DOWNSTREAM FISH MIGRATION ALONG THE LOW MEUSE RIVER

LIFE16 NAT/BE/000807

Action D2

Monitoring of the effectiveness of the pilot solutions

Part I : silver eels

Deliverable report

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I. Introduction

During the developments of the different actions conducted under the LIFE4FISH project, a selection of different eel protection measures have been selected to be tested at the pilot scale on the different sites of Luminus production dams.
The selection varies between salmon smolts and silver eels, in the present reports, we will only focus on the pilot measures concerning silver eels.

II. Material and Methods

II.1 Pilot mitigation measures tested

The selection of the different mitigation measures has been made through an official tender described in Actions C1&C2, the elements are available in the corresponding deliverable reports (Recordon 2019 a & b). The selected study sites to test pilot protection measures were (Figure 1) : hydroelectric plant of Grands-Malades (CHG) for the electrical barrier, plant of Andenne (CHA) for turbine shutdown with prediction model and plant of Ivoz-Ramet (CHR) for the bubble barrier.

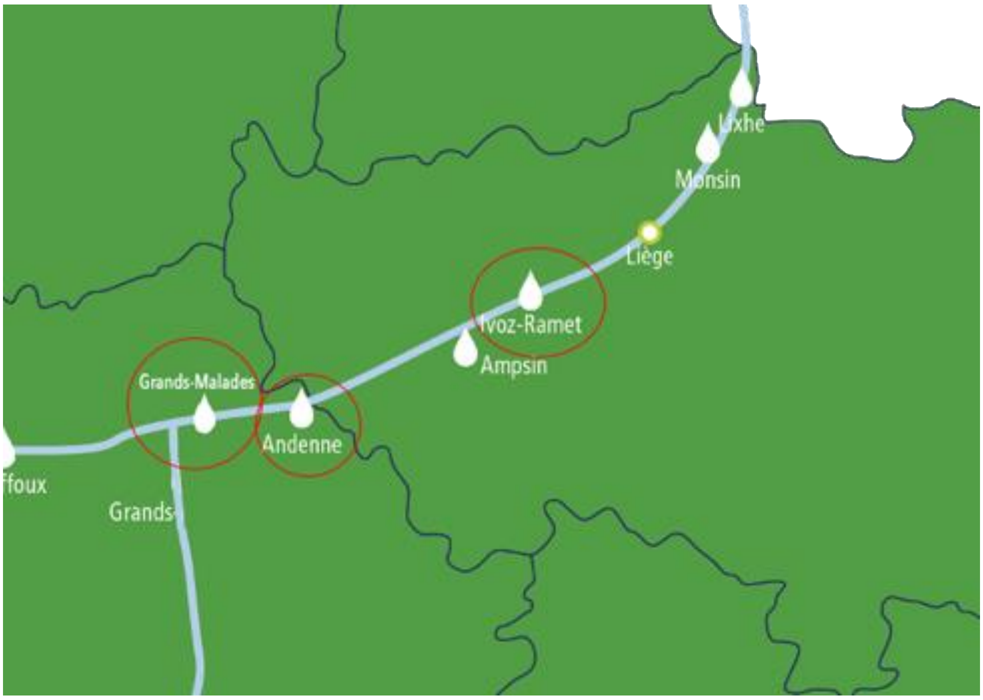


Figure 1 : view of the 3 pilot sites selected to test the eel protection measures.

II.1.1 Neptun electrical barrier in CHG

The CHG inlet has been equipped by a Neptun electrical barrier proposed by the company Procom System in Poland. The details of the technology are available in the C1 deliverable report (Recordon 2019b).
In simple, the electrical barrier is made of stainless-steel pipes installed vertically across the river. The vertical position is reached using bottom anchoring of the tube and buoys on the top of the tubes. Two lines of electrodes are installed, the first line is composed by positive electrodes, separated each other by 1m, and the second line by negatives electrodes separated by 1,5 m. The two lines are separated by a distance of 2 m. The electrical barrier virtually close the entrance of the CHG forebay (Figure 2).

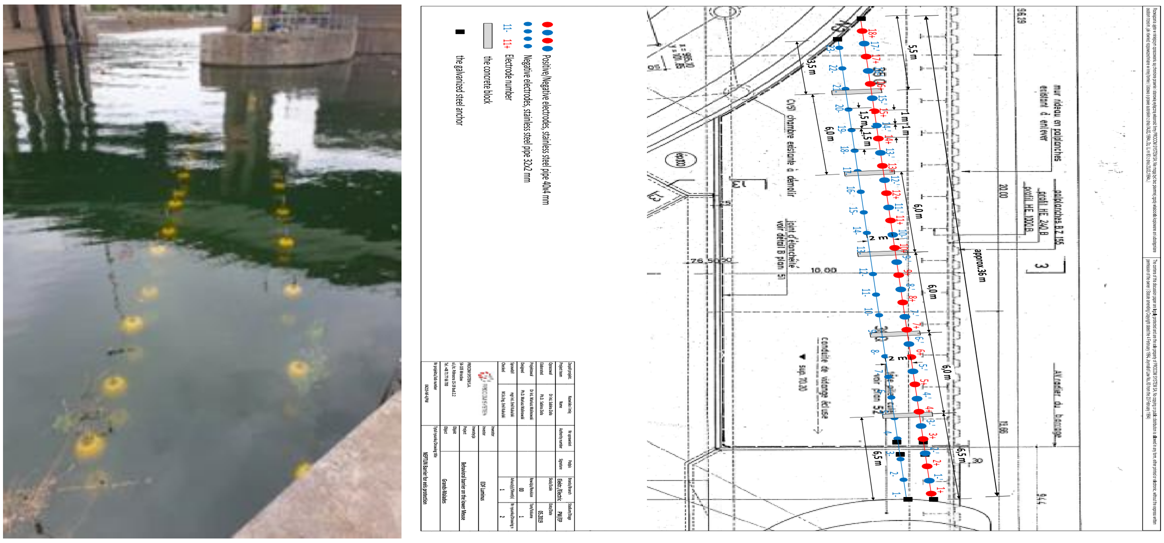


Figure 2 : view of the Neptun barrier installed at CHG (left) and drawing of the installed electrodes.

The electrical parameters of the barrier operation are kept confidential by the supplier, so that we have not the possibility to report the used voltage, power, electrical field, …

II.1.2 Turbine management and migration model at CHA

In the A4 action of the LIFE4FISH project, a prediction model has been developed based on different environmental factors to predict downstream migration peaks of silver eels (Teichert et al. 2019, Teichert et al. 2020). A total of 10 environmental factors have been statistically tested on their influence on the probability of eel migration over the 2017 telemetry dataset (with a minimum relative importance > 5%). Among them, 3 variables showed a relative importance: delta values in the discharge (1 day and 5 day) and turbidity (Figure 3).

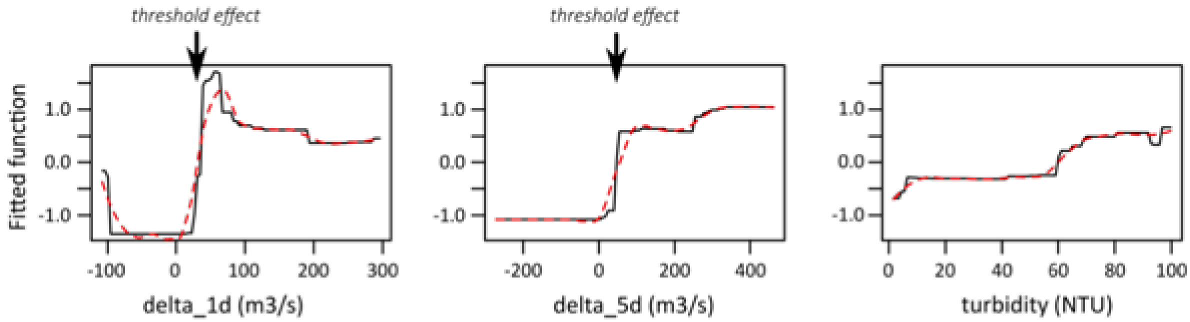


Figure 3 : Partial dependence of the plots of the tree most important variables influencing the probability of silver eel migration on the six hydropower plants of the Meuse River for the migration period 2017-2018. Sources : Teichert et al. 2019.

Consequently, it appeared that using delta values of discharge could provide suitable indicators to forecast eel migration. These variables have been integrated in an existing prediction model developed on the Dordogne River (Courret et al. 2016), a river having a good hydrological proximity with the River Meuse. The final model operational sequence for the River Meuse is as follow :

- Calendar date included between 20 August and 28 February
- River Meuse discharge over 200 m^3/s

- Discharge gradient over 35 m^3/s in Meuse River compared to the previous 5 days or discharge gradient over 15 m^3/s in Ourthe River compared to the previous 7 days.
- Once an event of eel migration is predicted, the hydropower turbines should be shutdown during the night of the day d from 18Pm to 06AM.

Run on the 2017 dataset, the model succeeded to predict 88% of the eel passage over a total of 24 predicted migration days, but the prediction dropped down to 53% when considering the date and the time of passage between 18Pm and 06 AM, which is the expected efficiency range if turbine shutdown are operated from 18PM to 06AM.

II.1.3 Bubble barrier at CHR

The bubble barrier delivered by APUMAS consists in sending compressed air (200 m^3/h) into a pierced pipe installed on the bottom of the River along the intake of CHR intake canal at its junction with the River Meuse. The technical details are presented in the Deliverable Report of Action C2 (Recordon et al. 2019a). The pipes have been installed 10 m away from the water intake, in order to avoid bubbles to be entrained in the intake canal before to reach the surface of the water (Figure 4).

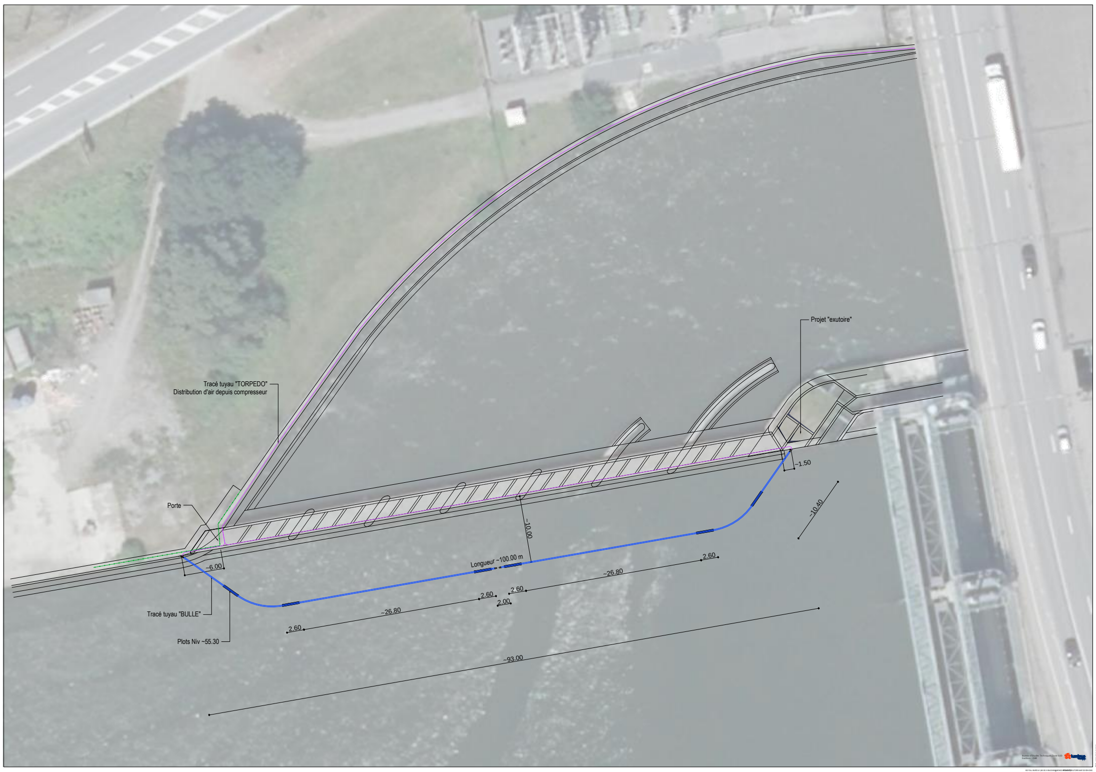


Figure 4 : schematic view of the bubble barrier installed along the intake of CHR (Ivoz-Ramet).

II.2 Assessment of the efficiency

The method of assessment of the efficiency of the fish protection measures has been determined in the deliverable report of Action A1 (De Oliveira et al. 2018).

For the guidance devices, the efficiency measurement takes into account (Figure 5) :

- Number of fish arriving on site in the vicinity of the guidance device influence (N barrier in)
- Number of fish crossing the guidance device or going back upstream without crossing the dam (N barrier failure)
- Number of fish passing over the dam (N barrier out)

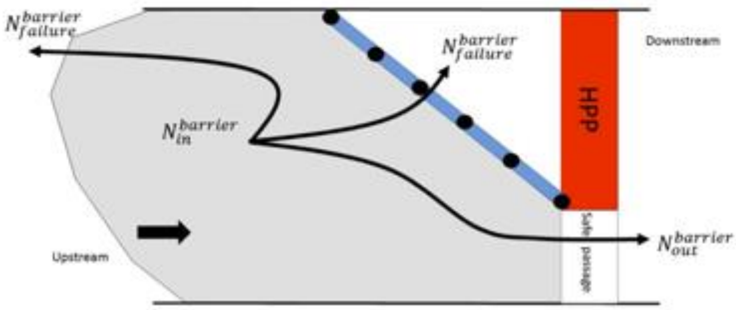


Figure 5 : Efficiency measurement of a behavioural guidance barrier (from De Oliveira et al. 2018)

The efficiency of the guiding barrier will be established considering the fish repartition between the different behavioural categories that will be observed :

° Barrier in : number of fish approaching the attraction area of the intake
° Barrier failure : number of fish blocked upstream or fish passing through the barrier
° Barrier out : number of fish passing successfully over the spillways.

The efficiency of the guiding device is the ratio between the number of fish successfully passing over the spillway and the total number of fish entering the attraction area of the intake.

$$S^{barrier} = \frac{N_{out}^{barrier}}{N_{in}^{barrier}}$$

This concept implies to be able to determine with precision the position of the fish when they arrive upstream the sites. This is why these 2 sites have been equipped with an additional network of receivers aiming to develop a 2D positioning of the detection.

II.3 Telemetry study

II.3.1 Telemetry network

We used the JSAT technology (LOTEK WHS 4250 receivers) to track silver eel passages, detecting coded pulsations transmitted by acoustic tags within the frequency of 416.7 kHz. This technology has been selected after several performance tests comparing the detection range of different acoustic telemetry technologies.
At each site, a first configuration of telemetry network has been deployed based on the performance of detection pre-established during preliminary tests, aiming to establish passage routes. The network was composed by one hydrophone per concrete pillar of the dam (spillway length being 22-30 m long) and 2 to 3 hydrophones installed in the HPP forebay. When existing, one hydrophone was also installed in the boat sluice. Finally, 1 to 2 hydrophones were installed on the pillar of the nearest bridge downstream each dam, to confirm fish passage. Hydrophones were anchored by either mechanical anchors in the concrete structure, or by the mean of steel anchors of 600 kg installed by divers. A detailed description can be found in the corresponding Milestone report (Sonny et al. 2018, Lerquet et al. 2020).
Hydrophones were downloaded on a monthly basis, excepted when discharge conditions excluded the possibility to work close to dangerous area like spillways.

A second telemetry network was installed at two sites, CHG (Grands-Malades) and CHR (Ivoz-Ramet), since these two sites have been selected to be pilot sites to test behavioural cues and/or bypass. This second network aimed to obtain 2D positions of fish, and was composed by additional receivers located in the forebay of these 2 HPP. Hydrophones position where obtained by the use of a differential GPS with a centimetric precision in X and Y axis. The 2D tracks of the fish have been obtained by the use of UMAP software, provided by LOTEK.

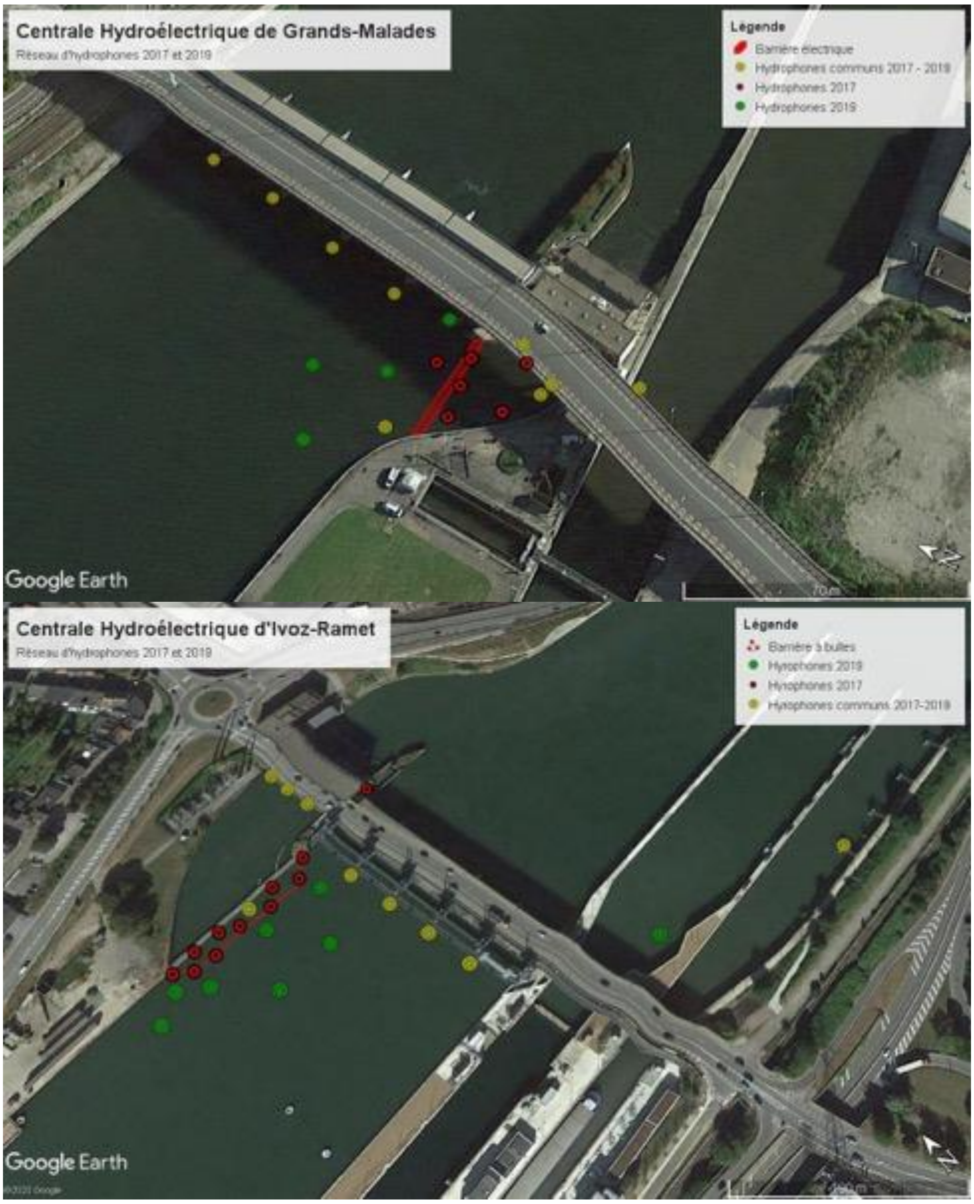


Figure 6 : 2D telemetry network installed at CHG (up) and CHR (down). Some receivers positions changed from 2017 and 2019 : common positions are in yellow, 2017 positions are in red and 2019 positions are in green.

II.3.2 Fish tagging procedure and release strategy

During the 2017 and 2019 study, a total of N = 290 silver eels has been tagged with L-AMT-14-12 (14 x 45 mm, 8g) with a pulse period of 3 s, allowing a life duration of more than 400 days. Among these eels, N = 30 individuals have been caught directly in our silver eel fishery in the River Meuse (Action D2 – Silver eel fishery), and the rest (N = 260) were originating from a professional fishery from the Rhine River, Germany, near Karlsruhe. Eels from the

Meuse have been tagged and released at different dates, depending on their date of capture from September to early November (Sonny et al. 2018, Lerquet et al. 2020).

The tagging procedure was conducted under anaesthesia using a solution of Eugenol (0,8 ml/l of 10% Eugenol), following a strict surgical procedure conducted by an experienced fish surgeon (incision, insertion of the tags, closing stitches, disinfection). After wake-up, eels have been kept in open circuit tanks for 2 h before released, in order to make sure that all eels were recovering correctly from the surgery.
The release plan of both years is described in Figure 7.

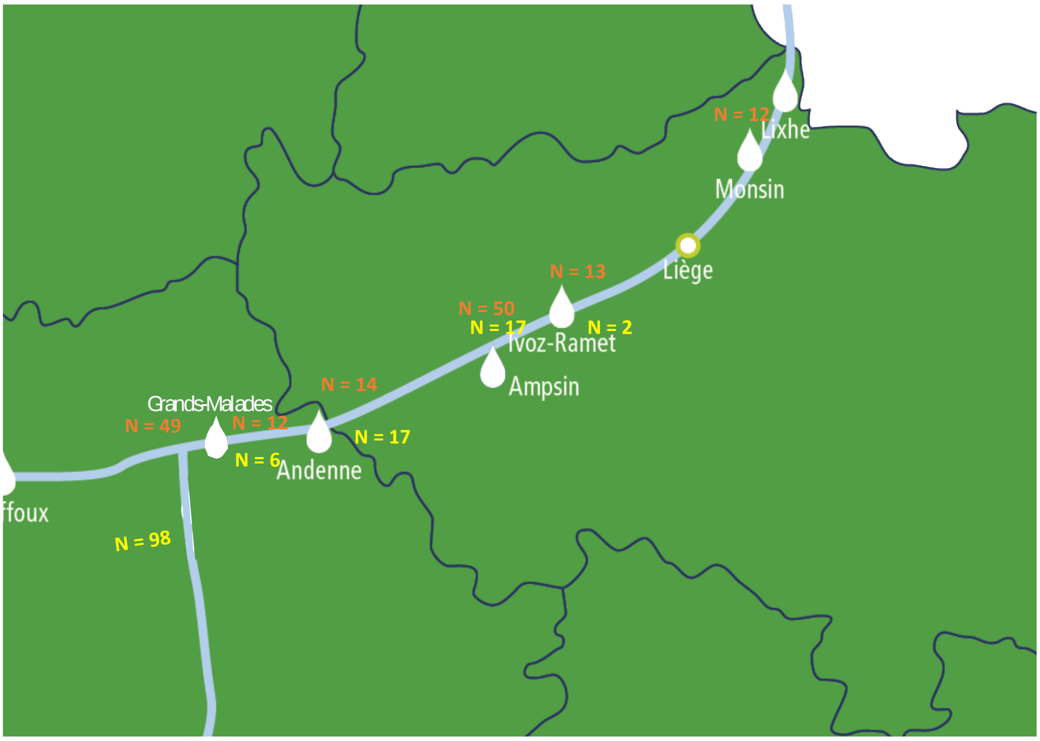


Figure 7 : tagged eels release locations along the 6 HPP operated by Luminus on the Meuse River in 2017(in orange) and 2019 (in yellow).

II.3.3 Data treatment

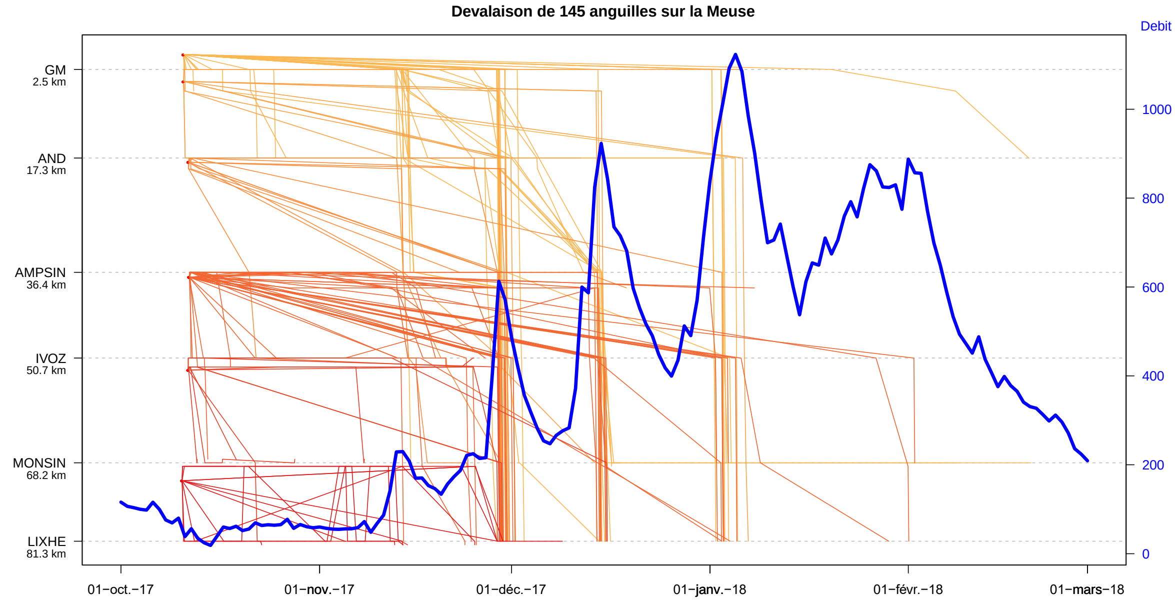
Several steps are crossed from the raw data set to the final interpreted passage data, all of them are detailed in the Milestone report. In simple, these steps are :

1° Hydrophones times resynchronisation (not possible in 2017)
2° Erasure of the false negative and positive detections : using filters based on coded frequency of fish and pulse frequency
3° Passage identification : validated when > 80% of the detections of the last 30 s are detected on the hydrophones of the dam or of the forebay and that the ID has been detected on a downstream station.
4° Link with operational discharge data : some passages are re-considered when they are in opposition with the hydraulic conditions.
5° 2D treatment, data with a DOP < 2 (Dilution of Precision) are considered as valid (Roy et al. 2014), DOP value is given by the UMAP software for each position.

III. Results

III.1 Main migration patterns

Figure 8 presents the global pattern of migration observed for all eels during both years.



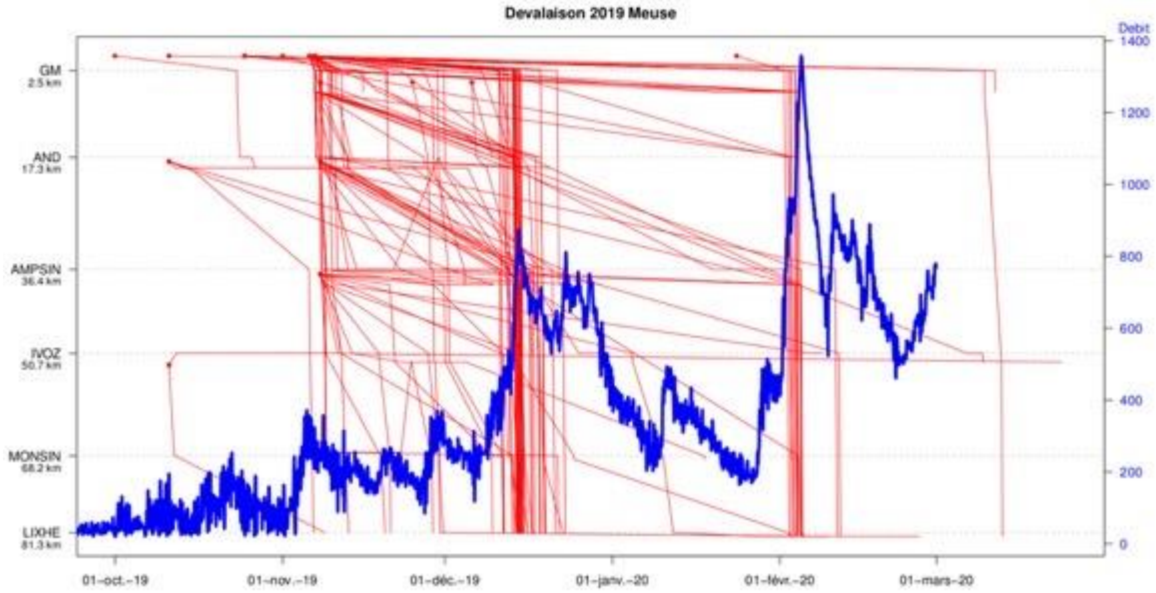


Figure 8 : Main migration patterns observed on all detected silver eels during the 2017 and the 2019 surveys, in relation with their progression along the river continuum (Y axis, km from most upstream release point) and the daily river discharge (YY axis, m³/s).

III.2 Neptun electrical barrier at CH Grands-Malades (CHG)

The assessment of the Neptun electrical barrier uses the database of eel passage and 2D positioning data obtained during the telemetry surveys. After the 2017 telemetry survey, a

reference situation has been established without electrical barrier. Consequently, the assessment of the barrier has to take into account the 2017 dataset as a control group in comparison with the 2019 dataset as a treatment group.
As defined in the nomenclature in the Action 1 Deliverable Report (Oliveira et al. 2018), the efficiency of the barrier (S barrier) is calculated based on the following variables :

° N barrier in : number of fish arriving in the area of influence of the barrier/water intake

° N barrier failure : number of fish passing through the barrier towards HPP or non passing the site.

° N barrier out : number of fish passing over the spillway.

The main challenge associated with the databases is to be able to establish with precision which eel has been exposed to the area of influence of the barrier (or of the water intake). We will present below S barrier for the 2019 survey, but since a reference situation exists with the 2017 survey, we will then compare different variables between both years to adjust the barrier efficiency with the most accurate precision.

III.2.1 Estimation of S Barrier for 2019

To calculate the influence of the barrier, as referred in the A1 report, we must take into account only eels that have been exposed to the influence of the barrier. In our 2019 dataset of eel passages, we are selecting then the following individuals :

- All turbine passages, confirmed by a downstream detection, are considered since they have been *de facto* exposed to the barrier (N = 19).
- All confirmed spillway passages with at least one 2D position in the influence area of the barrier (N = 10).

The Figure 9 presents the 2D tracks of these concerned eels in 2019 and the definition of the influence area that corresponds to the area where eel can choose between spillways or the CHG forebay.

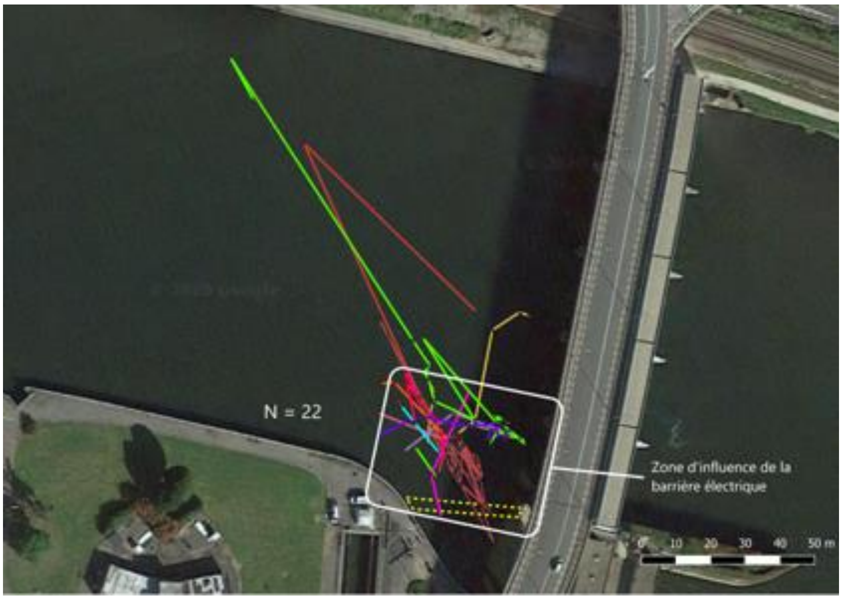


Figure 9 : 2D positions and tracks of eels that have been geopositioned at least once within the influence area of the intake (white frame) at CHG in 2019. The yellow dots localize the electrical barrier. N = 22 (including undetermined passage routes).

Considering these eels, the S barrier calculation is :

$$Sbarrier2019 = \frac{10}{29} = 0{,}34$$

During the 2019 survey, from all 29 fish that are considered as having be exposed to a choice and possibly influenced by the barrier, the escapement rate (S barrier) was 34%.

III.2.2 Comparison of Sbarrier with the escapement in 2017

To assess how fine we can consider Sbarrier 2019 as a barrier efficiency, we propose to determine with the same criteria S barrier in 2017.

- All turbine passages, confirmed by a downstream detection, are considered since they have been *de facto* exposed to the barrier (N = 14).
- All confirmed spillway passages with at least one 2D position in the influence area of the barrier (N = 6).

$$Sbarrier2017 = \frac{6}{20} = 0{,}30$$

During the 2017 survey, from all 20 fish that are considered as having comparable behavioural distribution than in 2019, the escapement rate is 30%

The comparison between both years hardly reveals an improvement of the escapement rate induced by the barrier.

This can be explained by the fact that many eels, passing over the spillways, are removed from both dataset, due to an absence of 2D position in the influence of area. In 2017, since the 2D network was inside the CHG forebay, it was less efficient to localize position in the influence area than in 2019. Moreover, during both years, the 2D network detection range varied due to hydrologic conditions and shortened life duration of some receivers. All these facts do not allow to give sufficient confidence in this method to assess the barrier efficiency.

III.2.3 Comparison of the escapement rate during hydrological ranges

To better compare the escapement of eels over both years, we analyse the number of eels passing through each route during 2017 and 2019, classified along steps of 100 m^3/s of River Meuse. The CHG turbine discharge during both years is strongly correlated to the river discharge until 300 m^3/s in the river (Figure 10), which is close to the double of CHG capacity. In this range of discharge, we assume that the flow repartition between CHG and the spillways behaves similarly.

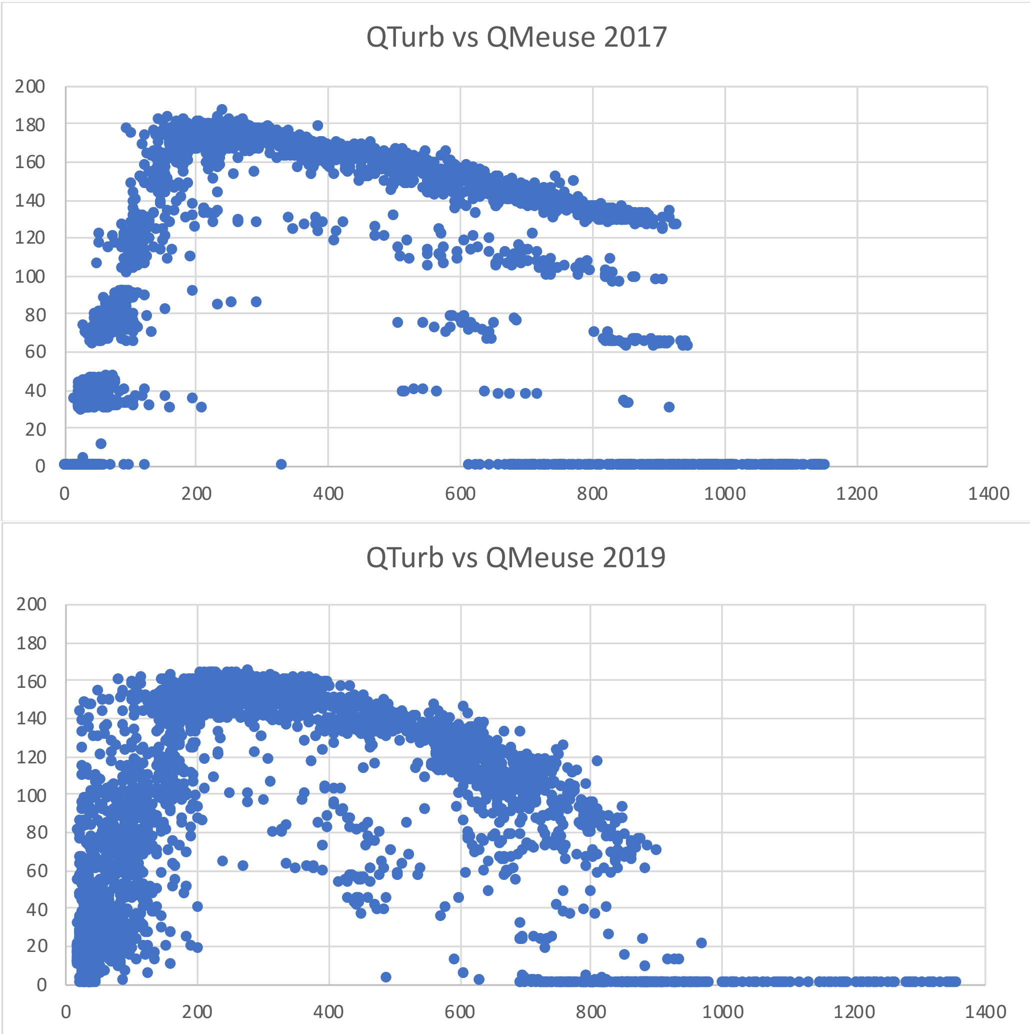


Figure 10 : Relation between hourly CHG Turbine discharge (Q CHG, Y, m³/s) with river Meuse discharge (X, m³/s) in 2017 and 2019.

In 2017, 33 eels had determined and confirmed passages routes (turbine vs spillways), and 73 eels in 2019. For both years, the table 1 below presents the passage repartition and the escapement rate for steps of 100 m^3/s in the River Meuse.

	2017			2019			
QMeuse (m^3/s)	**N Turb**	**N Spill**	**Escapement**	**N Turb**	**N Spill**	**Escapement**	**Delta escapement**
< 100	6	1	0,14				
100-200	3	1	0,25	4	2	0,33	0,08
200-300	5	1	0,17	10	16	0,62	0,45
300-400				3	7	0,70	
400-500	0	4	1,00	2	4	0,67	-0,33
500-600				0	5	1,00	
600-700	0	5	1,00	0	3	1,00	0
700-800	0	3	1,00	0	6	1,00	0
800-900	0	2	1,00	0	7	1,00	0
900-1000	0	1	1,00	0	2	1,00	0
>1000	0	1	1,00	0	2	1,00	0

Table 1 : eel repartition and escapement rate in 2017 and 2019 at CHG.

A non-parametric Mann-Whitney comparison test performed over the 11 range values of Table 1 revealed a non-significant difference of escapement between 2017 and 2019 ($P = 0.8$). When restricting the test to the discharge range of the 5 first values (0 – 500 m^3/s), the difference remains non-significant ($P = 0.34$).

In 2017, pooling all passages with river discharge < 300 m^3/s, *i.e.* the conditions when the majority of the river discharge is passing through turbines, the escapement rate was 18% for 56 % in the same conditions in 2019. This corresponds to an increase of 38% of the escapement rate, but without being able to give a statistical confidence.

The escapement in 300-400 m^3/s range was 70% in 2019, while no data are unfortunately available in the same range in 2017.
Above 400 m^3/s, the escapement rate was 100 % in 2017, which was similar in 2019 except in the 400-500 m^3/s range, where 2 eels over 6 passed through turbines. For these 2 ID, the turbine discharge at the passage was 91 and 92 m^3/s, which is around 60% of the CHG capacity, conditions that should favor a good operation of the barrier and passage over the spillways.

The escapement rate can be considered oppositely with the turbine entrainment rate (1 – escapement rate). Under 300 m^3/s, the entrainment rate decreased from 82% in 2017 to 44% in 2019. Referring to 2017, which is our control year, the entrainment is reduced by 46% ($=1 - \frac{44}{82}$).

Above 300 m^3/s, the effect of the barrier becomes probably less influent due to a natural high escapement over the spillways.

III.2.4 Comparison of the escapement logistic regression.

Logistic regressions have been used by several publications to explain the escapement rate in relation with the discharge ratio passing over the spillway (Travade et al. 2010, Bau et al. 2010). We used the same model to compare the escapement rate over both years (Figure 11).

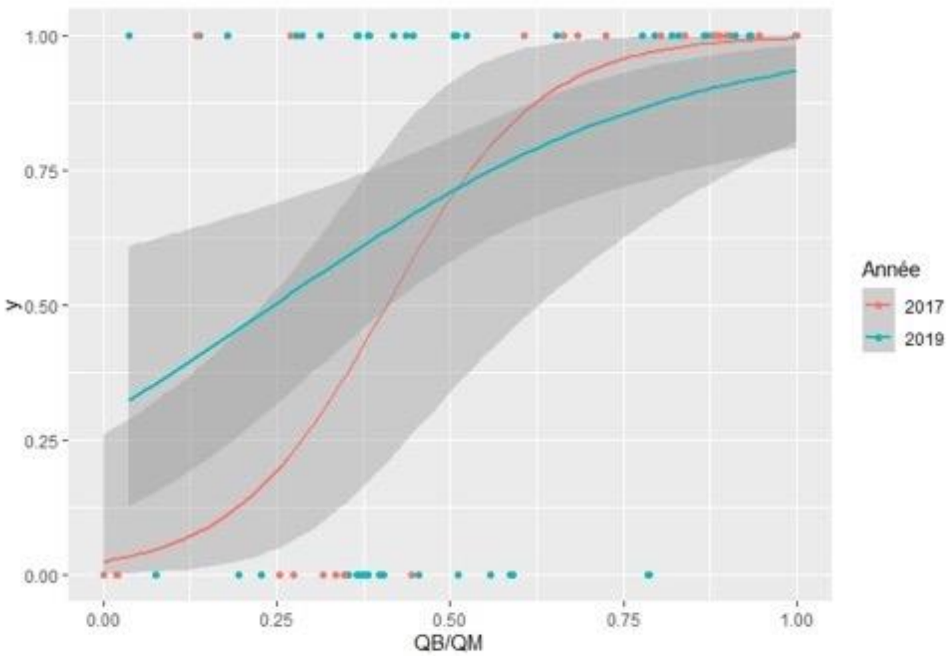


Figure 11 : Escapement probabilities (passage over the spillways) at CHG dam in relation with the ratio of discharge passing over the dam (QB/QM). The grey band show the 90% confidence of interval for each year. N = 33 in 2017 and N = 73 in 2019.

In 2019, the escapement probability seems higher than in 2017 as long as the discharge over the spillways is lower than in the turbines (QB/QM < 0,5), which is typically observed for QMeuse < 320 m^3/s since the capacity of CHG is around 180 m^3/s. This suggests that under hydrological conditions were the turbine discharge is higher than the spillway discharge, the escapement over the spillway seemed better in 2019 than in 2017. This trend is confirmed by the previous similar observation made for eel passages repartition at $Q_{Meuse} < 300 m^3/s$.

A deviance reduction test confirmed that the interaction between the year and the discharge ratio influenced the escapement rate differently over the two years, with a significant difference (P 0.035). Consequently, this reveals that in 2019, the difference of escapement observed in 2019 was significantly due to the presence of the barrier.

The turbine entrainment rate observed in 2019 for QB/QM < 0.5 was of 42% compared to 88% in 2017. Referred to 2017, the control year, the entrainment rate decreased by 52%, which could be considered as the efficiency of the electrical barrier to divert eels away from the turbines towards the spillways.

III.2.5 Influence of eel size

To analyse if the passage through the barrier can be related to some intrinsic values linked with individuals, we compared the size of eels passing through turbines in 2019 (barrier failure) with eels passing over the spillways. Fish size being the most important variable that influences the sensitivity to electrical field.
The Figure 12 suggests no size difference between both groups, confirming that the barrier has not a selective effect on fish size in the range concerning our eel sample (741-1076 mm).

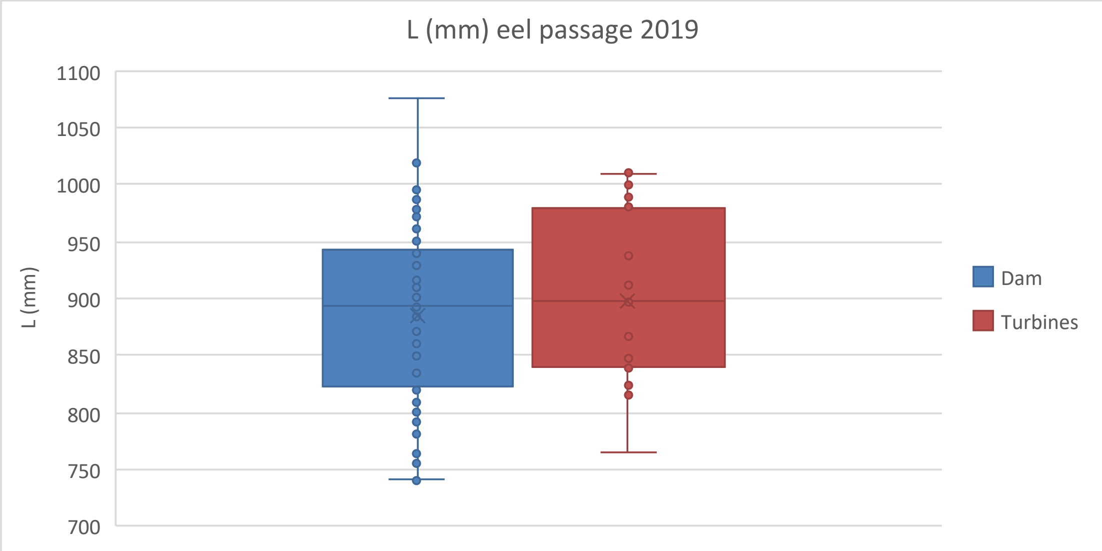


Figure 12 : eel size (mm) in relation with their passages in 2019 at CHG. N=73.

III.2.6 Discussion

The efficiency of the barrier can be considered by different ways with different results observed.
While the A1 action established the formula to estimate the barrier efficiency (Sbarrier), this formula is weakened by 2 elements. At first, it does not take into account the natural escapement rate of eels in absence of an electrical barrier, while a survey has been conducted in 2017 precisely to establish a reference state in absence of barrier. Secondly, it is influenced by the selection/erasure of ID's that are influenced by variable detection range capacities (in space and time) of the telemetry network that is not giving a confidence on the ID considered as exposed or not to the influence area of the barrier.
We have seen that Sbarrier 2019 was 0.34 in 2019, but the same calculation gives 0.30 in 2017. If we replay these calculations for both years but with all determined passages (without taking into account their exposition to the barrier), S barrier 2019 reaches 0.59 in 2019 against 0.35 in 2017.

Since S barrier can't be considered as sufficient, we decided to explore the escapement rates observed for both years considering only the determined passages confirmed by a downstream detection, removing a significant proportion of undetermined passages for both years.

11 on 45 passages (24%) were undetermined in 2017. This can be mainly explained by overlaps of turbine/dam hydrophones detection ranges and unprecise data synchronisation in the 2017 dataset. The modified network of 2019 associated with precise data synchronisation allowed us to reduce the proportion of undetermined passages to 11% (9/83).
When comparing the river discharge of the undermined passages with turbine passages and spillway passages during both years, as presented in Figure 13, it appears that both years, the undetermined passages are closer of the range of river discharge associated with turbine passages than with spillway passages.

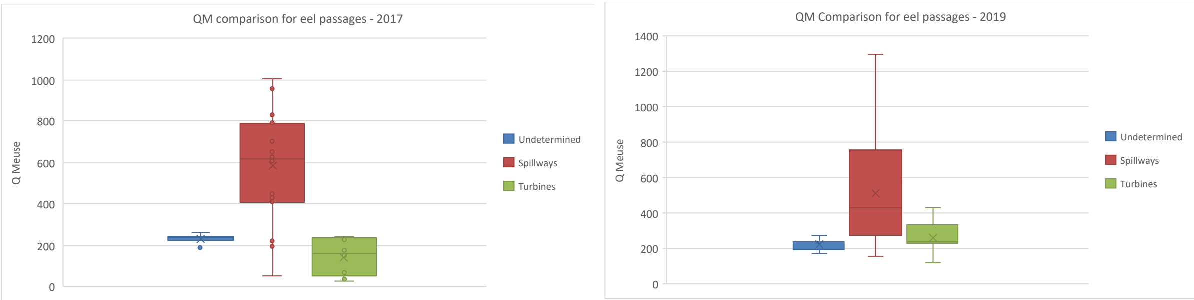


Figure 13 : Blox plot presentation of the instantaneous QMeuse (m^3/s) for undetermined, spillways or turbine eel passages at CHG during years 2017 and 2019.

In 2017, Q_{Meuse} for undetermined passages were significantly different from spillway passages (Anova test, $P<0,001$), but not different from turbine passages ($P=0.211$).
In 2019, Q_{Meuse} for undetermined passages were significantly different from spillway passages ($P=0.001$) but not different from turbine passage ($P=0.677$).

Consequently, for both years, undetermined passages could be very likely considered as turbine passages, but since this can't be 100% confirmed by real detection patterns, we excluded these undetermined passages from the analysis presented so far.

It is however interesting to note that assuming undetermined passages as turbine passages in the analysis presented previously, the results are progressing as presented in Table 2.

	QM < 300	QB/QM < 0.5
Escapement 2017 -determined passages	0,1765	0,125
Escapement 2017 – undetermined as turbine	0,1071	0,074
Escapement 2019 – determined passages	0,5625	0,5806
Escapement rate 2019 – undetermined as turbine	0,4186	0,45

Table 2 : Evolution of the escapement rate observed in 2017 and 2019 when considering undetermined passages as turbine passages.

With all determined passages converted into turbine passages, all the escapement rates were lower than without, which is easy to understand since we add to the dataset only individuals that are not escaping. We still note a better escapement rate in 2019 than in 2017 for both criteria concerned. When comparing the entrainment rate, we observed a reduction of 35% for QM < 300 m^3/s (in place of 46% with determined passages), and a reduction of 41% for QB/QM<0.5 in place of 52%. These values are helping us to better evaluate the efficiency rate in terms of reduction of entrainment, allowing us to estimate a minimal order of magnitude of 40% of efficiency under low discharge conditions.

So far, the Neptun electrical barrier efficiency has not been yet well documented. Some experiments are ongoing in Germany, where after a small scale tests in flume that revealed encouraging results on different fish species including eels (Rost & al. 2014), some full scale experiments hardly revealed a demonstrated efficiency on silver eels mainly due to a failure of the monitoring system or the barrier itself facing strong hydrological conditions (Weibel & Wust 2016; Wust & Weibel 2020).

III.3 Turbine management triggered by the eel migration model at CHAndenne

III.3.1 Dataset

From the 20th October 2019 until 29th February 2020, the total study period, a total of 75 eels have crossed the site, but 11 of them crossed the site under high hydrological conditions and have not been detected by our telemetry network. 64 passages are timed precisely at their arrival on site (first detection) and their passage time (last detection). In most cases, the delay between first and last detection is limited to a few minutes. Since the detection range is restricted to a distance < 40 m most of the time, we considered the first detection on site as the reference time of the migrating eel. The last detection time can be influenced by exploration behaviour of the eels due to the obstacle, consequently, last detection time can be delayed and be not representative of a fluent migration dynamics.

III.3.2 Operation of the alarms

Within this framework, the prediction model triggered an alarm over 32 dates spread during the study period. These alarms induced turbine shutdown during varying duration in the night.
The timeframe of the shutdown did not follow the 18h-06h since EDF R&D improved their model in predicting the eel proportion passing within shorter timeframe in relation with the hydrological conditions (Teichert et al. 2019, unpublished data). The final timeframe used in the model is the following :

- 20h-04h
- 19h-05h
- 21h-03h

The shutdown duration was always timed during the night, with total duration varying from 06h to 10h.
Several problems occurred at different stages of the process between the software prediction alarm and the turbine shutdown, that requires a coordination with the SPW-DGO2 for the spillway synchronised management:

- The predicted daily discharge data coming from the SPW probe was not provided by the SPW : 11 occurrences.
- The alarm was not followed by an effective shutdown due to a problem of coordination with the dam operator (SPW DGO2) : 8 occurrences.
- Missed alarm due to a problem of characters in the algorithm or internal trouble of communication : 12 occurrences.

In total, only 12 alarms have been successfully managed by turbine shutdown, including 2 dates where the turbine were already stopped due to high discharge conditions in the river.

III.3.3 Effectiveness of the alarms

The 64 passages have been classified under two main categories :

- All data : all fish passages considered : N = 64
- Valid data : eel passages occurring > 7days after release : N = 44

For both categories, eel passages are classified into the following subcategories :

- Right date : fish passing during a prediction date, without timeframe consideration.
- 18-06h : eel passage during the 18-06h of a predicated date
- Operating timeframe : eel passing during a real predicted shutdown (without considering the appliance problems).

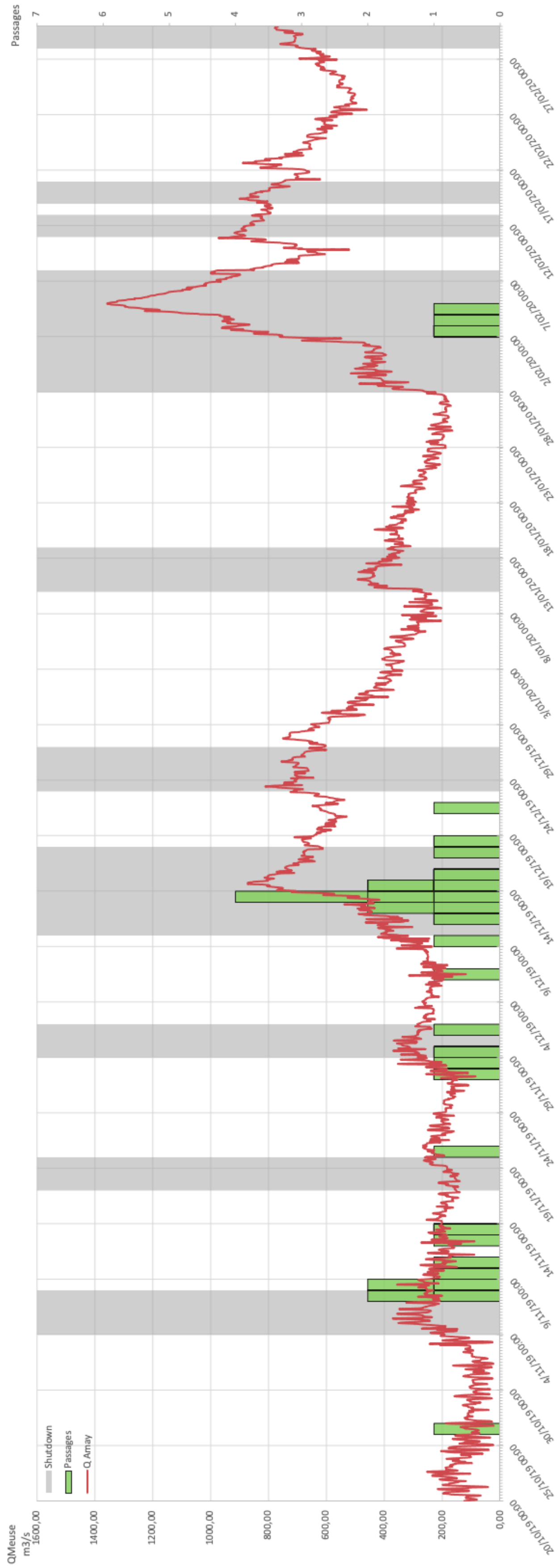


Figure 14 : Evolution of the River discharge (Q, m³/s, Amay station, red line), alarms onset (grey) and eel passage (green) at CHA during the study period.:

The Figure 15 presents a synthesis of the prediction efficiency

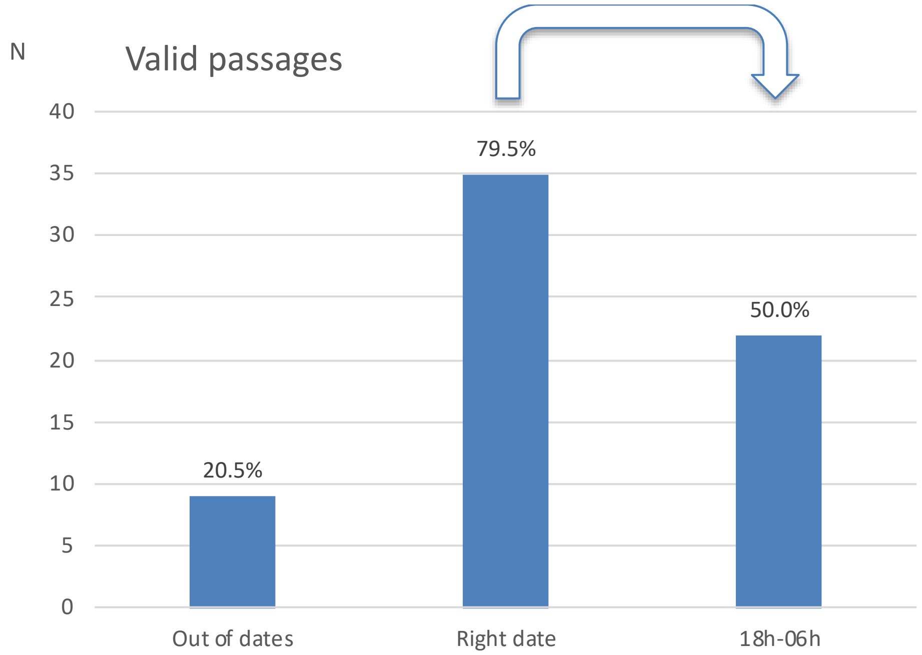


Figure 15 : proportion of eel passage subcategories for valid eel passages (right, N = 44).

Considering all passage data, the model failed to predict 40,6% of the migrating dates. Within the 59,4% successfully predicted, 39,1% of the eel passed during the 18-06h timeframe, and 20,3% within the operational timeframe of shutdowns.
To establish the model over the 2017 database, eel passing within the first 7 days after their released were excluded from the dataset, to avoid an influence of the time of release on the time of passage. When excluding the same values in our 2019 dataset, 20 eel passages (31,5%) were erased, mainly occurring between 07th and 13th November, *i.e.* the first week after the main tagging session. Considering this new sub-dataset, the success of prediction of the date reached 79,5% (versus 88,0% in 2017). 50,0% of the eel passages occurred within the 18-06h timeframe (versus 53,0% in 2017). Only 29,5% of the eel passage occurred within the operational timeframes.

On the 35 valid passages that occurred on a valid date, all passages where observed over the spillways. No eels used the spillway due to a turbine shutdown operated by the model. During the 2017 and the 2019 survey, CHA and CHL where the two sites observed with the highest natural escapement over the spillway.

III.3.4 Discussion

Considering the same categories of fish passage (> 7j post-release), the performance of the model to predict migration days and timeframe (18-06) succeeded to reach very similar performances in 2019 than in 2017 (magnitude of 50% for the 18-06h timeframe and magnitude of 80% for the date).
Beside this positive observation, some elements need to be discussed to describe the complete context of the study.

All eels tracked in 2017 were originating from the Rhine river and have been translocated and released in the Meuse, while a minor part (N = 9 in CHA) of eels came from the Meuse itself in 2019. Among these eels, only one passed during a theoretical shutdown, but less than 7 days after its release. In 2017, eels were released after tagging in early October, close to one month before the first discharge increase that induced a migration peak. In 2019, the release of most of eels had been post-pone due to the installation process of the barriers, delaying the release of the fish in early November, in the hydrological tail of the first peak of discharge that could have influenced the migration (Figure 16). These conditions have obviously stimulated a direct start of the migration of a large proportion of the eels, a couple of days after this peak predicted by the model.
The timeframe of the shutdown has been established based on the passage of the 2017 dataset, that was influenced by a different fish repartition upstream the CHA site than in 2019. During years 2017 and 2019, we observed a stronger repartition of the eel passage during the first half of the night on the upstream HPP, and a progressive reduction of this nocturnal pattern on the downstream sites. But this pattern could have been influenced by the bigger sample size of eels released in the upstream stretch of the river. The data tend to indicate a start of the migration during the first half of the night, and then once started, eels seem to keep migrating over the next hours of the night and day on the downstream sites. Taking into account all eel passages at all sites in 2019 (Figure 16), we can see a majority of night passages but a significant proportion of passages during the day.

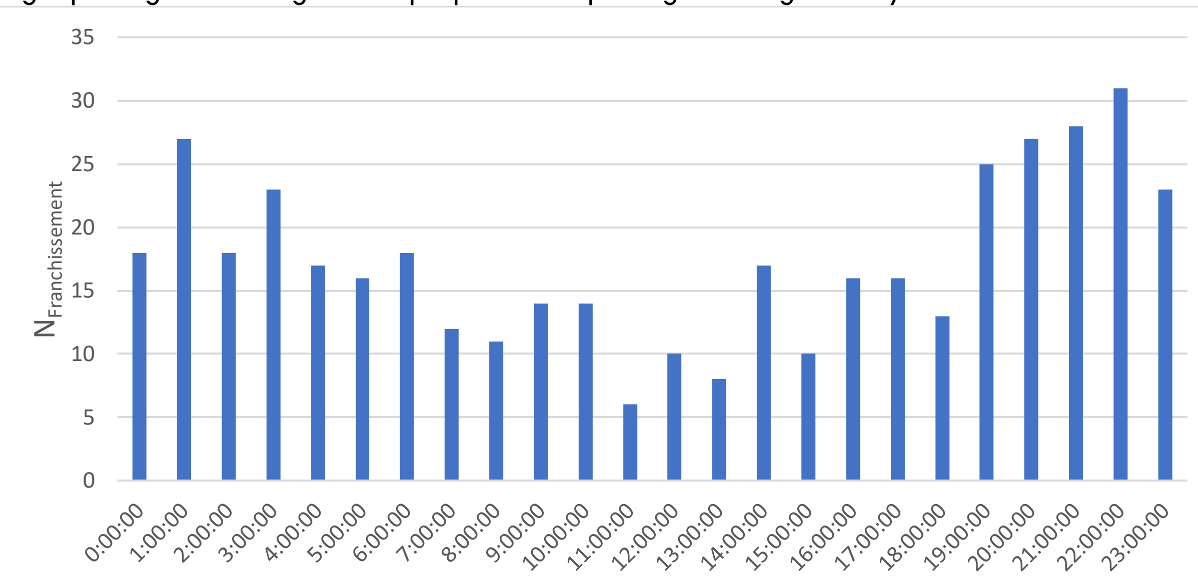


Figure 16 : time repartition (UT) of all eel passages at all sites during the 2019 telemetry survey.

Consequently, this observation is consistent with the increased performance of the model when it is considered at the day (24h) compared to the 18-06h timeframe.
Finally, while we did not investigate it deeply, each year has its own hydrological pattern, and very likely, the hydrological pattern of the 2019 migration was different somehow from the 2017 pattern. Moreover, these conditions are playing on a limited size of sampling, so that if all eels have passed within the first peaks of migration, no more eels are left in the sample to characterize the influence of later hydrological peaks, while these could have some effects on resident eels.
Based on these considerations, the prediction model seems to confirm the possibility to reach a first level of efficiency higher than 50% within a timeframe 18h-06h (UT). CHA, as CHL, are site were a majority of eels are already migrating over the spillways, meaning that these sites are not target ones to setup turbine management as a final solution. Two HPP of the Luminus parc are equipped with a higher capacity than the river mean discharge : CHR and CHM. At these two sites, the proportion of eel passing through the turbine is higher than observed at the

4 other sites. These sites could be targeted to setup the turbine management model, adjusting the timeframe from 18-06h to 24h depending on the required efficiency in the range 50 % to 80%.
The real procedure to perform the turbine shutdown needs an improved coordination with the SPW-DGO2 services, since the dam spillways opening needs to be synchronized to avoid flood waves on the river axis. While the model can be validated, the operational implementation seems to need serious progresses.

III.4 Bubble barrier at CHR

III.4.1 Eel passage observation in 2019

The bubble barrier has been commissioned on the 12th September 2019, but some adjustments had to be made, delaying the real operational date to the 20th September 2020. Due to an increase of the river discharge, the bottom pipe did not resist to debris/water forces, and the barrier was considered as non-operational from the 30th November 2019.

During that operational time frame, a total of 15 tagged silver eels has been reported passing the CHR site. Among these fish, 12 eels have been reported passing through the power plant. 3 eels are reported as having likely passed through turbines, but their passage could not be confirmed since not detected by anywhere in the network downstream.

Among the 15 eels potentially exposed to the barrier, 14 have positional data within the installed 2D network (Figure 17). 1 eel is only positioned in the centre of the river, while the last 11 eels show positions nearby the barrier. So we can consider the variable N barrier as 11. No eels passed over the spillways.

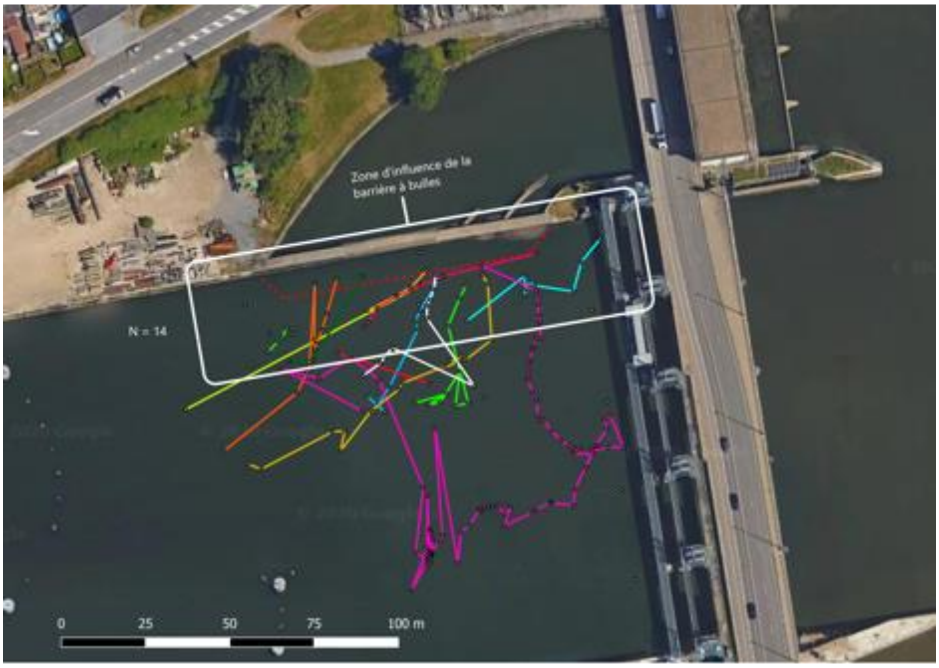


Figure 16 : View of the 14 eel trajectories observed over the 15 eels passing CHR during the operation time of the bubble barrier.

Following the calculation defined in the nomenclature, the barrier efficiency can be estimated as follow :

$S_{barrier} = 0/11 = 0\%$.

Based on the calculation, the bubble barrier reveals no efficiency, but this is considered on a very short sample. Moreover, for these passages, the proportion of river discharge passing through the turbines ranged from 79% to 92%, within a river discharge ranging from 89 to 284 m^3/s. In this kind of hydraulic conditions, the possibilities of passing over the spillway are reduced for eels, since the water height remaining over the spillway is very shallow.
If we compare these data with eel passage at CHR in 2017 within the same range of river discharge, 9 eels passed CHR, 6 through turbines, 2 through unknown passage (but with a

strong discharge ratio for the turbines), 1 via the boat sluice. Comparatively, no eels succeeded to pass over the spillway in 2017 in the same hydrological conditions.

III.4.2 Discussion

The bubble barrier did not reveal any obvious effect on silver eels, but the sample is probably too small to demonstrate it. We did not find referenced publication describing an effect of bubble barrier on silver eels, while some references in the literature reveal efficiency (Welton et al. 2002) or inefficiency (Gosset & Travade 1999) on salmon smolts. The barrier installed did not resist to a normal winter flood which weaken the confidence in the applied technology for the future. Finally, from the HPP operator point of view, the supply of compressed air in the pierced pipe was provided by a huge air compressor with a huge energy consumption and a noise level considered as dangerous for operators.

IV. General conclusions

The telemetry survey conducted on silver eels in 2019-2020 was aimong to evaluate the efficiency of 3 different mitigations measures deployed at a pilot scale on 3 sites.
On the site of Grands-Malades, the Neptun electrical barrier succeeded to induce significantly a better escapement rate over the spillways compare with the reference situation in 2017. The quantification based on turbine entrainment rate evaluated the efficiency at a value of 52%. While this efficiency remain quite low, taking into account that silver eels naturally migrate in majority over the spillways in the River Meuse, it can be considered as sufficient to be considered as potentially applied at other sites at the full scale deployment phase that should occur in 2021.

On the site of Andenne, 50.0% of the eel passage felt into the predicted date and timeframe 18PM-06AM warned by the model. However, on the logistic point of view, real turbine shutdown revealed to be less efficient due to complex communication process with the dam regulation operators. The efficiency of the model might be improved by adjusting it to further eel passage dataset to adjust the timeframe. Extending the turbine shutdown to a 24h period would reach a level of 80% of prediction in the present dataset. Similarly, to the Neptun barrier, the eel migration model can be considered at this stage as potentially applied at other sites for the full scale deployment.

On the site of Ivoz-Ramet, the bubble curtain has been deployed. On the mechanical point of view, the barrier did not exhibit enough resistance to a normal autumnal flood, meaning that new tests would require to improve and re-install the system. Moreover, while the dataset observed was small, no evidence of influence was noticed on eel behaviour. For these reasons, the bubble barrier will probably not be tested in the future on salmon smolts, and will probably not be selected in the LIFE4FISH project as one of the solution potentially available.

The next step of the project is now to evaluate the balance between : i) deployement cost; ii) the ecological context of each dam; iii) the ecological gain by each measure. This approach will be conducted in order to deploy, at the 6 sites scale, a global eel protection plan to be evaluated in 2021-2022.

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