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RESEARCH ARTICLE

Effectiveness of an Electrical Barrier to Improve Silver Eel (*Anguilla anguilla*) Escapement Over a Hydropower Dam on the Meuse River, Belgium

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ABSTRACT

The European eel population is in severe decline, leading to several regulations to save the species from extinction. Various factors impact various stages of the complex lifecycle of this species, and improving the survival of silver eels migrating downstream through turbines is essential in hydropower plants (HPPs). While adapted physical barriers ensure total protection in new small HPPs, effective solutions are still needed for larger existing facilities. An electrical barrier was installed across the forebay of 160 $m^3\ s^{-1}$ HPP. An acoustic telemetry study compared silver eel passage via the dam versus the turbines between reference values in the year prior to the installation of the barrier versus migration after installation and operation of the electrical barrier. The dam passage rate increased significantly with the electrical barrier, in hydrological conditions similar to those of the reference year. Under flow conditions where the nonturbine flow was the lowest, a reduction of 52% in turbine passage could be explained by the electrical barrier. While this efficacy is far from perfect, the results encourage using this technology in large HPPs as a first step in eel protection. At our pilot study site, the technology was adopted as a permanent solution, associated with turbine shutdown according to an eel migration prediction model.

1 | Introduction

The European eel, *Anguilla anguilla*, has undergone severe decline in recent decades (Dekker et al. 2003; Dekker and Beaulaton 2016; Castonguay and Durif 2016) and is now an endangered species according to the International Council for the Exploration of the Sea (ICES) (ICES 2019). The European Union introduced a regulation (Council Regulation EC n° 1100/2007; EU 2007) to reduce anthropogenic pressure on this amphibiotic catadromic species. A panoply of interacting factors in the continental phase of juvenile eels has played a role in the decrease in the European eel population: overfishing of glass eels, loss, or artificialization of habitat (Kettle, Vollestad, and Wibig 2011; Chen, Huang, and Han 2014) and anthropogenic contamination (Bourillon et al. 2022). In large rivers, downstream migrating silver eels can be exposed to significant impacts due to river fragmentation by hydropower plant (HPP) dams (Winter, Jansen, and Breukelaar 2007; McCarthy et al. 2008; Bruijs and Durif 2009). Survival rates mainly depend on the technical specifications of the turbine: type, size, and rotation speed (Gomes and Larinier 2008). The respective weights of each factor are not well established, but improving survival in downstream migrating silver eels at HPPs is one of the first measures to be progressively implemented in national regulations, via the operating permits required for HPP facilities. For the hydropower sector, meeting these obligations requires mitigation measures that can entail significant costs, whatever the solutions adopted (Drouineau et al. 2018).

Physical barriers aim to prevent eels passing through the turbine, by means of mechanical structures such as screens. Initially designed to prevent debris from damaging turbines, screens can also help to prevent fish from passing through the turbine, when their design is specifically adapted and associated with an alternative migration route or bypass, offering a fish downstream passage solution (FDPS) that physically guides eel swimming toward the bypass. For this, FDPSs must meet certain criteria: reducing bar spacing to 20 mm (or less in some cases, such as for male eels), and inclining the screen vertically or laterally to increase its surface area and consequently reducing the tangential velocity of the water through the bars to $< 0.5\,\mathrm{m\ s^{-1}}$ (Courret and Larinier 2008). For example, a radio-telemetry study reported 100% efficiency for these FDPS criteria regarding female silver eels at four successive HPPs with intake capacities ranging from 28 to 45 $\mathrm{m^3\ s^{-1}}$ (Tomanova et al. 2023).

Despite this proven efficacy, physical barriers are easier to implement in new than in existing HPPs, where inappropriate site geometry may incur production, installation, and maintenance costs as head loss. Moreover, this type of FDPS is limited by HPP discharge capacity, which is around 120 $\mathrm{m^3\ s^{-1}}$ (David et al. 2022). This limit is an order of magnitude rather than a threshold, but other types of FDPS have to be considered for existing HPPs with large capacity. Trap and transport plans have been tested in Europe as a temporary solution that showed significant efficacy in the River Erne in Ireland (McCarthy et al. 2014) and in the Mosel in Germany (Kroll 2012), but cannot be considered as a sustainable permanent measure. Turbine management with full or at least significant discharge over the dam is also a straightforward form of FDPS if it can be programmed at eel migration peaks, to minimize production loss. A recent analysis crossed silver eel migration data from 10 river catchments, to produce a predictive model (Teichert, Tétard, Trancart, Oliveira, et al. 2020). Silver eel migration was predictable with relatively good accuracy based on water discharge gradients, determining thresholds that can be used to synchronize turbine management on days with a high probability of migration (Teichert, Tétart, Trancart, Feunteun, et al. 2020). However, the authors recommended including, if possible, a few years' local field observations to confirm model predictions so as to weigh loss of production against FDPS efficacy, as was recently done in the Seine River. Since turbine management incurs a significant loss of production, manufacturers have started to adapt designs to minimize such impact (Watson et al. 2022; Koukouvinis and Anagnostopoulos 2023).

Behavioral barriers have also been explored for several decades, to deflect fish away from water intakes (Popper and Carlson 1998; Noatch and Suski 2012), and may play the same role as a physical barrier. Since eels are nocturnal animals (Hadderingh et al. 1999), light was one of the first stimuli tested to deflect eels, with variable success. Constant and strobe light screens both seemed to exert an avoidance effect on silver eels (Lowe 1952; Patrick, Sheehan, and Sim 1982; Hadderingh, Van Der Steop, and Habraken 1992; Cullen and McCarthy 2000; Versar 2009; Vowles and Kemp 2021). However, the water turbidity encountered during migration limits the efficacy of light as a barrier (Hadderingh 1982). Moreover, the system requires maintenance to keep the light source free of biofouling.

Sound is another cue that has been explored to deflect eels. Sand et al. (2000) reported that infrasound could guide silver eels laterally toward the opposite bank in a small shallow river in Norway. A similar observation was made in a small river in the UK (Piper et al. 2019). This technology was able to deflect cyprinid species at a cooling intake (Sonny et al. 2006) but failed to deflect silver eels away from an HPP turbine in a river in the French Pyrenees (Baran et al. 2012). These contradictory observations are typical of the global literature on behavioral barriers for eels (Popper et al. 2020); so far, no proven solution is available as a turnkey system on the market.

Lastly, the effects of electrical fields were explored for various fish species, like to prevent invasive species from entering water bodies (Johnson et al. 2014; Parker et al. 2015) or to keep fish away from hazardous areas such as turbine outlets during upstream migration (Faria, Viana, and Martinez 2014). In small-scale tests in flumes, electrical fields were able to deflect downstream migrating fish, including eels, laterally toward a bypass (Rost et al. 2014). In silver eels, this was confirmed recently in a laboratory flume study (Miller et al. 2021). As a variant of electrical fields, screen electrification was able to retain fish upstream of an electrified bar rack at a maximal velocity of $0.43\,\mathrm{m\ s^{-1}}$ in a concrete section of a vertical slot fishway along the Danube River (Haug et al. 2022). These results were mostly restricted to small-scale sites, and studies of electrical fences for downstream migrating silver eels at large HPPs are lacking.

To meet permit requirements for the protection of Atlantic salmon smolts and European silver eels at 6 HPPs in the Meuse River, Belgium, an ambitious program called LIFE4FISH (LIFE16 NAT/BE/000807, www.life4fish.be) was launched by the power company, in association with other partners. Various FDPSs were explored, including behavioral cues to increase the rate of spillway passage. After a market study performed by the power company, it was decided to implement a full-scale electrical barrier at one pilot site, to test its efficacy in reducing silver eel entrainment into the turbines and increasing escapement over the spillway. Acoustic telemetry was conducted to compare turbine vs spillway passage rates between 2 years, one under normal operating conditions (reference year, 2017) and the second with an electrical barrier in operation (test year, 2019).

2 | Materials and Methods

2.1 | Study Site

The Belgian Meuse River is fragmented by 15 dams along its 125 km stretch between the French and the Dutch border. A single power company operates hydropower along the last 6 dams, located between Namur (km 48) and Lixhe (km 125), with a total annual production of 240 GWh (Figure 1). The pilot site selected for this experiment was the Grands-Malades HPP, first upstream of the 6 HPPs (HPP1). It comprises four Kaplan turbines with a total capacity of 170 $m^3\,s^{-1}$ and a head of 2.6-4 m. Mean annual river discharge is 220 $m^3\,s^{-1}$.

The electrical barrier was supplied by Procom System (Poland) and was composed of stainless steel pipes (cross-section 40 × 4 mm for positive and 32 × 2 mm for negative) anchored at the bottom by a chain and concrete blocks and connected to the power through underwater cables and connectors (Figure 2).

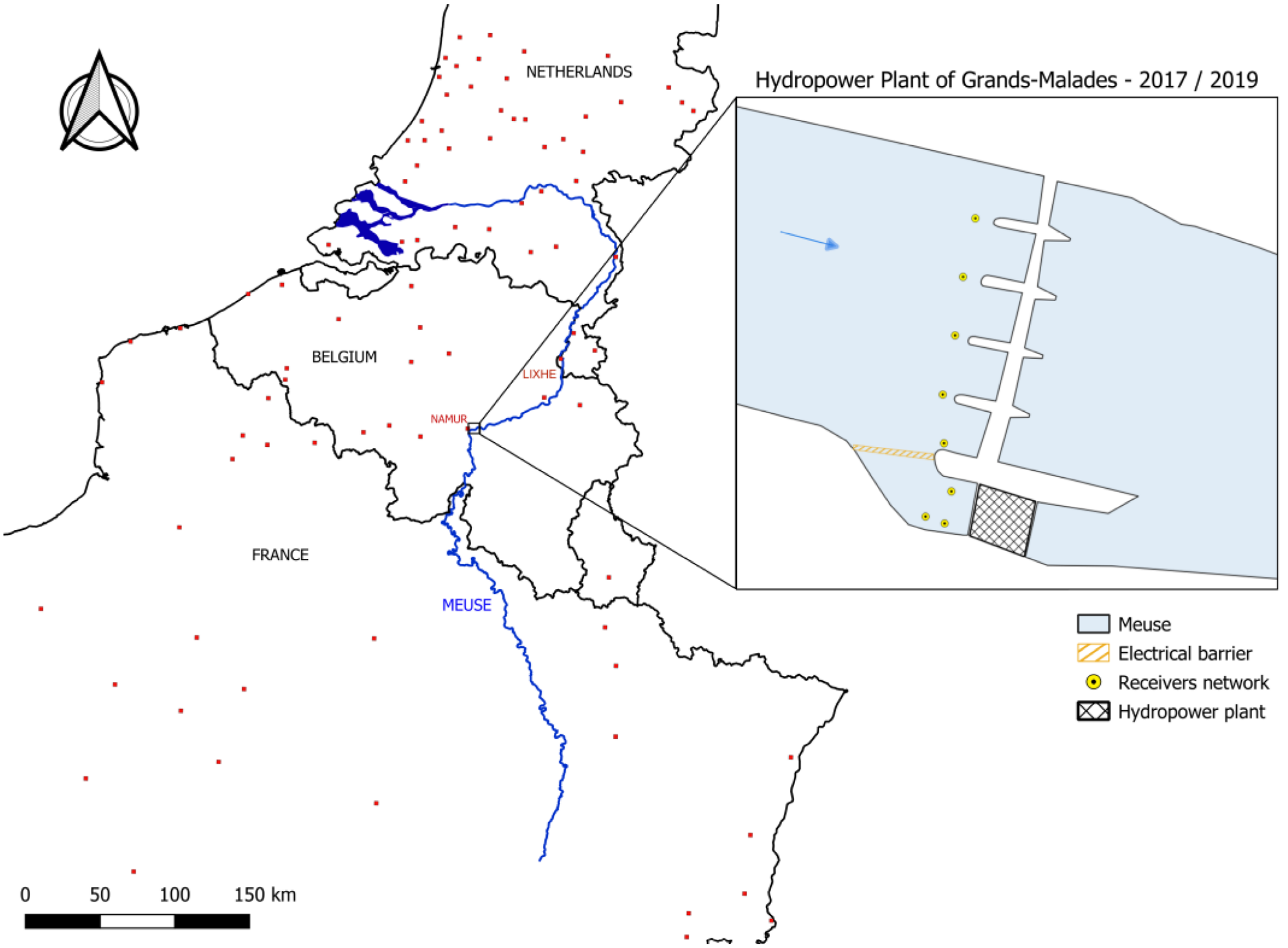

FIGURE 1 | Overview of the Meuse River basin and focus on the Grands-Malades HPP. The position of the electrical barrier and the locations of hydrophones along the dam are shown. [Color figure can be viewed at wileyonlinelibrary.com]

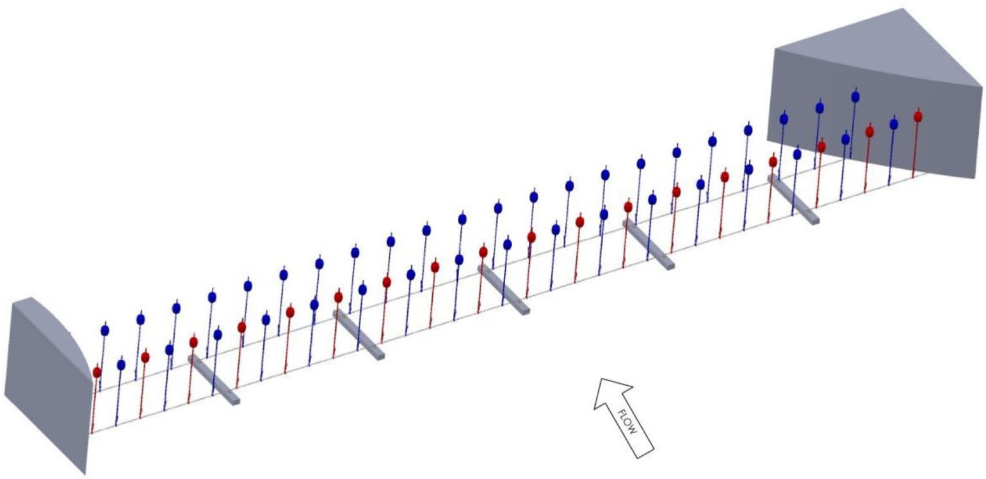

FIGURE 2 | Diagram of the two rows of electrodes installed across the forebay entrance of Grands-Malades HPP. Positive electrodes in red and negative electrodes in blue; flow direction is represented by the arrow. [Color figure can be viewed at wileyonlinelibrary.com]
Source: Procom System.

The electrodes were kept vertical by buoys along their length. Two rows of electrodes were installed, the first, upstream, front row alternated positive and negative electrodes at 1 m intervals, while the second row, 2 m downstream, was polarized negative, with 1.5 m intervals between electrodes. During the study, the electrical parameters established by the supplier were: 100 V, pulse duration 60 ms, and repetition 100 ms.

2.2 | Environmental Parameters

During the study, turbine discharge was recorded continuously by a data logging devised by the power company, at a rate of 1 value per minute. River discharge was obtained by autonomous loggers managed by the Navigation Water Authorities (SPW) and recorded at the Amay station, 40 km downstream of HPP1, at a rate of 1 value per minute. To improve the precision of the discharge rate at the time of presumed eel passage, SPW recalculated the discharge spilled by the dam's gate, using hydraulic models on the height opening measurements recorded for each gate.

2.3 | Telemetry Network

Fish passage in spillways or turbines was assessed using acoustic telemetry. After preliminary detection performance tests, LOTEK WHS 4250 hydrophones (JSATS, 416.7 kHz) were used to build a dense and robust telemetry network to identify fish passage. The telemetry network of HPP1 was composed of five hydrophones covering the five spillways of the dam, and three hydrophones covering the HPP forebay (Figure 1). Two hydrophones were installed 730 m downstream of the dam on either bank of the river, to confirm downstream passage. The hydrophones were anchored either by mechanical anchors drilled into the concrete structures or by steel anchors installed by divers. The hydrophones were kept in a vertical position along a rope beneath a 12 L buoy. All hydrophones were installed 1 m above the bottom, depth being maintained by a 12 mm rope connecting the buoy to the bank by a set of pulleys attached to the anchors. The hydrophones were accessible from the bank after the release of the rope entraining the buoy, and its pending hydrophone, back to the surface. Hydrophone data were downloaded on a monthly basis, except when discharge conditions prevented working close to dangerous areas like spillways.

2.4 | Fish Tagging Procedure and Release Strategy

Wild silver eels were trapped by electrofishing by a professional fisherman in the Rhine River (Germany). The Rhine and the Meuse basins are neighboring, and the fishing site was located only 170 km south and 250 km east of HPP1 on the Meuse River. Eels were transported to the site by truck in a 500 L oxygenated tank. Transportation followed the European TRACES recording regulation. After 4–5 h of driving, the eels were exposed to a mix of the transport water and river water for 1 h, before a complete transfer to a 700 L river water tank. The initial difference in water temperature between the transport tank and the river was $<1.5°C$. After the transition to river water, the eels stayed 48 h under observation before tagging. None had to be removed for suspected health issues.

Eels were anesthetized with a 0.6 mL/L solution of 10% clove oil, to reach stage 5 of anesthesia. After size and weight measurement (mean body length = 883 mm; mean body weight = 1104 g), and Durif index maturity assessment (only FIV and FV eels; Durif, Dufour, and Elie 2005), fish were implanted with L-AMT-14-12 tags from LOTEK (14×45 mm, 8 g, pulsing period 3 s) after a ventral incision, the opening was closed by three stitches. Eels were transferred back to a tank after recovery from anesthesia, for a 24-h observation period before release in the river. During the 2017 and 2019 surveys, respectively, 49 and 98 silver eels were released in early October (2017) or early November (2019), 2.5 km (2017) and 6 km (2019) upstream of the Grands-Malades HPP.

2.5 | Data Processing

WHS hydrophones record up to several hundred thousand detections per hydrophone per day. Since detection ranges close to spillways and turbines are quite low (20–40 m, based on a field test), we first combined all the detections by hydrophones covering each route: (i) the five hydrophones installed at the dam: "Dam cluster"; (ii) the three in the HPP forebay: "Turbine cluster"; and (iii) the two in the downstream station: "Downstream cluster". WHS4250 hydrophones were found to drift variably in time, so that each dataset had to be synchronized afterward as the first step in the data processing. Time drift was found to be linear in a dataset acquired in the workshop. Since it was not possible to use a "time master" beacon in each cluster (Nebiolo and Meyer 2021) at each download, we recorded the drift between hydrophone time and the real PC time (synchronized a few hours before going in the field). The real time of the dataset was corrected after applying the linear time drift through the entire recording period. The second filtration process consisted of removing all identifications recorded that were not part of our tagging data set. After this step, a lot of false-positive identifications were still present and needed to be removed. A signal was considered true positive when associated with a second signal in the associated cluster of hydrophones within a particular time period. Several time periods were compared, and finally 120 s was considered as a reference (Figure A1). A similar filtration method was described by Martinez et al. (2021).

Dam or turbine passage was confirmed first by analyzing the detection data for the 2 min before the last upstream signal. In this timeframe, dam or turbine passage was validated when $>80\%$ of the signals were detected in the turbine or dam hydrophone clusters, respectively. Since there was a small overlap of detection between the two hydrophone clusters, the proportion of signals of some eels passing by this area was spread between the two clusters. In that situation, when less than 80% occurrence was recorded in one of the two clusters, the passage was considered nondetermined. To avoid any confusion, nondetermined passages were removed from analysis.

Finally, the precise time of the identified passage was compared with the dam and turbine operating data, to check that no dam passages could be validated while the dam was in fact closed; and the same for turbine passage. In some extreme river discharge situations, turbines are shut down due to reduced head at the dam. In this situation, the HPP forebay becomes a calm lateral area, which enhances the detection range of hydrophones situated in it, due to reduced background noise. This results in a dataset suggesting turbine passage while the HPP is not operating, the performance of the hydrophones of the dam being impaired by the background noise induced by the high flow. For this reason, the dataset was modified manually when such conditions occurred.

2.6 | Statistical Analysis

All statistical analyses were performed in the R environment v. 4.0.5 (R Core Team 2018). Interannual changes in hydrological conditions during eel passages were compared using Wilcoxon tests. The same test was used to compare eel lengths between different years and dam vs. turbine passage. Patterns of eel escapement were compared between the 2 years using a generalized linear model with a logistic link function (logistic GLM). Eel passage was treated as a binary variable: escaping by the dam = 1, crossing the turbine = 0. The rate of discharge passing over the dam (i.e., nonturbine flow rate) and the surveyed year were treated as explanatory variables to investigate how escapement success varied between the reference year (2017) and when the electrical barrier was operational (2019). For this, deviance reduction tests were conducted to test for the significance of the year and the river discharge rate, and the interaction between the two.

3 | Results

3.1 | Detection Rate and Eel Passage Distribution in 2017 and 2019

In 2017, 91.8% of released silver eels were detected at HPP1, versus 84.7% in 2019 Fisher exact test, $p = 0.455$. Overall, eel migration dynamics from release to passage at HPP1 coincided with the rising phase of discharge peaks in both years (Figure 3). While the timing of eel release differed by 1 month between the two study years, all eel passages at the HPP were under similar hydrological conditions (Figure 4). River discharge at eel passage (turbine and dam pooled) did not differ between years (Wilcoxon test, $p = 0.494$). A similar trend was observed for river discharge passing by the dam associated with all eel passages in both years (Wilcoxon test, $p = 0.070$; Figure 4).

Eleven of the 45 eels detected in 2017 at HPP1 (24.4%) had to be removed from the dataset due to a nondetermined passage route; also, one sluice passage was removed, not being within the dam-turbine area, leaving 33 eels for analysis. We excluded 10 of the 83 eels detected in 2019 (12.0%) due to nondetermined passage route, leaving 73 eels for analysis (Table 1). Nondetermined passages occurred with turbine capacity close to nominal discharge value (median, 157.8 $m^3 s^{-1}$ for both years pooled) and river discharge slightly above full HPP capacity (median, 200.2 $m^3 s^{-1}$ for both years pooled). In these median conditions, the flow goes mainly toward the turbine, with a small discharge into spillways, both routes being available for eels.

3.2 | Comparison of Escapement Patterns

The proportion of turbine passage decreased from 42.4% during the 2017 reference year to 26.0% in 2019, when the electrical barrier was operating. Logistic regression was used to compare dam escapement patterns in relation to the proportion of river discharge passing through the dam in the 2 years (Figure 5). The probability of escapement by spillways increased significantly with increasing nonturbine flow rate but did not differ according to year (Table 2). In contrast, the interaction between discharge rate and year showed that the distribution patterns of silver eels significantly differed between the 2 years (Table 2). After the electrical barrier came into operation in October 2019, the escapement rate was greater when most of the flow was through the turbines (Figure 5); when the rate of nonturbine flow exceeded 0.5, the escapement rate was high in both years, as indicated by the interannual overlap of confidence intervals.

Foreseeably, eel passage distribution between turbine and dam correlated with the proportion of flow through the two routes. In the 2017 reference year, the dam passage rate was 100% when nonturbine flow was > 0.5, while the turbine passage rate was 87.5% when nonturbine flow was < 0.5 (Table 3). Under the same conditions in the presence of the barrier (2019), turbine passages dropped to 41.5% (Table 3): that is, 52.6% less than in the reference year.

Under the same hydrological conditions, with < 0.5 nonturbine flow in the presence of the barrier (2019), we compared the sizes of eels that passed by the dam and the turbines (i.e., despite the barrier). There was no significant difference in size between passage groups (Wilcoxon test, $p = 0.442$), while the 83 eels detected at HPP 1 in 2019 (length, 894 ± 80 mm) were significantly larger than the 45 detected in the reference study in 2017 (862 ± 56 mm; Wilcoxon test, $p = 0.019$).

4 | Discussion

In both years, the detection rate of released tagged eels was satisfactory compared to reports in similar studies, confirming that the surgery had no obvious impact on survival (Stein et al. 2016) and little or no impact on migration onset. Only 28% of 354 tagged eels (stages III, IV and V) were detected by acoustic telemetry in the Elbe River (Stein et al. 2016), while 92% of 90 tagged eels were detected in the Ätran River in Sweden (Kjærås et al. 2022).

In 2017, eels were released in early October under dry conditions. While a few eels exhibited passage in the days after release, most waited for the first significant discharge increase in November to start migration. In 2019, most of the eels were released in November, during a discharge increase, which induced immediate migration. While the first few days after the release of tagged fish are sometimes removed from datasets (Trancart et al. 2018; Teichert, Tétard, Trancart, Oliveira, et al. 2020), we decided to keep all detections, since our study focused on passage distribution between turbines and spillways more than on migration dynamics.

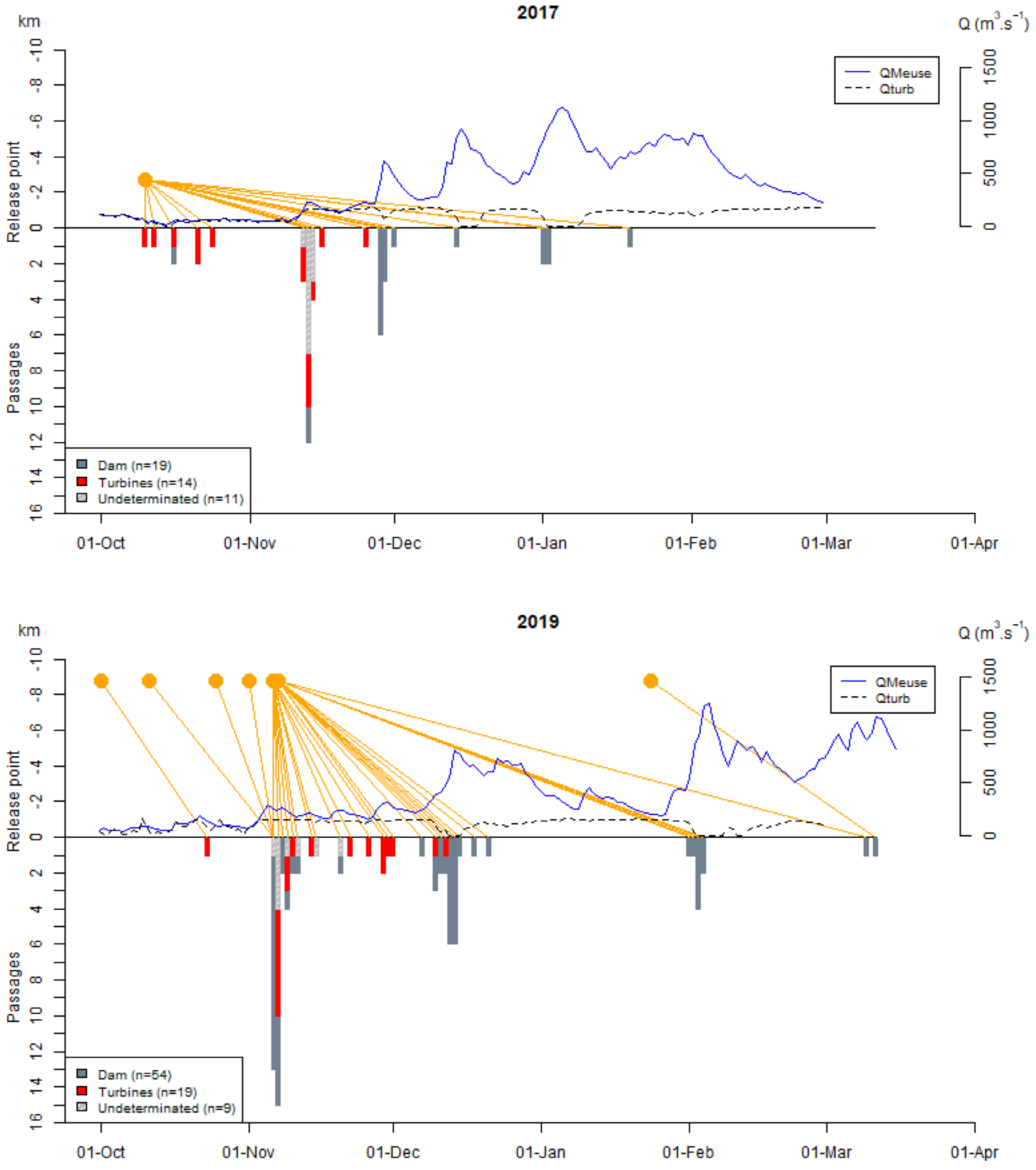

FIGURE 3 | Downstream migration of silver eels observed during 2017 (top) and 2019 (bottom) at Grands-Malades HPP. The upper Y axis represents the distance upstream of the HPP (negative values to 0) while the lower Y axis represents the number of eel passages, classified as through the dam (full gray), through the turbine (red) and nondetermined (hatched gray). Yellow spots indicate the time of release of silver eel batches. The YY axis shows the mean hourly discharge measured at Amay station (blue, $m^3.s^{-1}$) and the turbine discharge (black dotted, $m^3.s^{-1}$) during the duration of the study (X axis). $N=45$ eels in 2017 and $N=83$ eels in 2019. [Color figure can be viewed at wileyonlinelibrary.com]

Passage proportions differed significantly between 2017 and 2019. Passage proportion between dam and turbine can be analyzed by logistic regression as a function of flow distribution (Bau et al. 2008; Travade et al. 2010; Tomanova et al. 2023). Similar results were reported by Bau et al. (2013) at five successive HPPs in the Gave de Pau River in France, investigating escapement at each dam over several seasons; each site showed a specific dam escapement pattern which remained largely constant between years. In this study, the escapement pattern in 2019 differed significantly from the pattern in 2017,

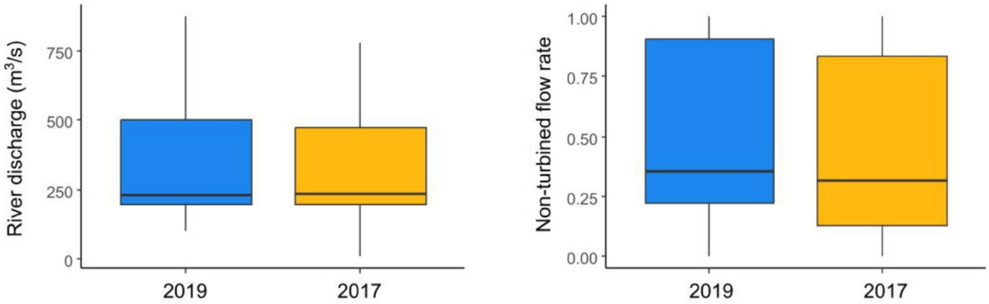

FIGURE 4 | Boxplots illustrating the flow conditions during all eel passages at Grands-Malades HPP in 2019 when the electrical barrier was operating (blue) and during the 2017 reference year (yellow). The left-hand graph presents river discharge conditions for all passages, and the right-hand graph presents the rate of flow not taken by the turbine and consequently flowing through the dam. $N=45$ eels in 2017 and $N=83$ eels in 2019. [Color figure can be viewed at wileyonlinelibrary.com]

with better escapement when nonturbine flow was lowest. Since hydrological conditions and flow distribution did not significantly change between the 2 years, this change can be attributed directly to the electrical barrier. The electrical barrier reduced turbine entrainment by 52.6% compared to the reference year under conditions where the HPP received most of the flow.

Stimuli such as light or electrical field showed promising results in affecting silver eel behavior in the lab (Hadderingh et al. 1999; Rost et al. 2014; Miller et al. 2021; Moldenhauer-Roth et al. 2022; Haug et al. 2022), but very few studies have been implemented in the field at the scale of a large HPP inlet (> 120 m^3 s^{-1} capacity). The Neptun electrical barrier at the entrance of the intake canal of a small HPP along the Murg River was compared with a similar site upstream equipped with a horizontal fine mesh screen for an HPP of 14 m^3 s^{-1} (Weibel and Wüst 2017). In this case, the bypass transit rate was 69% with the physical screen, versus 17% with the electrical barrier, and 41% of eels crossing the electrical barrier. The two sites differed in size and configuration, which weakens the comparison of these results with this study, but no other references could be found.

Since there was no barrier of any kind in place during the 2017 reference survey, we cannot exclude a possible effect of the actual physical structure of the electrical barrier on silver eel behavior. For instance, flow-field distortion induced by underwater structures was reported to influence silver eels by guiding their path (Piper et al. 2019). On the St Lawrence River, eels exposed to underwater structures holding powerful lights exhibited avoidance of the light platform even when the light was off (Versar 2009 NYPA). But, even if the efficacy of the electrical barrier is partly due to its physical structure, this still contributes to its global efficacy.

At the scale of a pilot site, the Neptun barrier helped to significantly reduce the proportion of eels passing through the turbines, but not enough to meet the protection criteria required by the permit. Since the efficacy of the barrier was not total, it might be necessary to combine this solution with others; turbine shutdown driven by an eel migration prediction model (Teichert, Tétart, Trancart, Feunteun, et al. 2020) is now used at this site as an additional permanent solution. With the assistance of the barrier, the shutdown model might be used with a less sensitive threshold, to reduce the number of days of lost production compared to using it without the barrier. It is likely that eels could exhibit a higher guidance response to

TABLE 1 | Silver eel passage distribution during the two telemetry surveys at Grands-Malades HPP.

	2017	2019
N released	49	98
N detected	45	83
N valid passages	34	73
N turbine passages	14	19
N dam passages	19	54
N sluice passages (removed)	1	0
N nondetermined passages (removed)	11	10

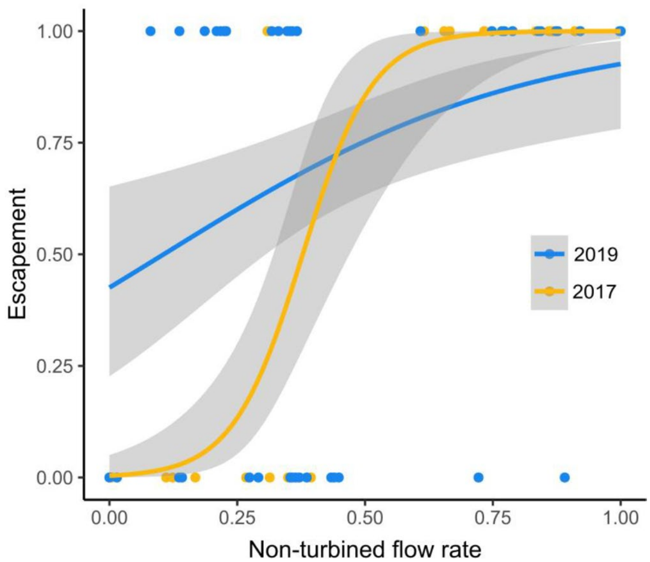

FIGURE 5 | Escapement probabilities (eel passage over spillways) at the dam, predicted from the logistic regression model, in relation to the rate of river discharge passing over the dam (nonturbine flow rate). The gray band shows the 95% confidence interval for each year. $N=33$ eels in 2017 and $N=73$ eels in 2019. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 | Deviance reduction tests conducted to investigate the influence of nonturbine flow rate (discharge rate) and the surveyed year on silver eel distribution at the Grands-Malades HPP.

	Degree of freedom	Residual degree of freedom	Residual deviance	Explained deviance	p
Null model		105	131.473		
Discharge rate	1	104	95.455	36.018	**> 0.001**
Year	1	103	92.77	2.684	0.053
Discharge rate × Year	1	102	82.838	9.933	**> 0.001**

Note: Significant effects ($p < 0.05$) are indicated in bold.

TABLE 3 | Eel distribution between dam and turbine passage in 2017 and 2019 depending on the relative quartile of turbine discharge related to global Meuse River discharge.

	2017 – reference			2019 – barrier		
Nonturbine flow rate	N turb	N dam	Entrainment	N turb	N dam	Entrainment
0.75–1	0	12	0.0	1	28	0.03
0.50–0.75	0	5	0.0	1	2	0.33
0.25–0.50	4	2	0.7	13	7	0.65
0–0.25	10	0	1.0	4	17	0.19

Note: $N = 33$ eels in 2017 and $N = 73$ eels in 2019.

the electrical field under lower water velocities through the barrier. Electrical barrier production probably needs scaling up to ensure that the investment is compensated by reduced loss of production compared with using the turbine shutdown model alone. Consequently, it is likely that the Neptun electrical barrier should mainly be combined with another protection system, and be used only on sites where other more efficient FDPSs are not feasible. Also, the effectiveness of electrical barriers for downstream deflection is expected to be lower in larger HPPs (> 160 $m^3 s^{-1}$) in relation to the hydrological regime of the river, associated transport of natural floating solids and higher water velocities, requiring site-specific assessment.

Since fish sensitivity to electromagnetic fields is size-dependent (Dolan and Miranda 2003; Kowalski, Gardunio, and Garvey 2022), particular attention should be paid to collateral risk to other species and sizes. Although not considered in this study, unwanted nontarget fish behavioral effects or mortality may be associated with the intended guiding/blocking role of an electrical barrier (Johnson et al. 2021). On the other hand, the electrical barrier may also assist other migrating species to avoid turbine passage.

Guiding silver eels (and other migrating fish) toward the dam is the aim of the majority of the protection measures implemented in large HPPs. Dam passage can be achieved by overflow or below the dam gates, depending on the river discharge and the dam technology. Fish survival after dam passage is variable in the literature. It was very high for eels passing a bottom gate followed by a 58 m high concrete slope (Watene and Boubée 2005). In contrast, turbulence induced by 90° fall in a spillway tended to be avoided by silver eels in flume conditions and is expected to induce mortality at full scale (Silva et al. 2015). This was confirmed by the patterns of eel detection at the sites downstream of HPP1 and covered by the LIFE4FISH global telemetry study, where 5%–10% disappearance was reported after eel passage at some dams (unpublished results).

Finally, while this paper focused on testing a solution at a single site, this test was part of a larger study of migratory fish protection strategy over a river stretch comprising six successive HPPs. Migratory fish protection strategies should be considered at the whole-basin scale, which is complex when the river passes through different regions or countries, as in the case of the River Meuse. Fish protection strategy also has to take into account the number of HPP sites that fish will encounter during migration, bearing in mind that behavioral barriers do not show constant efficacy at different sites. Consequently, at this stage of development, monitoring is necessary to assess the need for complementary solutions in addition to electrical barriers.

5 | Conclusion

The good performance of the acoustic telemetry study allowed us to compare silver eel passage at Grands-Malades HPP in a normal reference situation (2017) and a new situation in the presence of an electrical barrier (2019). This study, conducted for a large HPP (> 120 $m^3.s^{-1}$), showed that the electrical barrier significantly reduced the silver eel turbine passage. In conditions where most of the river flow was via the turbines, the efficacy of the electrical barrier was 52%. At our pilot site, this efficacy was enough for the electrical barrier to be considered as a permanent solution, but in combination with complementary turbine shutdown driven by a migration prediction model. Electrical barriers are still far from being able to replace other protection systems at HPPs, such as fine mesh screens associated with bypasses, but can still be part of the toolbox when conventional solutions are limited.

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Ethics Statement

The authors declare that they are aligned with the editorial policies and ethical considerations in terms of data sharing, data accessibility, data citations, conflicts of interest, funding, and authorship.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A

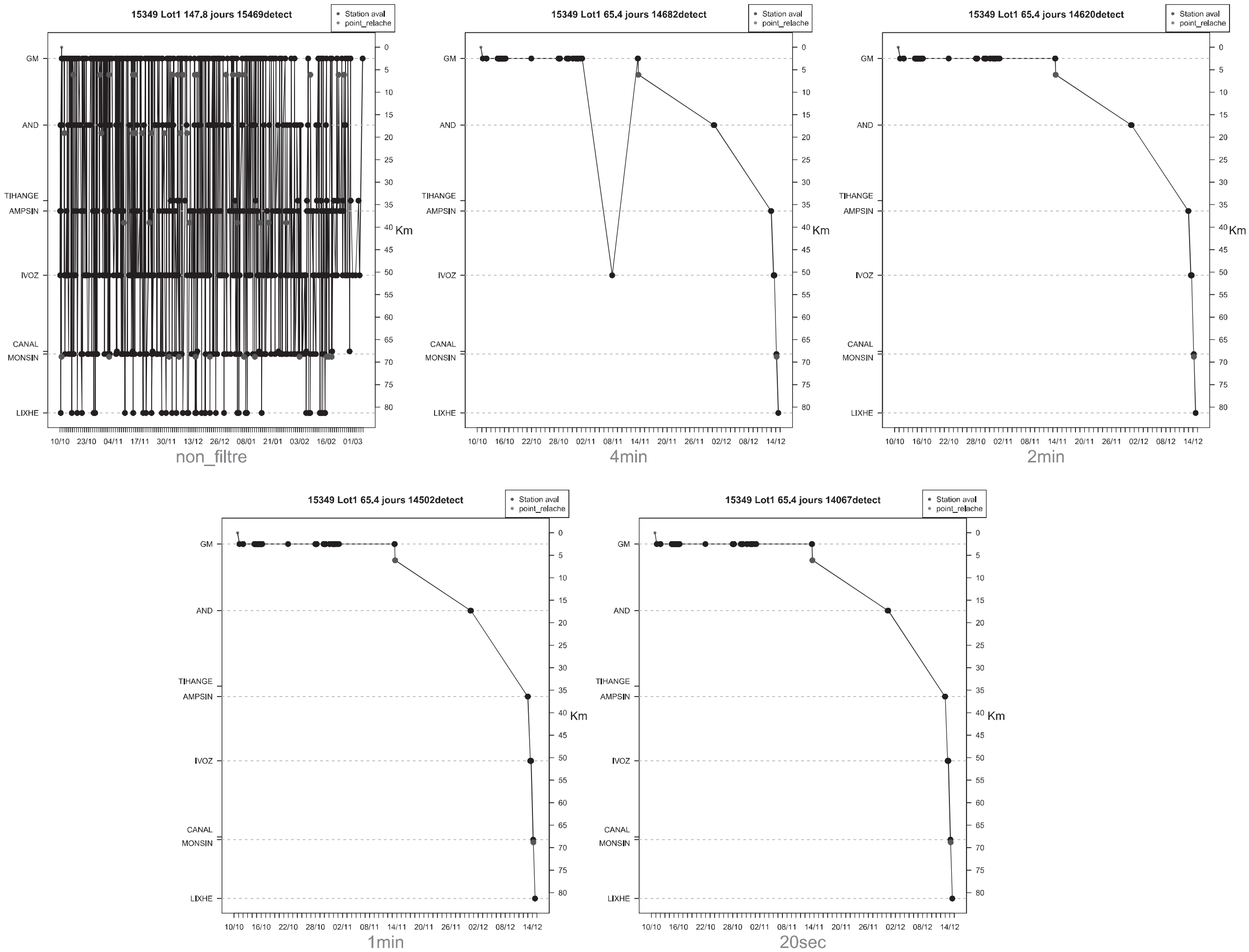

FIGURE A1 | Example of the database of a fish ID within the study network. Y axis presents the dams along the river Meuse (upstream at the top, with GM for Grands-Malades HPP) and the X axis is the study period. Spots in the graphs refer to ID detection with different filtering procedures, from no filtration (left) to 20 s filtration (right). [Color figure can be viewed at wileyonlinelibrary.com]