Journal of Environmental Management 261 (2020) 110212

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

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

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ARTICLE INFO

Keywords:
Anguilla Anguilla
Turbine shutdown
Conservation policy
Multiple-criteria decision
Decision rules

ABSTRACT

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

1. Introduction

The widespread fragmentation of river ecosystems across the globe is a crucial issue for freshwater biodiversity management (Nilsson et al., 2005). Among other anthropogenic impacts, the alteration of ecological connectivity within and between river networks contributes to obstruct lateral and longitudinal dispersal of aquatic organisms, resulting in decline or loss of freshwater populations (e.g. Gehrke et al., 2002; Hall et al., 2011). Diadromous fish are particularly sensitive to this threat because effective migrations in both upstream and downstream directions are essential requirements for their biological cycles (van Puijenbroek et al., 2019). While every obstacle affects accessibility of catchments during upstream migration, hydropower turbines are source of immediate and/or delayed mortality during the downstream movements (Besson et al., 2016; Drouineau et al., 2017; Larinier, 2001). The impacts of hydroelectric dams on silver freshwater eels (Anguillidae) during the downstream migration was reported in various rivers catchment (Eyler et al., 2016; Pedersen et al., 2012; Trancart et al., 2018b; Verbiest et al., 2012; Winter et al., 2007) and management solutions are urgently needed to enhance escapement success (Dekker, 2016; Feunteun, 2002). For example, fisheries and hydroelectric power stations were reported as the main causes of mortality for European eel

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https://doi.org/10.1016/j.jenvman.2020.110212
Received 12 July 2019; Received in revised form 19 December 2019; Accepted 27 January 2020

in the River Meuse, leading a sharp decline in escapement rate at the basin scale (Verbiest et al., 2012; Winter et al., 2006). Nevertheless, the turbine-related mortality appears highly site-specific depending on the local configuration of hydropower dam and its location within the river catchment (Boubée and Williams, 2006; Jansen et al., 2007; Mateo et al., 2017).

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

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

Overall, the definition of operational decision rules for turbine shutdown is challenging due to the duality between the expected benefit for eel conservation and the concomitant cost in term of hydropower generation (Drouineau et al., 2018). Stakeholders usually plan monitoring surveys of silver eel on hydropower dams to evaluate the ecological impact and acquire knowledge on the local phenology of fish migration (Eyler et al., 2016; Smith et al., 2017). On the basis of these data, decision makers have to resolve the trade-off involving the escapement rate of silver eels and the modalities of turbine shutdown operations (e.g. triggering criteria, extent of shutdown periods; Smith et al., 2017; Trancart et al., 2013). Therefore, analytical tools and methods applied can play an essential role in the successful negotiation between stakeholders to develop efficient management strategy (McShane et al., 2011). To be operational, simple and comprehensive decision rules should be preferred to ensure that all stakeholders can fully interpret, assess and subsequently implement the conservation policy. According to this principle, simple decision criteria are already implemented in turbine management strategies for several European hydropower plants. The shutdown policies are commonly based on calendar dates and river flow conditions, which are assumed the primary triggers of eel movements. In such cases, hydropower turbines are switch off from nightfall to dawn during the migration period when river discharge or variation in river discharge exceed given threshold values defined by expert judgments. Although this expert-based approach provides promising results, analytical tools are still lacking to define robust and optimal threshold values for the decision criteria based on the monitoring data collected at hydropower plants.

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

2. Materials and methods

2.1. Proposal of decision scheme

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

In the present study, the downstream migration of silver eel was assumed to be triggered by a sharp increase in river flow (e.g. Behrmann-Godel and Eckmann, 2003; Cullen and McCarthy, 2003) within a favorable temporal window of migration (Fig. 1). To capture this pattern, four parameters were considered: the migration period (onset and end dates), the river discharge (Q, $m^3.s^{-1}$), the discharge difference compared to one or more previous days (deltaQ, %), and the delayed response of eel to hydrological cues (N_{delay}, day). The migration period was defined as the calendar dates during which silver eels are expected migrate downstream to reach the marine spawning areas. Environmental authorities generally fix this period in conservation policies. In Europe, the downstream migration generally extends from autumn to early spring, but varies between localities (e.g. Righton et al., 2016; Vøllestad et al., 1986). Turbine shutdowns can be operated during this

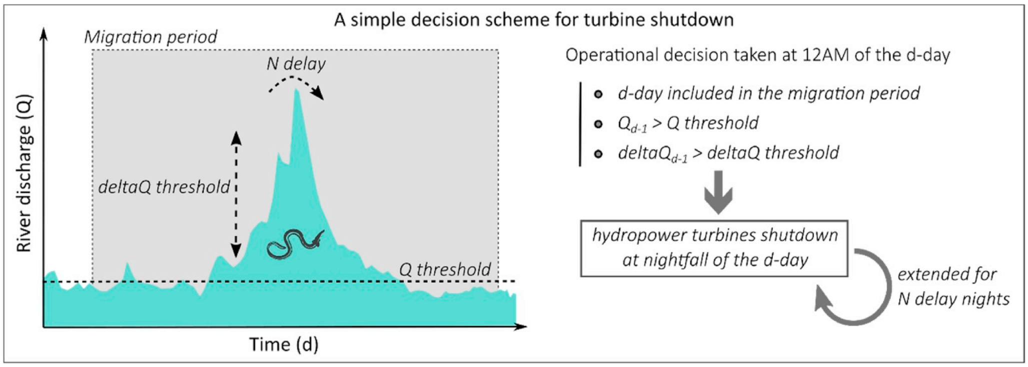

Fig. 1. Illustrative view of the decision scheme for turbines shutdown to ensure silver eel escapement in hydropower plants. The hydropower turbines are stopped when river discharge and delta discharge exceed threshold values within the migration period. The decision is made at 12AM on the basis of daily 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.

temporal window to enhance escapement and survival of silver eels. Within this period, the migration peaks can be identified using environmental data. Given the non-linear response of eel to hydrological cues, we assumed that a migration event can be predicted when the river flow conditions exceed both specific threshold values in river discharge (Q threshold) and in delta discharge (deltaQ threshold). This basic threshold model intuitively supposes that a minimum water flow associated with a minimum discharge pulse is required to stimulate the downstream migration. The values of delta discharge reflect the intensity of the flow pulse, as estimated by the relative difference in flow conditions of the d-day compared to the mean discharge of a moving reference period (from d-1 to d-Nday). Depending on the local hydrology, the extent of reference period (Nday) can be adjusted to correspond to the mean duration of a flow pulse, generally around 2–6 days. Once favorable hydrologic cues are encountered, silver eels are expected to engage their downstream migration. Nevertheless, some eels can still remain in migration for a few days after the flow peak, while the river flow is stabilizing or decreasing. To consider this situation, we introduced the possibility to repeat the turbine shutdown for several days (N_{delay}) after detecting a discharge pulse that trigged fish migration.

2.2. *Performances of cut-off alternatives*

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

Here, cut-off alternatives were produced by generating unique combinations of values for Q threshold, deltaQ threshold and N_{delay}. More precisely, 40 values evenly distributed between zero and the 95th percentile were generated for Q and deltaQ thresholds, as well as values ranging from 0 to 3 days for N_{delay}. This results in 6400 alternatives. When telemetry data are available, the time slot of daily shutdown can also be considered to determine an optimal window, instead of stopping arbitrarily the hydropower production from nightfall to dawn. In such a case, different time slots were generated as extra alternatives based on the hourly distribution of eel observations. Time slots were incremented by adding 1 h successively, starting from the distribution mode until a duration of 18 h was reached. In combination with the previous parameters, a total of 108 800 alternatives was generated. No alternatives were generated according to the migration period because the dates of onset and end are usually determined and fixed *a priori* by environmental authorities on the basis of historical data or expert knowledge. Nevertheless, this period can differ between locations depending the biogeographic regions or local environmental conditions (Durif and Elie, 2008; Righton et al., 2016).

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

2.3. *Ranking alternatives for decision making*

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

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

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

2.4. Illustrative applications on actual data

Three data sets were used to illustrate and evaluate the applicability of the decision framework in contrasted river systems. The first example was based on telemetry data collected in a large river system, the Meuse River (950 km long, 36 000 km^2), whereas the second and third examples were based on fish trap data collected in the Dordogne River (475 km long, 24 500 km^2) and in the Scorff River (78 km long, 490 km^2). This large range of hydrological conditions was selected to be representative of the different river systems inhabited by the eel in the European regions. Moreover, the method transferability was illustrated by the use of various monitoring techniques commonly implemented in hydropower plants.

The Meuse River is extensively used for hydropower generation and silver eel migration was monitored at six power plants located in Wallonia (Sonny et al., 2018), between Namur and the Belgium-Dutch border (*c.a.* 100 km river section). Silver eels (n = 150) were captured by a professional fishery in the Rhine River (Deutschland, 7 October 2017) and implanted with acoustic transmitters (LOTEK JSAT L-AMT-8.2). In agreement with the environmental authorities, the eels were then released in the Meuse river (11 October 2017) at different sites, from 0.5 to 2.5 km upstream of the hydropower plants. Between October 2017 and March 2018, the passages of tagged fish at sites were recorded in using a network of 76 acoustic receivers (LOTEK WHS 4250 D) distributed along the hydropower facilities (between 21 and 9 receivers depending on the plant) to ensure high detection capacity. Accordingly, several receivers were placed on each site to cover all the possible pathways, i.e. dam, turbines or navigation locks. After excluding the first 8 days following the fish release to avoid any bias related to manipulation stress (Trancart et al., 2018b), 403 eel passages were recorded at the six plants during the study period. The eel passages were used to illustrate the decision scheme, in combination with measures of river discharge recorded in the middle of the river section. River flow data were provided by the Public Service of Wallonia (Direction générale opérationnelle de la Mobilité et des Voies hydrauliques, Boulevard du Nord 8–5000 Namur) at the Amay station. For the TOPSIS analysis, cut-off alternatives were generated using a large period of migration extending from October 1 to February 28 to be conservative. The relative difference in river discharge was calculated using a 5 days moving reference period (Nday = 5). As telemetry data were used, the time slot of turbine shutdown was included in the decision process.

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

For the Scorff River, fish trap data were previously used by Trancart et al. (2013) to forecast eel migration using SARIMAX models in small rivers. Although no hydropower plants were implanted in this river, the data were used as illustrative example. Briefly, silver eels were collected between September 2000 and May 2011 using a fish trap located in the main stem of the river. As for the Dordogne River, the trap was checked daily during the eel migration period and silver eels were counted. The river discharge records were obtained from the Direction Régionale de l'Environnement, de l'Aménagement et du Logement de Bretagne (site: J5102210, DREAL Bretagne/HYDRO-MEDDE/DE). The cut-off alternatives were generated using the nine first migration seasons (i.e. from September 2000 to May 2009) and the two later season (i.e. from September 2009 to May 2011) were used as independent evaluation periods. The same migration period was used, but the moving reference period was fixed to 3 days to consider the smaller size of the river system. When using trap surveys, such as for the Dordogne and Scorff Rivers, the performance metrics are calculated at a daily scale and thus did not consider the influence of the time slots on eel escapement.

3. Results

3.1. Application 1: meuse telemetry survey

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

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

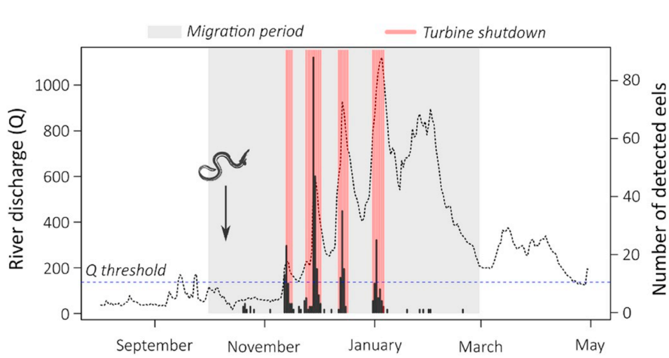

Fig. 2. Daily variation in river discharge (dashed line, $m^3.s^{-1}$) and daily distribution of eel detections at the six hydropower plants of the lower Meuse between July 2017 and May 2018. The release date of tagged eels is specified by an arrow (11 October 2017). The shutdown days recommended by 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Application 2: dordogne trap survey

During the study period, the river discharge of the Dordogne River ranged between 27.9 $m^3 s^{-1}$ and 913.4 $m^3 s^{-1}$, with a median value of 191.5 $m^3 s^{-1}$. Similarly to the Meuse River, the migrating eels were essentially recorded during pulses of river discharge. A total of 1733 silver eels were collected in the trap with an important variability between the migration seasons (2009: n = 214; 2010: n = 118; 2011: n = 98; 2012: n = 861; 2013: n = 47; 2014: n = 395). The migration waves occurred over nine to 35 non-consecutive days depending on the season.

The TOPSIS analysis was conducted to rank the cut-off alternatives generated from data collected between 2009 and 2013 (Fig. 5). According to this analysis, the best compromise alternative was associated to thresholds fixed at 102.2 $m^3 s^{-1}$ for river discharge and 23.3% for delta discharge, with no systematic shutdown repetition for the following days ($N_{delay} = 0$). This alternative would have led to stop the turbines for 118 nights between October 2009 and February 2014 (2009: 23 nights; 2010: 23 nights; 2011: 16 nights; 2012: 27 nights; 2013: 29 nights). For this period, the sensitivity and specificity values associated to the compromise alternative were 0.47 and 0.89 respectively, and 79.8% of silver eels were caught during the days when shutdowns would have been recommended. These results indicates that the best alternative well discriminated the main waves of migration, but does not advocate turbine shutdowns during low migration days (i.e. relatively low sensitivity value). Applying the compromise alternative to the independent period (i.e. season 2014) provided comparable outcomes. For this season, the sensitivity and specificity values were 0.51 and 0.97 respectively and the percentage of eel escapement reached 89.1% (Fig. 5b). Overall, although the peaks of flows were less marked than on the Meuse River, the decision scheme clearly identified the main migration waves of the Dordogne River, resulting in 36 nights of shutdowns recommended for 2014.

3.3. Application 3: scorff trap survey

From September 2000 to May 2011, the river discharge of the Scorff River ranged between 0.36 $m^3 s^{-1}$ and 91.7 $m^3 s^{-1}$, with a median value of 3.16 $m^3 s^{-1}$. Over this 10 years period, 95 migration days were recorded during which 531 silver eels were collected. The annual migrations generally occurred in non-consecutives waves, with the largest number of eels caught in 2002 (n = 180) and the minimum in 2001 (n = 4).

The best compromise alternative determined for the Scorff River would have recommended to shutdown when the river discharge was over 1.2 $m^3 s^{-1}$ and values of delta discharge exceed 19.2%, without shutdown repetition during the following days (Fig. 6a). This alternative would have led to stop the turbines for 251 nights between October 2000 and February 2009, with a minimum of 22 shutdown nights in 2005 and a maximum of 34 nights in 2006. The sensitivity and specificity values for this period were 0.60 and 0.84 respectively, and 81.1% of silver eels were collected during the days when shutdowns would have been recommended. The compromise alternative was applied to two independent seasons of migration (Fig. 6b). The numbers of shutdown days recommended for these seasons were respectively 35 and 26 for 2009 and 2010. A total of 81.8 and 100% of eels were collected during these days, resulting in acceptable values of sensitivity (0.5 and 1.0 for 2009 and 2010, respectively) and specificity (0.77 and 0.84 for 2009 and 2010, respectively). Interestingly, in this small size river, most of the downstream migration events occurred during the autumn period, so that shutdowns are usually unnecessary at the end of the migration period (Fig. 6b).

4. Discussion

Several methods have been proposed to forecast the downstream migration of silver eels based on temporal autoregressive methods

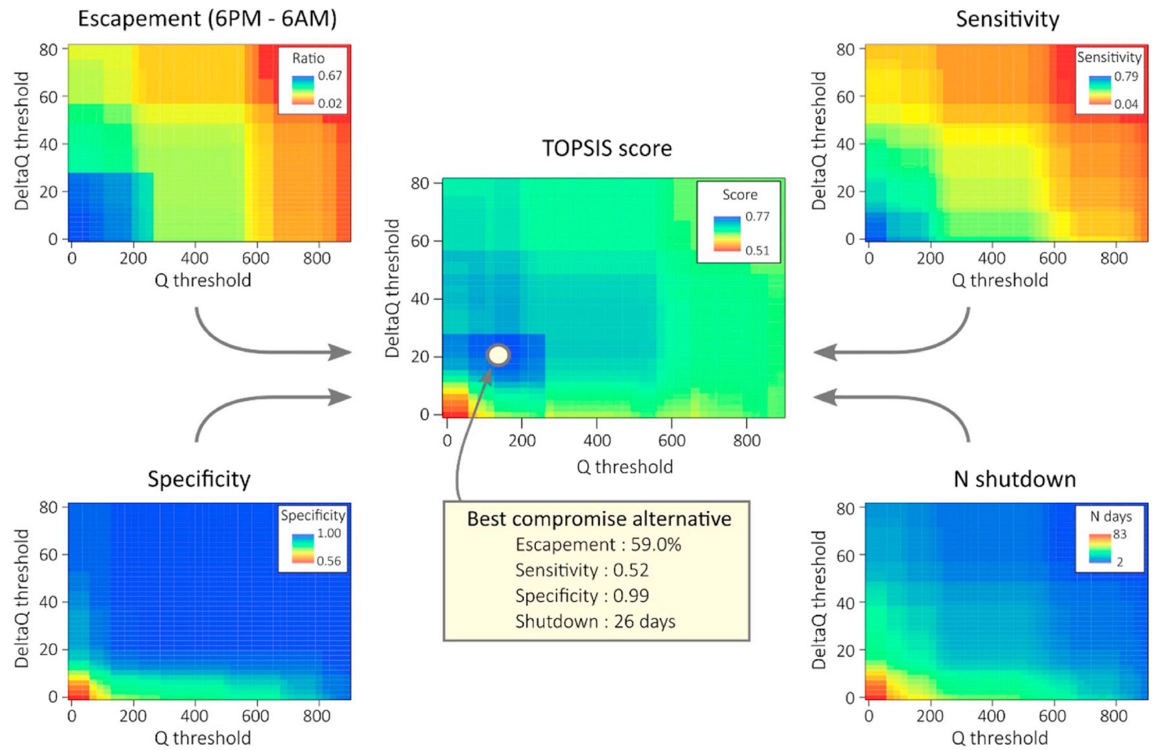

Fig. 3. Performances of the cut-off alternatives generated from the decision scheme on the basis of the 403 eel passages recorded at the six hydropower plants of the Meuse River between July 2017 and May 2018. The escapement rate, sensitivity, specificity, number of shutdown days and TOPSIS score are 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 $N_{delay} = 1$ 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

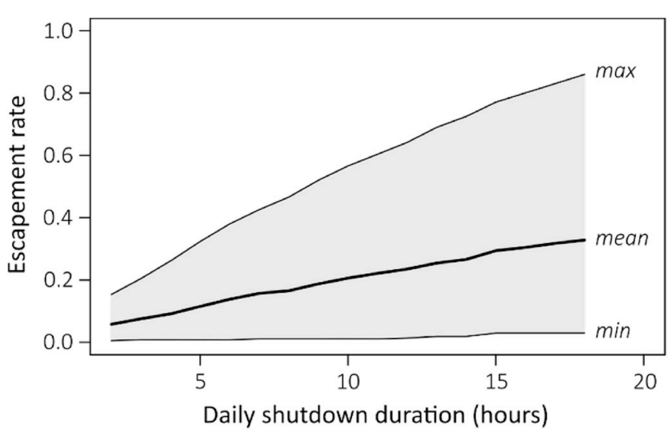

Fig. 4. Influence of the daily shutdown duration on the rate of silver eel escapement as estimated by the cut-off alternatives generated from the decision scheme in the Meuse River. The minimum and maximum escapement rates obtained from alternatives of each time slot are provided, as well as mean values.

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

Although several environmental factor have been proposed as triggers of silver eel activity (Durif and Elie, 2008; Sandlund et al., 2017; Trancart et al., 2013), the river flow is certainly a central factor for quantifying impact of hydropower plants on eel migration (Gosset et al., 2005; Jansen et al., 2007; Vøllestad et al., 1986). Indeed, this factor is highly linked with climatic (e.g. rainfall) and physico-chemical (e.g. turbidity, conductivity) variables, so that it can be used as proxy in models to forecast migration activity (Drouineau et al., 2018). River discharge also influences the repartition of eels passing through alternative routes (Jansen et al., 2007; Trancart et al., 2018b), as well as the traveling speed during the downstream migration (Barry et al., 2016). River flow appears especially relevant within an operational context because this parameter is commonly monitored across European river networks and particularly in hydropower plants. Therefore, real-time data are less challenging to obtain for river discharge than for

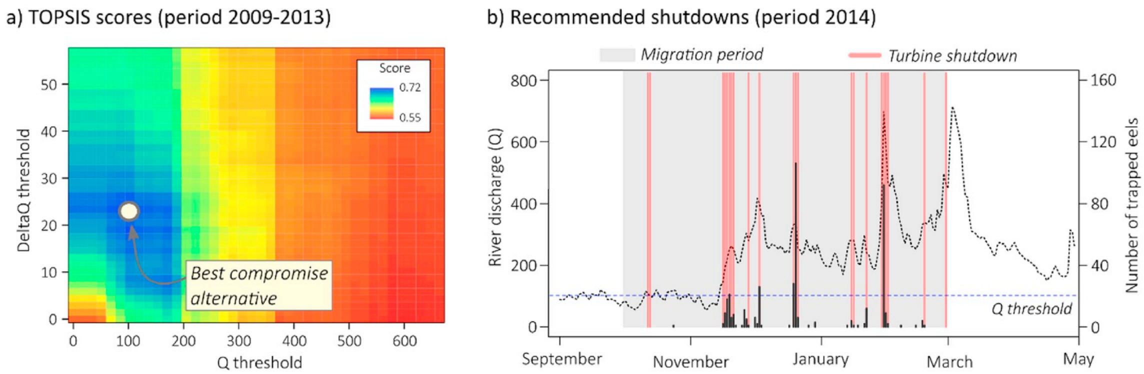

Fig. 5. a) TOPSIS scores of the cut-off alternatives generated from data collected between September 2009 and May 2014 in the Dordogne River. Scores are provided as function of the threshold values in river discharge (Q) and in delta river discharge (deltaQ), and for $N_{delay} = 0$. b) River discharge (dashed line, $m^3.s^{-1}$) 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

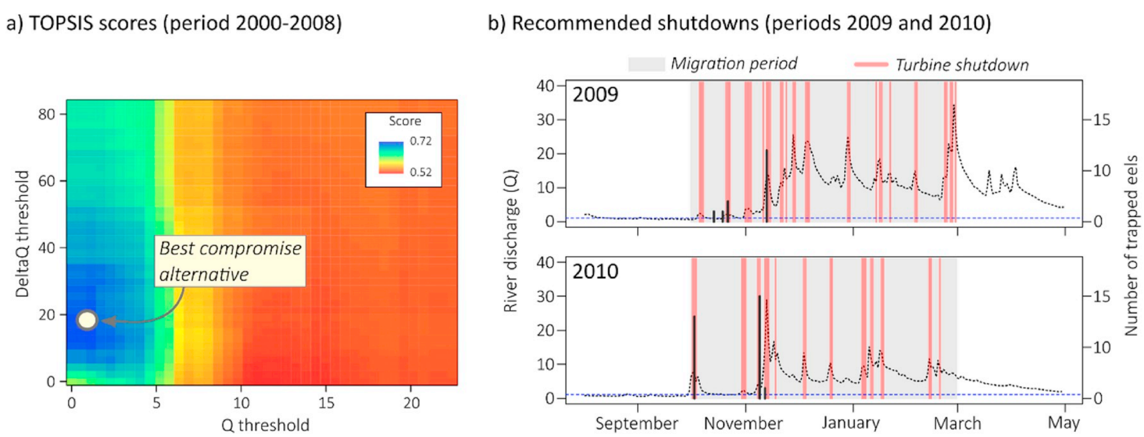

Fig. 6. a) TOPSIS scores of the cut-off alternatives generated from data collected between September 2000 and May 2008 in the Oir River. Scores are provided as function of the threshold values in river discharge (Q) and in delta river discharge (deltaQ), and for $N_{delay} = 0$. b) River discharge (dashed line, $m^3.s^{-1}$) 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

turbidity or conductivity, for which continuous records require an important effort in probe maintenance. In the present study, the decision scheme was based on the assumption that eel migration can be predicted when the river flows exceed specific threshold values in river discharge (Q threshold) and in delta discharge (deltaQ threshold). This statement was supported by our results and previous studies showing that silver eel movements generally occurred over non-consecutive waves related to a rising river flow phase (Behrmann-Godel and Eckmann, 2003; Drouineau et al., 2017; Vøllestad et al., 1986). For the three illustrative applications, the main migration trends were thus accurately discriminated whatever the hydrological context, suggesting that the method can be applied in a large range of river systems.

To estimate relevant threshold values in the decision scheme, we generated a serial of alternatives simulated from the data collected in three river sites. This numerical exploration was associated to a multiple-criteria decision analysis for assessing the relevance of alternatives based on the dual objective of eel conservation and hydropower production. Indeed, the TOPSIS analysis provides opportunity to rank the alternatives as function of trades-off between multiple criteria, including conflicting concerns (Huang et al., 2011). Whereas sensitivity and escapement rate promote the conservation value for silver eel in the decision analysis, the specificity and shutdown duration contribute to restrict the number of unnecessary shutdown operations under an escapement decision rule (i.e. targeted percentage of silver eel escapees). The best compromise alternative represents a situation where hydropower turbines are turned on most of the time, but stopped during the main migration waves to ensure that the majority of eels reach downstream areas without injuries. Such alternatives were identified and detailed for the three applications. For example, 59.0% of silver eels were detected in the Meuse River during the 26 days where shutdowns would have been recommended between 6PM and 6AM. Nevertheless, identifying a unique alternative can be insufficient, for example, if the outcome is lower than an escapement objective determined *a priori* by environmental authorities. In this case, the best compromise should be rejected and the TOPSIS ranking can be used to identify another alternative that fulfill the conservation objective. The final management decision generally involves a number of stakeholders with disparate expertise and possible antagonist interests (e.g. environmental management officers, hydropower producer, fishermen, scientists, environmental police/controllers, water supply managers). Therefore, the purpose of our approach is not to avoid debate between stakeholders, but rather to provide transparent and informative decision tools to fuel negotiations aiming to reach consensus (Hajkowicz, 2008). In this perspective, providing a serial of ranked alternatives is a proficient option to facilitate a structured debate between decision makers. The expertise of graphic outputs can help understanding the competitive interests between eel conservation and hydropower production, while visually identifying a range of consensual alternatives to support the choice of operational thresholds.

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

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

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

CRediT authorship contribution statement

Nils Teichert: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Stéphane Tétard:** Conceptualization, Methodology, Writing - original draft, Data curation. **Thomas Trancart:** Conceptualization, Methodology, Supervision, Funding acquisition. **Eric Feunteun:** Conceptualization, Methodology, Supervision, Funding acquisition. **Anthony Acou:** Conceptualization, Methodology, Data curation. **Eric de Oliveira:** Conceptualization, Methodology, Writing - original draft, Data curation, Supervision, Funding acquisition.

Acknowledgements

The European Union financially supported this study through the LIFE Nature and Biodiversity program, as part of the LIFE4FISH project (LIFE16 NAT/BE/000807). We are grateful to the two anonymous referees for their comments and suggestions that have contributed to improve the relevance of our manuscript. We are grateful to the team of Profish Technology that conducted the telemetry surveys in the Meuse River, which were supported by the LIFE4FISH project. We like to thank the professional fishermen, ECOGEA and EDF-CIH for the data collection and eel project management in the Dordogne River. These samplings were funded by EDF and Adour-Garonne Water Agency. Finally, we like to thank our INRA colleagues, F. Marchand and D. Azam, for eel data acquisition in the Scorff River.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110212.

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