent seasons of migration (Fig. 6b). The numbers of shutdown days recommended for these
378 seasons were respectively 35 and 26 for 2009 and 2010. A total of 81.8 and 100% of eels were
379 collected during these days, resulting in acceptable values of sensitivity (0.5 and 1.0 for 2009 and
380 2010, respectively) and specificity (0.77 and 0.84 for 2009 and 2010, respectively). Interestingly, in this
381 small size river, most of the downstream migration events occurred during the autumn period, so that
382 shutdowns are usually unnecessary at the end of the migration period (Fig. 6b).

383 **4. Discussion**

384 Several methods have been proposed to forecast the downstream migration of silver eels based on
385 temporal autoregressive methods (Trancart et al., 2013) or regression models (Sandlund et al., 2017)
386 with the aim of implementing turbine management decision rules (Smith et al., 2017). These models
387 generally predict occurrence or abundance of eels at the hydropower dams on the basis of temporal
388 trends and environmental covariates known to promote eel activity (e.g. rainfall, river flows,
389 temperature, lunar phase). Cut-off values of model predictions (i.e. occurrence probability threshold)
390 are then defined by stakeholders to determine when turbines should be turned off or left on (Smith et
391 al., 2017). These approaches provide accurate outcomes for the sites in which they were adjusted, but
392 the model development and result interpretation require a substantial background in statistical
393 ecology and long-term data to implement the model. This is perhaps why most of shutdown policies
394 currently implemented in European hydropower plants involve simple decision rules only based on
395 hydrologic criteria. Such decision rules are probably easier to interpret for all stakeholders implied in
396 negotiation (e.g. environmental authority, hydropower producer...) allowing explicit discussion among
397 stakeholders on concrete parameters, such as water depth or river discharge. Similarly, the use of cost
398 criteria related to the hydropower production allow to explicitly account for the economic
399 considerations of the energy producer, which in turn can facilitate the negotiations. Indeed, ensuring
400 that each stakeholder properly assesses the cost and benefit of the different management alternatives
401 is crucial to improve acceptance and sustainability of the final conservation policy. In this perspective,
402 the current study provides an effective way to resolve the trade-off between silver eel escapement
403 and hydropower generation throughout an intuitive and easily understandable framework.

404 Although several environmental factor have been proposed as triggers of silver eel activity (Durif and
405 Elie, 2008; Sandlund et al., 2017; Trancart et al., 2013), the river flow is certainly a central factor for
406 quantifying impact of hydropower plants on eel migration (Gosset et al., 2005; Jansen et al., 2007;
407 Vøllestad et al., 1986). Indeed, this factor is highly linked with climatic (e.g. rainfall) and physico-

408 chemical (e.g. turbidity, conductivity) variables, so that it can be used as proxy in models to forecast
409 migration activity (Drouineau et al., 2018). River discharge also influences the repartition of eels
410 passing through alternative routes (Jansen et al., 2007; Trancart et al., 2018b), as well as the traveling
411 speed during the downstream migration (Barry et al., 2016). River flow appears especially relevant
412 within an operational context because this parameter is commonly monitored across European river
413 networks and particularly in hydropower plants. Therefore, real-time data are less challenging to
414 obtain for river discharge than for turbidity or conductivity, for which continuous records require an
415 important effort in probe maintenance. In the present study, the decision scheme was based on the
416 assumption that eel migration can be predicted when the river flows exceed specific threshold values
417 in river discharge (Q threshold) and in delta discharge (ΔQ threshold). This statement was
418 supported by our results and previous studies showing that silver eel movements generally occurred
419 over non-consecutive waves related to a rising river flow phase (Behrmann-Godel and Eckmann, 2003;
420 Drouineau et al., 2017; Vøllestad et al., 1986). For the three illustrative applications, the main
421 migration trends were thus accurately discriminated whatever the hydrological context, suggesting
422 that the method can be applied in a large range of river systems.

423 To estimate relevant threshold values in the decision scheme, we generated a serial of alternatives
424 simulated from the data collected in three river sites. This numerical exploration was associated to a
425 multiple-criteria decision analysis for assessing the relevance of alternatives based on the dual
426 objective of eel conservation and hydropower production. Indeed, the TOPSIS analysis provides
427 opportunity to rank the alternatives as function of trades-off between multiple criteria, including
428 conflicting concerns (Huang et al., 2011). Whereas sensitivity and escapement rate promote the
429 conservation value for silver eel in the decision analysis, the specificity and shutdown duration
430 contribute to restrict the number of unnecessary shutdown operations under an escapement decision
431 rule (i.e. targeted percentage of silver eel escapees). The best compromise alternative represents a
432 situation where hydropower turbines are turned on most of the time, but stopped during the main
433 migration waves to ensure that the majority of eels reach downstream areas without injuries. Such
434 alternatives were identified and detailed for the three applications. For example, 59.0% of silver eels
435 were detected in the Meuse River during the 26 days where shutdowns would have been
436 recommended between 6PM and 6AM. Nevertheless, identifying a unique alternative can be
437 insufficient, for example, if the outcome is lower than an escapement objective determined *a priori* by
438 environmental authorities. In this case, the best compromise should be rejected and the TOPSIS
439 ranking can be used to identify another alternative that fulfill the conservation objective. The final
440 management decision generally involves a number of stakeholders with disparate expertise and
441 possible antagonist interests (e.g. environmental management officers, hydropower producer,

442 fishermen, scientists, environmental police/controllers, water supply managers). Therefore, the
443 purpose of our approach is not to avoid debate between stakeholders, but rather to provide
444 transparent and informative decision tools to fuel negotiations aiming to reach consensus (Hajkowicz,
445 2008). In this perspective, providing a serial of ranked alternatives is a proficient option to facilitate a
446 structured debate between decision makers. The expertise of graphic outputs can help understanding
447 the competitive interests between eel conservation and hydropower production, while visually
448 identifying a range of consensual alternatives to support the choice of operational thresholds.

449 In the three illustrative applications, the thresholds in river discharge recommended by the best
450 compromise alternatives were lower than the median values of discharge observed during the studied
451 periods. This result indicates that downstream migration can occur even in low flow conditions, as it
452 has been previously reported (e.g. Drouineau *et al.*, 2017). Therefore, although operated in several
453 hydropower plants, using only a threshold in river discharge as decision rule for turbine shutdown
454 strategy can lead to the omission of several waves of eel migration. Its combination with a threshold
455 value of relative variation in river discharge was thus relevant to identify periods of eel movement, as
456 demonstrated by Drouineau *et al.* (2017). Interestingly, the threshold values in delta discharge
457 suggested from the TOPSIS analysis were almost comparable for the three river sites (i.e. from 19 to
458 23%), suggesting that a consensual response to change in river discharge can potentially occur.
459 Nevertheless, additional replications are required to determine whether this baseline value can be
460 reliability extrapolated to other river sites. Our analysis also proposed to repeat the turbine shutdowns
461 the day following the discharge pulse to account for the possibility of delayed response of eel to
462 hydrological cues. Likely, this parameter is principally relevant for larger rivers with extended networks
463 where the discharge peaks can spread over several days, as it was observed in the Meuse River.
464 Nevertheless, the migratory activity was highly concentrated around the flow pulses ($N_{\text{delay}} = 0$ or N_{delay}
465 $= 1$), which is consistent with the behavioral response of silver eels that preferentially migrate when
466 water velocity is higher (Barry *et al.*, 2016). On overall, the best compromise alternatives advocated
467 from 16 to 36 shutdown nights per year depending on the site and hydrological season. Such decision
468 rules clearly reflects a win-win solution in comparison to a management policy where hydropower
469 turbines are turned off all the nights during the migration period (Smith *et al.*, 2017). Here, we
470 considered a migration period from October 1 to February 28, but the period can be extended if
471 necessary, particularly to ensure that early migrating males are fully included in the migration window
472 (Tesch, 2003). Moreover, the timing and the duration of migration are influenced by several
473 environmental factors, including water level or temperature experienced during the silvering process
474 (Feunteun *et al.*, 2000; Durif and Elie, 2008; Sandlund *et al.*, 2017). Therefore, the accuracy of turbine
475 management policy could be improved by using models to forecast the onset and the end of

476 migration. For instance, unnecessary shutdowns would have been common at the end of the
477 migration period in the Scorff River because most of silver eels had migrated since early season. This
478 concern could also be solved by determining a maximum number of shutdown nights per year during
479 the negotiation process.

480 On the other hand, our analysis also pointed out the importance of the time slots for turbine
481 shutdown policy. The common strategy consists to switch the hydropower turbines off from the
482 nightfall to dawn in accordance with the nocturnal behavior of eels (Aarestrup et al., 2010; Riley et al.,
483 2011). Although this approach maximizes the chances that turbines will be stopped when migrating
484 eels are crossing the dam (Eyler et al., 2016; Smith et al., 2017; Winter et al., 2006), the daily
485 migration pattern can differ between sites and environmental conditions (Behrmann-Godel and
486 Eckmann, 2003; Bultel et al., 2014). When telemetry surveys are available, it can thus be useful to
487 integrate the time slot duration in the decision analysis to consider the total shutdown duration
488 (hours) instead of a number of nights. In this case, the scoring inherently determines whether it is
489 preferable to extend the number days and/or the time slot of daily shutdown to minimize the total
490 shutdown duration. For instance, in the Meuse River, the daily pattern of eel activity appears
491 extended in comparison to others sites (Drouineau et al., 2017; Riley et al., 2011), so that increasing
492 the time slots duration can be a key issue to reach the targeted escapement rate.

493 In summary, we proposed a simple decision framework for turbine shutdown based on hydrological
494 criteria to guide negotiations between stakeholders toward a trade-off between silver eel
495 conservation and hydropower generation. The method was successfully applied in three river sites
496 featured by contrasted hydrological conditions, and where various types of monitoring data were
497 collected. The approach can thus be transposed to other hydropower sites, while ensuring flexibility
498 regarding the input data (e.g. telemetry data, fish trap, camera records). Nevertheless, further
499 investigations are still required to determine how the decision scheme can be efficiently extrapolated
500 to the large diversity of river types in Europe. In this purpose, the analytical approach can be easily
501 tested or applied in other sites using the generic functions coded in R (Appendix A), providing that
502 monitoring surveys and flow data are available. Our approach provides objective and easy-to-interpret
503 elements for evaluating and ranking a series of alternatives in order to identify the most relevant
504 decision rules depending on the environmental objectives. When a consensual alternative is selected,
505 the turbine shutdown policy can easily be operated day-to-day by managers only by examining the
506 records of river discharge at noon in order to anticipate a potential shutdown procedure at nightfall.

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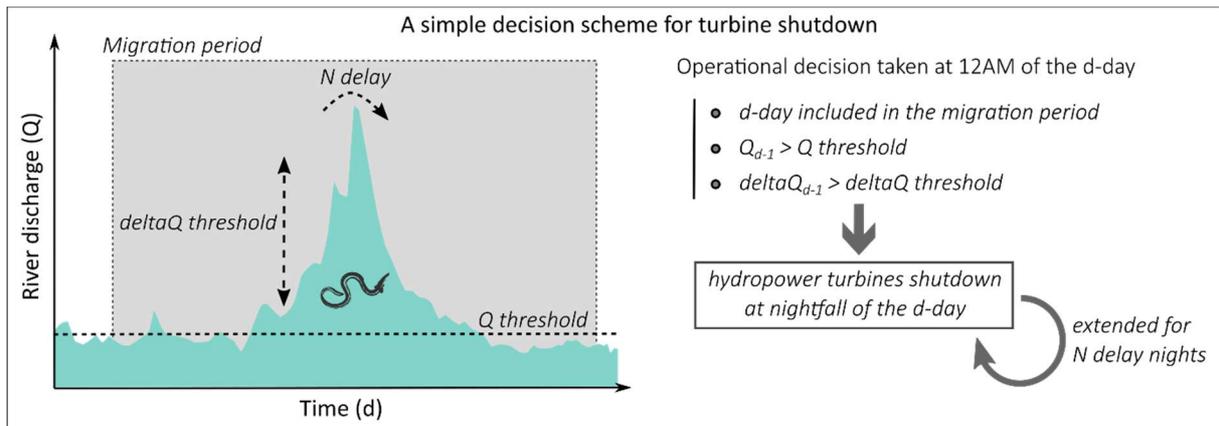


Figure 1: Illustrative view of the decision scheme for turbines shutdown to ensure silver eel escapement in hydropower plants. The hydropower turbines are stopped when river discharge and delta discharge exceed threshold values within the migration period. The decision is made at 12AM on the basis of daily mean hydrological records to anticipate a procedure of turbine shutdown at nightfall. Then, the stopping decision can be extended for several days to consider the delayed response of eel to hydrological cues.

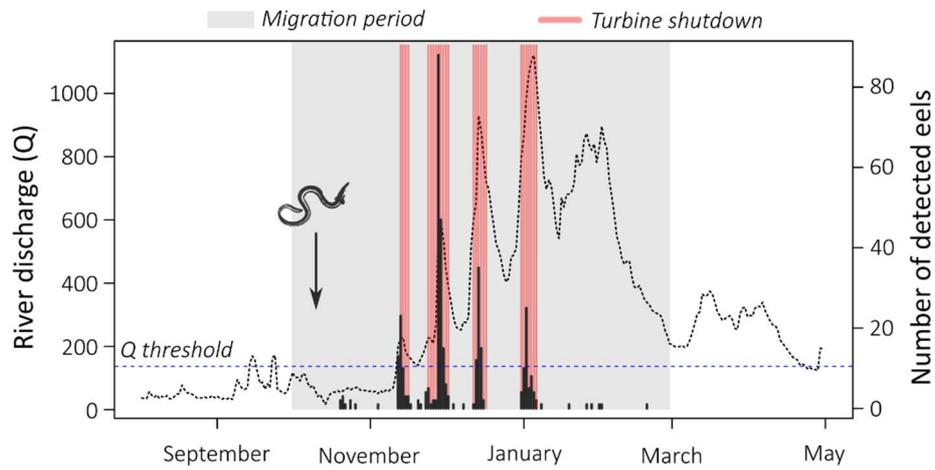


Figure 2: Daily variation in river discharge (dashed line, $\text{m}^3 \cdot \text{s}^{-1}$) and daily distribution of eel detections at the six hydropower plants of the lower Meuse between July 2017 and May 2018. The release date of tagged eels is specified by an arrow (11 October 2017). The shutdown days recommended by the best compromise alternative are indicated (vertical red lines), as well as the fixed migration period (grey rectangle) and the threshold in river discharge (horizontal blue line). Total number of eel passages: 403. Total number of shutdown days: 26.

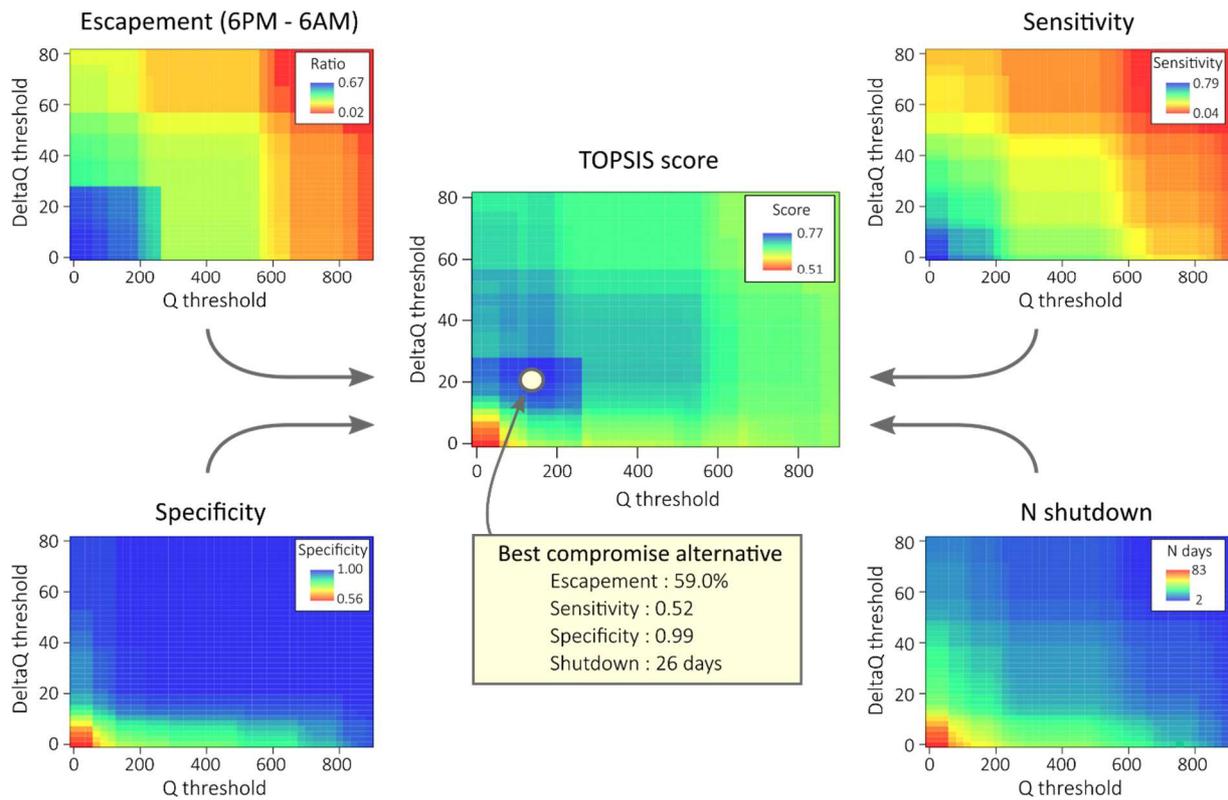


Figure 3: Performances of the cut-off alternatives generated from the decision scheme on the basis of the 403 eel passages recorded at the six hydropower plants of the Meuse River between July 2017 and May 2018. The escapement rate, sensitivity, specificity, number of shutdown days and TOPSIS score are provided as function of the threshold values in river discharge (Q) and in delta river discharge (deltaQ). The values of performance criteria are provided for $N_{\text{delay}} = 1$ and a time slot of daily shutdown between 6PM and 6AM. The yellow box details the performances of the best compromise alternative determined from the TOPSIS scoring process.

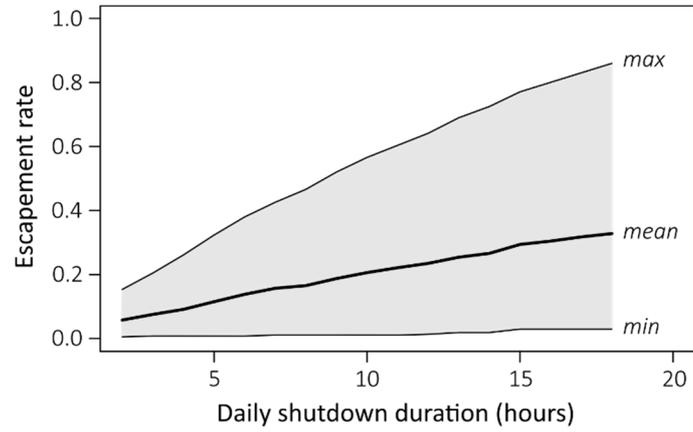
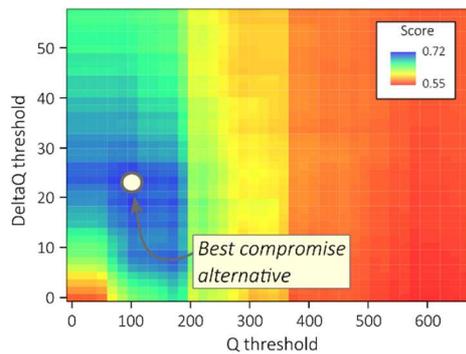


Figure 4: Influence of the daily shutdown duration on the rate of silver eel escapement as estimated by the cut-off alternatives generated from the decision scheme in the Meuse River. The minimum and maximum escapement rates obtained from alternatives of each time slot are provided, as well as mean values.

a) TOPSIS scores (period 2009-2013)



b) Recommended shutdowns (period 2014)

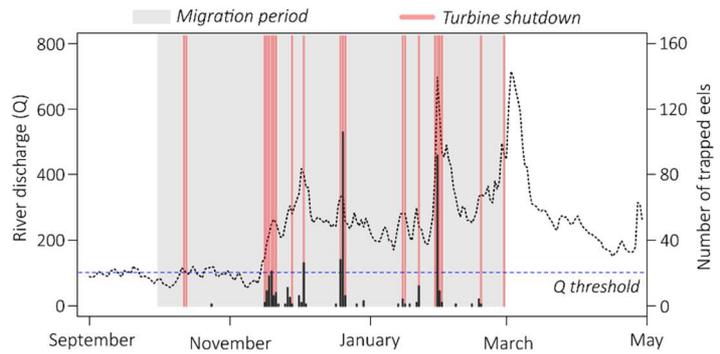
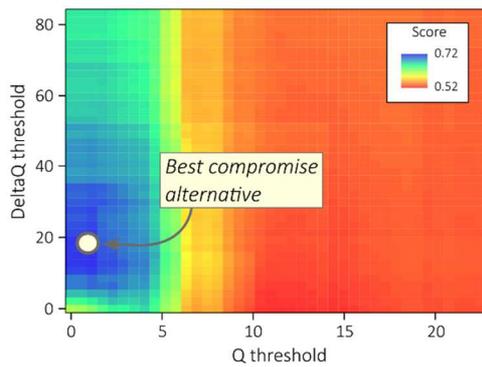


Figure 5: a) TOPSIS scores of the cut-off alternatives generated from data collected between September 2009 and May 2014 in the Dordogne River. Scores are provided as function of the threshold values in river discharge (Q) and in delta river discharge (deltaQ), and for $N_{\text{delay}} = 0$. b) River discharge (dashed line, $\text{m}^3 \cdot \text{s}^{-1}$) and number of silver eels collected in the trap between September 2014 and May 2015 at the hydropower plant. The shutdown days recommended by the best compromise alternative are indicated (vertical red lines), as well as the fixed migration period (grey rectangle) and the threshold in river discharge (horizontal blue line). Total number of eel trapped: 395. Total number of shutdown days: 36.

a) TOPSIS scores (period 2000-2008)



b) Recommended shutdowns (periods 2009 and 2010)

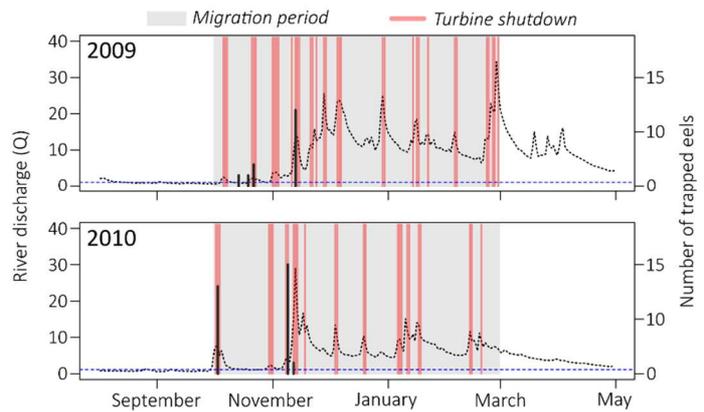


Figure 6: a) TOPSIS scores of the cut-off alternatives generated from data collected between September 2000 and May 2008 in the Oir River. Scores are provided as function of the threshold values in river discharge (Q) and in delta river discharge (ΔQ), and for $N_{\text{delay}} = 0$. b) River discharge (dashed line, $\text{m}^3 \cdot \text{s}^{-1}$) and number of silver eels collected in the trap for the two independent migration season (from September 2009 to May 2010 and from September 2010 to May 2011). The shutdown days recommended by the best compromise alternative are indicated (vertical red lines), as well as the fixed migration period (grey rectangle) and the threshold in river discharge (horizontal blue line). Total number of eel trapped: 11 in 2009 and 19 in 2010. Total number of shutdown days: 35 in 2009 and 26 in 2010.