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Hydroelectric power plant and upstream fish migration: evaluation of the efficiency of a behavioural barrier

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ABSTRACT

Hydropower plant (HPP) weirs disrupt river ecosystems by fragmenting habitats. Moreover, the strong water currents from HPP discharges can mislead fish, causing them to enter non-viable or dangerous output channels. This study investigates a submerged behavioural barrier installed downstream of an HPP in the Our River in Belgium. The barrier's goal is to repel fish from the turbine output channel and guide them towards a safer fishway passage, thereby aiding their upstream migration. We used radio telemetry to track the movements of brown trout (*Salmo trutta* L.) and evaluate the barrier's effectiveness in preventing misdirected migration. The results showed significant attraction for the output channel but 50% of the fish were successfully deterred by the behavioural barrier where the success was clearly influenced by changes in water flow conditions. The fishway had a moderate success rate, with 58% of fish using it effectively. Fish that passed through the barrier were less likely to use the fishway. These results highlight the interest of equipping certain sites with behavioural barriers during upstream migration and the need to improve their design to promote a balance between hydropower production and the conservation of aquatic biodiversity.

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1. Introduction

While hydropower generation is a renewable energy source, its harmful environmental impacts on free-flowing rivers are well-documented (Reid et al. 2019). However, the continued operation of older hydropower plants (HPPs) is driven by rising electricity demand and the need to mitigate greenhouse gas emissions (Zarfl et al. 2015). Dam construction causes environmental fragmentation, which greatly reduces sediment transport (Liermann et al. 2012), alters flow and temperature regimes (Olden and Naiman 2010), disrupts habitats, and prevents the free movement of aquatic organisms (Noonan et al. 2012). Specifically, these barriers interrupt the longitudinal connectivity of rivers, which isolates fish communities (Santos et al. 2017) and further threatens freshwater biodiversity. Longitudinal connectivity is a critical requirement for the persistence of fish communities, because it allows for seasonal movements, enhances reproductive success, and enables recolonization of areas affected by disturbances (Benejam et al. 2010; Ordeix et al. 2011). Significant attention has been paid to the numerous effects of barriers on the migration of diadromous fish for the most part, but attention is more recently being given to potamodromous fish. When bank stability and hydrological impact or societal conditions such as patrimonial or cultural ties are not prohibitive, some obstacles are removed (Gregory et al. 2002; Garcia de Leaniz 2008). Nevertheless, dam removals are often not possible, and fishways are constructed to facilitate fish movement using a wide variety of devices (Clay 1995; Silva et al. 2018). Early efforts to facilitate passage over dams focused on commercially and recreationally valuable species (Piper et al. 2012), such as salmon (*Salmo salar*) and trout (*Salmo trutta*), but these efforts have since expanded to include passage for entire fish communities (Benitez et al. 2015; Ovidio et al. 2020).

Adequate hydraulic conditions in the fishway ensure upstream passage for species with different swimming capacities (Lundqvist et al. 2008), and flow is one of the key factors in attracting fish to the entrance of the fishway, in order to avoid delays or interruptions in migration (Silva et al. 2018; Wilkes et al. 2018). The attraction efficiency acts as the first "filter" in fishway performance, and poor attraction can severely limit the ecological benefits of the structure (Bunt, 2001). Improving attraction efficiency is essential to ensure that fishways effectively support the movement of migratory species and contribute to river defragmentation programs (Ovidio et al. 2017). In the case of dams associated

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with hydroelectric power stations, outflows from HPP can draw fish migrating upstream into a non-viable route, causing injury, increasing the risk of predation, stress and delaying upstream migration (Arnekleiv and Kraabøl 1996; Scruton et al. 2007). Discharges of turbined flows at HPPs have been shown to divert fish from other more viable passage routes, which reduces the efficiency and attractiveness of fishways and impacts the ability of fish to pass dams (Dodd et al. 2017).

Many studies on route choice focus on downstream migration (Larinier and Travade 1999; Schilt 2007; Calles et al. 2012; Renardy et al. 2020), including analysing fish behaviour and exploring solutions to prevent fish from passing through an unsafe migration route like hydroelectric turbines, because these can cause a variety of negative impacts or death (Algera et al. 2020). To influence the natural behaviour of fish, particularly during downstream migration, and to prevent them from taking unsafe migration routes, a series of behavioural barriers have been installed at various obstacles. These barriers enable fish—at least a proportion of the population—to select a safer migration route, thereby reducing the time required to locate a suitable passage (Antonio et al. 2007; Noonan et al. 2012). Behavioural barriers can be physical (up- and downstream directions), such as louvers, but they can also involve an electric field (downstream direction), a bubble curtain (downstream direction), variations in flow velocity (up- and downstream directions), or even acoustic deterrents (downstream direction) (Noatch and Suski 2012).

Understanding fish movement patterns in the output channel of a hydroelectric power plant is a crucial step in assessing the ecological impact of these structures on the behaviour and migration patterns of fish moving upstream (Suzuki et al. 2017). Previous research on behavioural barriers in the upstream direction has mainly focused on two aspects: selective fish passage to prevent the spread of non-native species through ecological screening (Rahel and McLaughlin 2018), and the use of behavioural guidance systems to direct fish towards the entrance of fish passes (Yao et al. 2024). However, no study has yet specifically examined the effectiveness of behavioural barriers placed at the entrance to a non-viable route of a HPP during upstream migration. In this context, in the Our River in Belgium, a concrete submerged barrier was installed at the outlet of the output channel of a small HPP. The purpose of this barrier is to reduce the use of the HPP's output channel and to direct upstream fish migration towards the main river, which leads to a fishway, thereby promoting a safe migration route. The hypothesis is that adding a behavioural barrier specific to upstream migration, at a hydroelectric facility, reduces the use of a non-viable migration route. The objectives of this study, conducted using radio telemetry on brown trout (*Salmo trutta*) during one period of spawning migration, were (i) to analyse the mobility patterns of tagged fish and the effect of individual fish characteristics on the dynamics of upstream migration (ii) to determine if a concrete barrier acts as a behavioural barrier to upstream migration, and to assess how environmental and behavioural factors influence its deterrent effect and (iii) to determine if the behavioural barrier, in interaction with environmental and behavioural factors, affects the probability of complete dam crossing *via* a fishway.

2. Materials and methods

2.1. Study site

The Our River (belonging to the Rhine River basin) is a gravel-bed river that is a tributary of the Sûre River in Germany and is 96 km long with a mean slope of 4.9‰ (Figure 1). The river section studied is defined as a mixed barbel/grayling zone (Huet, 1949), characterised by moderate to fast-flowing water and by a slope between 2 and 5‰. With 16 native species, the dominant fish species of the Our River are the common barbel (*Barbus barbus*), common nase (*Chondrostoma nasus*), brown trout (*Salmo trutta*), common chub (*Squalius cephalus*), common minnow (*Phoxinus phoxinus*), loach (*Barbatula barbatula*), gudgeon (*Gobio gobio*) and European bullhead (*Cottus gobio*). Other fish species are more sporadically present including European grayling (*Thymallus thymallus*), common dace (*Leuciscus leuciscus*), and roach (*Rutilus rutilus*). Across river, the physicochemical parameters and prevailing macro-invertebrate communities are currently indicative of good water quality for 2020 (Public Service of Wallonia—AQUABIO).

The weir studied is the Weweler-Mühle HPP situated on the River Our (median flow = 2.3 m^3/s) in eastern Belgium, in the municipality of Burg-Reuland. In the context of restoring free movement on the Our River, more particularly in Belgium, all weirs were equipped with a fishway, with the Weweler-Mühle weir remaining the last major structure to be upgraded. The Weweler-Mühle ramp weir (with a height difference of 4.5 metres) serves both a fish farm and a HPP. The Weweler-Mühle HPP is equipped with one Banki turbine (cross-flow turbine) and one Francis turbine (169 kW/h), creating a 950 m-long bypassed river section. In 2019, modifications were made to the weir to install a fishway (Figure 1). The nature-like pool-type fishway consists of 13 pools, spanning a total length of 77 m. Its

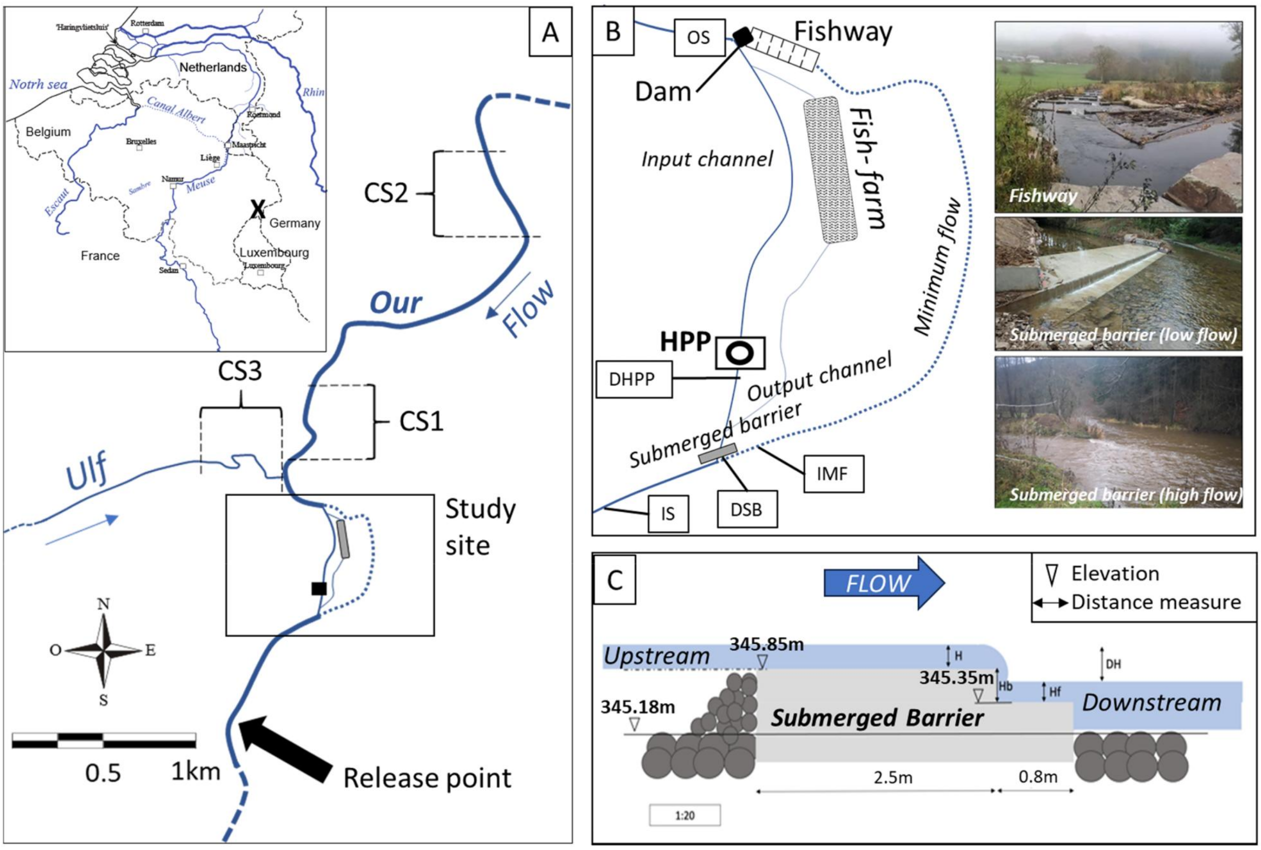

Figure 1. General situation of the study site on the Our River with locations of capture sites (CS) and release point [A], configuration of the study site with the location of the hydroelectric power plant (HPP), the submerged barrier, the dam and the position of the radio antennas (IS: Input system, DSB: Downstream the Submerged Barrier, DHPP: Downstream of the HPP, IMF: Input Minimum Flow and OS: Output System) [B] and configuration of the submerged barrier (side view) where the elevation data (triangle), height of water on the submerged barrier (H), the height of water in the plunge pool at the foot of the barrier (Hf) and the Head-drop (DH) are shown [C].

purpose is to facilitate upstream migration of fish at different flow rates while maintaining water supply to both the fish farm and the HPP. The initial 250 litres per second (l/s) are reserved for the fish farm, followed by a minimum flow of 1000 l/s for the bypassed river section (minimum flow). The HPP operates when the flow exceeds 1250 l/s, with a maximum flow capacity of 4000 l/s.

In order to encourage the choice of migration route using the new fishway, a permanent submerged barrier (made of concrete) was installed by the managers at the same time as the fishway. It was constructed downstream of the HPP output channel (Figure 1C), at the confluence of the river. The primary purpose of this barrier is to reduce the use of the output channel as an upstream migration route and to prevent fish from becoming trapped just downstream of the turbines. The barrier is designed as a step to deter fish while avoiding any increase in water levels at the turbine base, which could result in a loss of hydroelectric production for the operator, unlike the addition of fine grid or other obstacles susceptible to fouling. Across a width of 11 m, the submerged barrier forms a 0.5 m high step followed upstream by a concrete platform 2.5 m long. A concrete platform is also located just downstream and measures 0.8 m long. The immersion level of the barrier fluctuates depending on the flow rate and was measured several times during monitoring. Riprap was placed upstream and directly downstream of the barrier to stabilise the structure and protect it from erosion.

2.2. Environmental data and hydrodynamic measures

The water temperature (°C) of the Our River was recorded (Hobo Data Logger Onset; hourly measures; precision 0.1 °C) just downstream of the Weweler-Mühle weir. The water flow data (m^3/s; hourly measures) were provided by the Wallonia Public Service of hydrological studies (HYDROMETRY, Walloon Region) of a station installed in the Our River 200 m downstream of the submerged barrier. At the Weweler-Mühle HPP, there is no system for recording turbine flow or energy production. Only a real-time production display is available. Energy production was recorded on an *ad hoc* basis during weekly downloads of detection data. Different flow height and flow velocity (FV) were measured eight times at different flow conditions during the study period. The height of water on the submerged barrier (H) and the height of water in the plunge pool at the foot of the barrier (Hf) were measured on the left bank, in the middle of the bed and on the right bank. Head-drop (DH) was calculated using the formula DH = (Hsb + H) − Hf, where Hsb is the height of the submerged barrier (Baudoin et al. 2015). To measure flow velocity, we used a current metre (FLO-MATE MODEL 2000, Marsh-McBirney) at the barrier crest and at the entrance to the minimum flow, at four different points in width and two points in height. The estimated turbine flow was calculated by multiplying the mean velocity, the mean water depth, and the water width. This estimated turbine flow was then divided by the total flow of the Our River to determine the turbine flow ratio (Qt).

2.3. Fish capture and tagging

Our biological model was the brown trout because it is one of the most abundant species in the study area and has good swimming and jumping abilities. Trout individuals were captured upstream of the HPP during their reproductive migration period (in autumn, Ovidio et al. 1998) using electrofishing. We equipped individuals with radio transmitters and then released them downstream of the obstacle. This method induces a homing migratory impulse (Ovidio et al. 2017), i.e. a return to the initial habitat located upstream of the structure. A total of $N = 30$ trout large enough to maintain a 2% ratio with the transmitter (Brown et al. 1999), divided into three groups and two fishing days, were caught and tagged. On 21 October 2020 (Figure 1), the first group of $N = 4$ fish was caught by electrofishing 580 m upstream of the weir over a linear distance of 180 m (CS1) in the Our River. On the same day, a second group of $N = 9$ fish was captured 200 m upstream of the Weweler-Mühle dam (CS2), always in the Our River. A third group of $N = 17$ fish was captured on 28 October 2020 in the Ulf River (CS3: 400 m of the river), a small tributary of the Our River whose confluence is located 260 m upstream of the fishway. All fish were anaesthetised in a solution of 4-allyl-2-methoxyphenol (Eugenol: 0.1 ml/L), measured (fork length, in mm) and weighed (g). After biometric measurements, a 10-mm incision was made, and a radio transmitter has been inserted in the body cavity (Sigma Eight Inc.: Model TX-PSC-I-80-D; 22 mm × 10 mm × 10 mm; mass in air 3.3 g; 20 ms pulse/2s; expected lifetime 65 days). The incision was closed with two stitches using absorbable suture material and disinfected with eosin (Ovidio et al. 2020; Renardy et al. 2020). After a one-hour recovery period, the three groups were released 600 m downstream of the outlet of the HPP thanks to a 600-litre tank equipped with liquid air. The average size (fork length) of the tagged fish was 292.9 mm ± 49.1 mm, with an average weight of 295.4 g ± 145.5 g, an average Fulton's condition factor (K = Weight (g)/Size^3 (cm) × 100) of 1.10 ± 0.10 and an average ratio of weight tag/fish of 1.42% ± 0.74% (Table 1).

2.4. Detection system and behavioural metrics

A radio-telemetry system (Sigma-eight Inc.: Orion receiver) with five radio-antennas (weekly data download) was designed (Figure 1), installed on the study site and tested in terms of detection range in order to obtain information on fish behaviour from 21 October 2020 to 24 December 2020 (tag duration limit).

1. An underwater radio antenna at the input system (IS) was placed 85 m downstream of the submerged barrier across the entire width of the river (18 m wide) with a detection range of 5 m upstream and downstream across the entire width. This antenna validated the presence of fish on the study site.
2. An underwater radio antenna was placed downstream of the submerged barrier (DSB) across the entire width (11 m wide, up to 6 m downstream) of the output channel of the HPP. This antenna validated the presence of a fish close to the submerged barrier.
3. An underwater radio antenna was installed directly at the downstream outlet of the HPP (DHPP). The detection field was 3 m downstream from the antenna. It was used to confirm that a fish crossed the barrier and reached the upstream part of the output channel when searching for a migration route.
4. An underwater radio antenna was installed at the input of the minimum flow (IMF) section across the entire width (12 m wide) of the river and 6m upstream of the confluence between the river and the output channel with a maximum detection range of 5 m downstream so as not to overlap with antenna DHPP. This validated that a fish used the main course as a migration route towards the upstream fishway.
5. An aerial antenna was installed upstream of the dam and fishway at the output system (OS). Pointed upstream, this radio antenna could detect up to 30 m upstream from the dam. This antenna validates that a fish has crossed the system via the fishway.

Table 1. Tagging information of captured brown trout: date of capture/tagging; River, sector of capture, ID of tag, size, weight, fulton's condition factor (K) of fish and the ratio of tag/fish weight.

Date	River	Sector	ID	Size (mm)	Weight (g)	*K* factor	Ratio tag/fish weight (%)
21-10-20	Our	CS1	109	230	150	1.23	2.20
21-10-20	Our	CS1	62	230	140	1.15	2.36
21-10-20	Our	CS1	18	230	124	1.02	2.66
21-10-20	Our	CS1	152	231	140	1.14	2.36
21-10-20	Our	CS2	178	210	111	1.20	2.97
21-10-20	Our	CS2	46	212	112	1.18	2.95
21-10-20	Our	CS2	92	232	126	1.01	2.62
21-10-20	Our	CS2	80	246	200	1.34	1.65
21-10-20	Our	CS2	22	302	300	1.09	1.10
21-10-20	Our	CS2	82	318	355	1.10	0.93
21-10-20	Our	CS2	154	330	359	1.00	0.92
21-10-20	Our	CS2	40	341	388	0.98	0.85
21-10-20	Our	CS2	64	360	484	1.04	0.68
28-10-20	Ulf	CS3	155	261	188	1.06	1.76
28-10-20	Ulf	CS3	164	270	220	1.12	1.50
28-10-20	Ulf	CS3	122	272	230	1.14	1.43
28-10-20	Ulf	CS3	200	276	218	1.04	1.51
28-10-20	Ulf	CS3	181	279	226	1.04	1.46
28-10-20	Ulf	CS3	6	282	240	1.07	1.38
28-10-20	Ulf	CS3	61	283	270	1.19	1.22
28-10-20	Ulf	CS3	44	310	320	1.07	1.03
28-10-20	Ulf	CS3	150	315	286	0.92	1.15
28-10-20	Ulf	CS3	139	315	370	1.18	0.89
28-10-20	Ulf	CS3	110	318	380	1.18	0.87
28-10-20	Ulf	CS3	73	330	400	1.11	0.83
28-10-20	Ulf	CS3	212	337	420	1.10	0.79
28-10-20	Ulf	CS3	24	339	400	1.03	0.83
28-10-20	Ulf	CS3	120	343	394	0.98	0.84
28-10-20	Ulf	CS3	166	375	620	1.18	0.53
28-10-20	Ulf	CS3	33	410	690	1.00	0.48

Table 2. Definitions of the behavioural metrics used in the study.

Behavioural metrics	Definitions
Ascending delay	Time (in hours) between the release and first detection by IS
Approach	Number of detections at the same antenna with a 30-minute latency period
First approach rate	Percentage of individuals detected the first time at a migration route (IMF or DSB) in relation to the total number of individuals detected
Adjusted attractiveness IMF or DSB	Percentage of fish detected by IMF or DSB compared with the amount detected at IS
Adjusted efficiency of fishway	Percentage of individual fish that made a fishway passage compared with the amount detected at IS
Crossing time of fishway	Transit time (in hours) from last detection in IMF to first detection in OS
Adjusted passability of submerged barrier	Percentage of individual fish that made a barrier crossing compared with the amount detected at DSB

The data from the radio antennas enabled the definition of a number of passage metrics (Table 2) that can be quantified in order to determine fish behaviour in relation to the submerged barrier and the fishway. These metrics have already been defined in previous studies (Ovidio et al. 2017; Benitez et al. 2018; Ovidio et al. 2020).

2.5. Data analysis

For the first objective, all detection data obtained from the radio antennas were used to determine a median ascending delay and the mobility patterns of the tagged fish. To understand a possible link between the absence of trout in the detection system, we compared the biometric measurements (condition factor, tag/fish weight ratio and fish size) of trout detected after the release with those of undetected trout using a Wilcoxon test. A chi-squared (chi^2) test was also performed to assess whether the capture location (Our River vs. Ulf River) had a significant effect on the likelihood of detection by the monitoring system. For the second objective, to compare the first approach percentages of tagged fish according to migration route (output channel vs. minimum flow) and the adjusted attractiveness IMF or DSB, we used the chi^2 test. To test the relationship between hydrodynamic measurements (H, Hf, DH, flow velocity and proportion of turbined flow) and the flow rate of the river, we used Spearman correlation tests. To analyse the factors influencing the success of crossing the behavioural barrier and the fishway for the second and the third objectives, we used generalised linear models, more particularly a log-linear model assuming a binomial error distribution, and the logit link function (Zuur et al. 2013). In accordance with the recommendations for logistic regression modeling (Peduzzi et al. 1996), where the number of independent variables depends on the size of the dependent variable, a maximum of two predictive variables were included per model. For predicting successful passage of the submerged barrier during an approach, the explanatory variables were: flow rate, water temperature, biometric measures, number of prior approaches, Julian date of approach, and time spent at the base of the barrier. In the case of successful passage through the fishway during an IMF approach, the variables evaluated included flow rate, water temperature, fish size, number of prior approaches, Julian date of approach, and whether the fish had previously crossed the submerged barrier to reach the upstream part of the output channel. The variable selection in the log-linear model was evaluated based on the stepwise forward selection method by the AIC (Akaike information criterion: Boyce et al. 2002). We considered only the best model, the model with the lowest AIC. Goodness-of-fit of the best model was determined using the pseudo-R^2 (Menard 2001). Then the area under the curve (AUC) (Hanley and McNeil 1982) was interpreted as the probability of correctly classifying a pair of randomly selected subjects, one from the presence group and the other from the absence group (Fielding and Bell 1997). All statistical analyses were performed using the statistical program R (The R Foundation for Statistical Computing, Vienna, Austria, version 4.5.0.). Statistical significance was set at a confidence level of 95%.

3. Results

3.1. Detection profiles and mobility patterns

During the study period (between 21 October 2020 and 24 December 2020), flow ranged between 0.53 and 11.8 m^3/s (mean ± SD = 3.11 ± 2.43 m^3/s) and water temperature ranged between 2.35 °C and 12.85 °C (mean ± SD = 8.34 °C ± 2.40 °C). We observed during this period that 20 fish were detected by the detection device (67% of tagged fish) and the last detection the 7th December. There was no significant difference (Wilcoxon test, $p > 0.05$) between detected and non-detected individuals in the study area for the condition factors ($p = 0.47$), tag/fish weight ratio ($p = 0.52$) or fish size ($p = 0.96$). Furthermore, the proportions of detected/non-detected individuals between those captured in the Our River and those captured in the Ulf River were meaningfully different (chi^2 test, $X^2 = 3.32$, $p = 0.07$). All 20 trout detected reached the study system (detection at IS) with a median ascending delay of 30 h 32 min (range: 3 h 01 mim to 895 h 37 min). In the overall analysis of movements within the study area, three main categories of mobility patterns emerged among the individuals detected (Figure 2). The first category (Category 1) is characterised by passage through the output channel with at least one detection by the DHPP antenna (40%: 8 individuals), where only one passage through the barrier was observed for 7 out of 8 individuals. The second category (Category 2) includes individuals that were detected downstream of the submerged barrier (DSB antenna) but did not cross it (40%: 8 individuals). The last category (Category 3) is characterised by individuals detected at the entrance to the minimum flow (IMF antenna) without having been detected downstream of the submerged barrier at the DSB antenna (20%: 4 individuals). Among all the trout detected ($N = 20$), three trout were detected for the last time at the IMF antenna, ten trout were detected for the last time at the OS antenna and seven trout were detected for the last time at the IS antenna.

3.2. Behaviour and hydrodynamics conditions close to the behavioural barrier

Upstream of the IS, 55% of individuals made their first approach at the submerged barrier (DSB antenna), compared with 45% at the fishway entrance (IMF antenna) with no significant difference in proportions (chi^2 test, $X^2 = 0.4$, $p = 0.52$). The adjusted attractiveness of the natural river was higher than the submerged barrier, with a value of 95% (19/20 ind.) and 80% (16/20 ind.) respectively, but no significant difference was observed (chi^2 test, $X^2 = 2.05$, $p = 0.15$).

During the eight measurements carried out at the submerged barrier, the Our River flow rate ranged from 1.42 to 10.77 m^3/s. The average height of water on the submerged barrier (H) was between 0.09 and 0.32 m and the average height of water in the plunge pool (Hf) was between 0.05 and 0.61 m (Figure 3). H and Hf varied positively with the flow of the Our River (Spearman correlation: Rho = 0.97, $p < 0.001$ and Rho = 1, $p < 0.001$, respectively). Conversely, Head-drop (DH) varied negatively with Our River flow (Spearman correlation: Rho = −0.95, $p < 0.001$), with values ranging from 0.02 to 0.34 m. The average flow velocity over the dam crest ranged from 0.67 to 1.1 m/s, while for the minimum flow, the flow velocity varied from 0.04 to 0.6 m/s. The estimated percentage of turbined flow ranged from 30 to 56%. As the Our River flow increased, a significant increase in flow velocity was observed at the barrier crest (Spearman correlation: Rho = 1, $p < 0.001$) and in the minimum flow (Spearman correlation: Rho = 0.6, $p = 0.04$), while the proportion of turbined flow decreased (Spearman correlation: Rho = −0.66, $p = 0.03$).

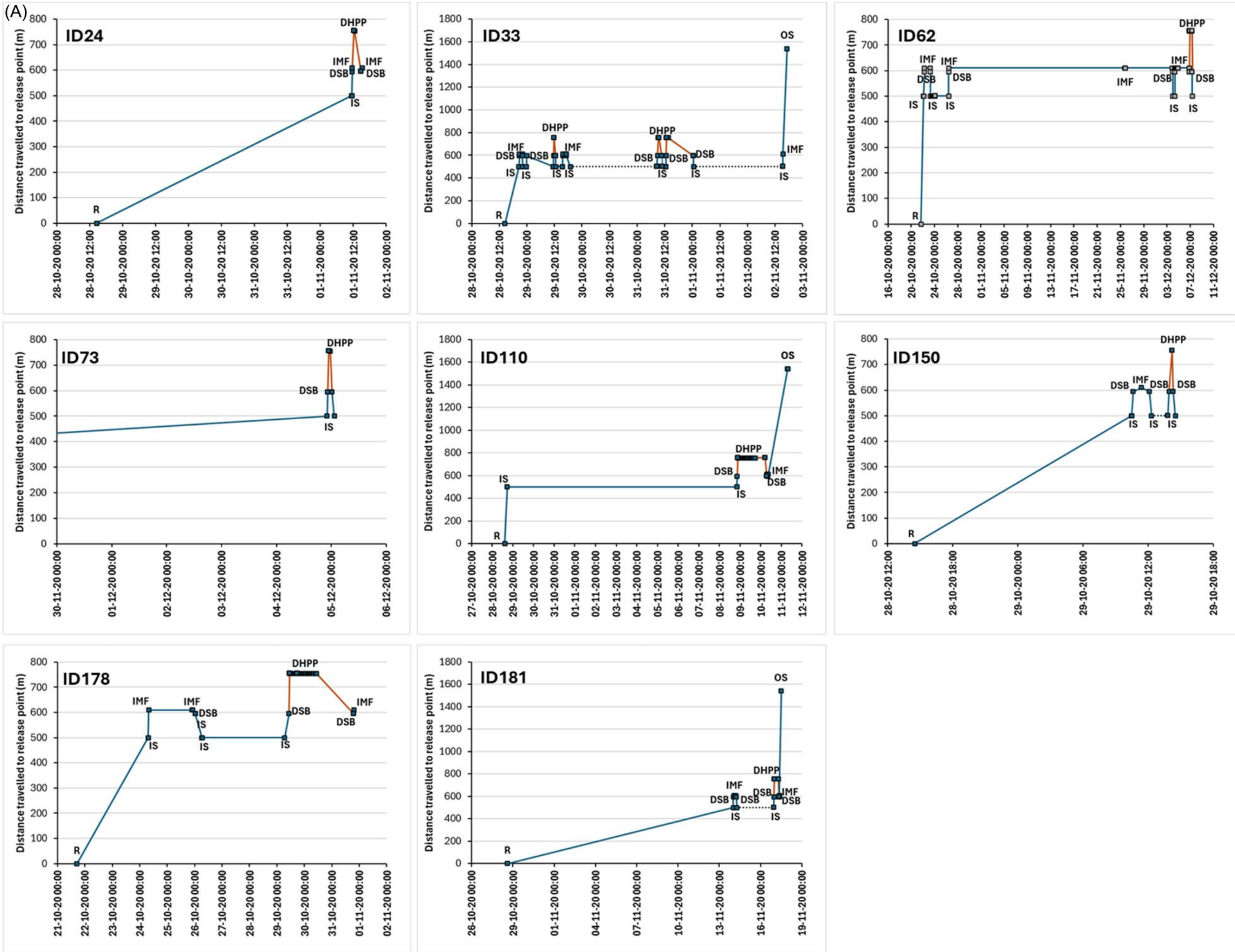

Figure 2. (A) Mobility patterns of category 1 (detected at DSB and DHPP antenna) trout detected in the system ($N = 8$) with the movements in the river shown in blue and the movements in the output channel shown in orange. The dotted lines represent movements outside the detection system. The zero point of the *y*-axis represents the release point. (B) Mobility patterns of category 2 (detected at DSB antenna) trout detected in the system ($N = 8$) with the movements in the river shown in blue. The dotted lines represent movements outside the detection system. The zero point of the *y*-axis represents the release point. (C) Mobility patterns of category 3 (no detected at DSB antenna) trout detected in the system ($N = 4$) with the movements in the river shown in blue. The dotted lines represent movements outside the detection system. The zero point of the *y*-axis represents the release point.

Of the 16 individuals detected at the submerged barrier, eight individuals crossed it (out of 42 approaches), giving an adjusted passability of the submerged barrier of 50%, with a median time spent in front of the submerged barrier of 24 min (range: 33 s – 2 h 19 min). As for the $N = 8$ individuals that crossed the barrier, the median time spent in the channel was 10 h 11 min (range: 20 min to 56 h 33 min). Among the initially considered predictive factors, the stepwise selection process identified only one variable that best explained successful passage of the submerged barrier during the study period (10 passages from 42 approaches, Figure 4): the flow rate of the Our River (log-linear model, Table 3). This model yielded an AIC of 41.46, an AUC of 0.81 and a pseudo-R^2 of 0.18, indicating that the likelihood of successfully passing the submerged barrier increased with higher flow rates in the Our River (Figure 4).

3.3. Behaviour related to crossing the fishway

A total of 11 fish passed through the fishway out of the 19 fish detected at IMF, giving an adjusted efficiency of the fishway of 58%, considering the 900 m of the river that is in instream flow with a median crossing time of 43 h 50 min (range: 2 h 15 min to 238 h 17 min). For the fishway (12 passages from 56 approaches, Figure 4), the final model, selected based on model fit criteria, included only the binary variable indicating prior passage of the submerged barrier (Table 3). Flow rate was not retained as a significant predictor of successful crossing. The results suggest a negative association between prior passage of the submerged barrier and subsequent success in crossing the fishway. This model yielded an AIC of 59.7, an AUC of 0.62, and a pseudo-R^2 of just 0.04, reflecting limited explanatory power.

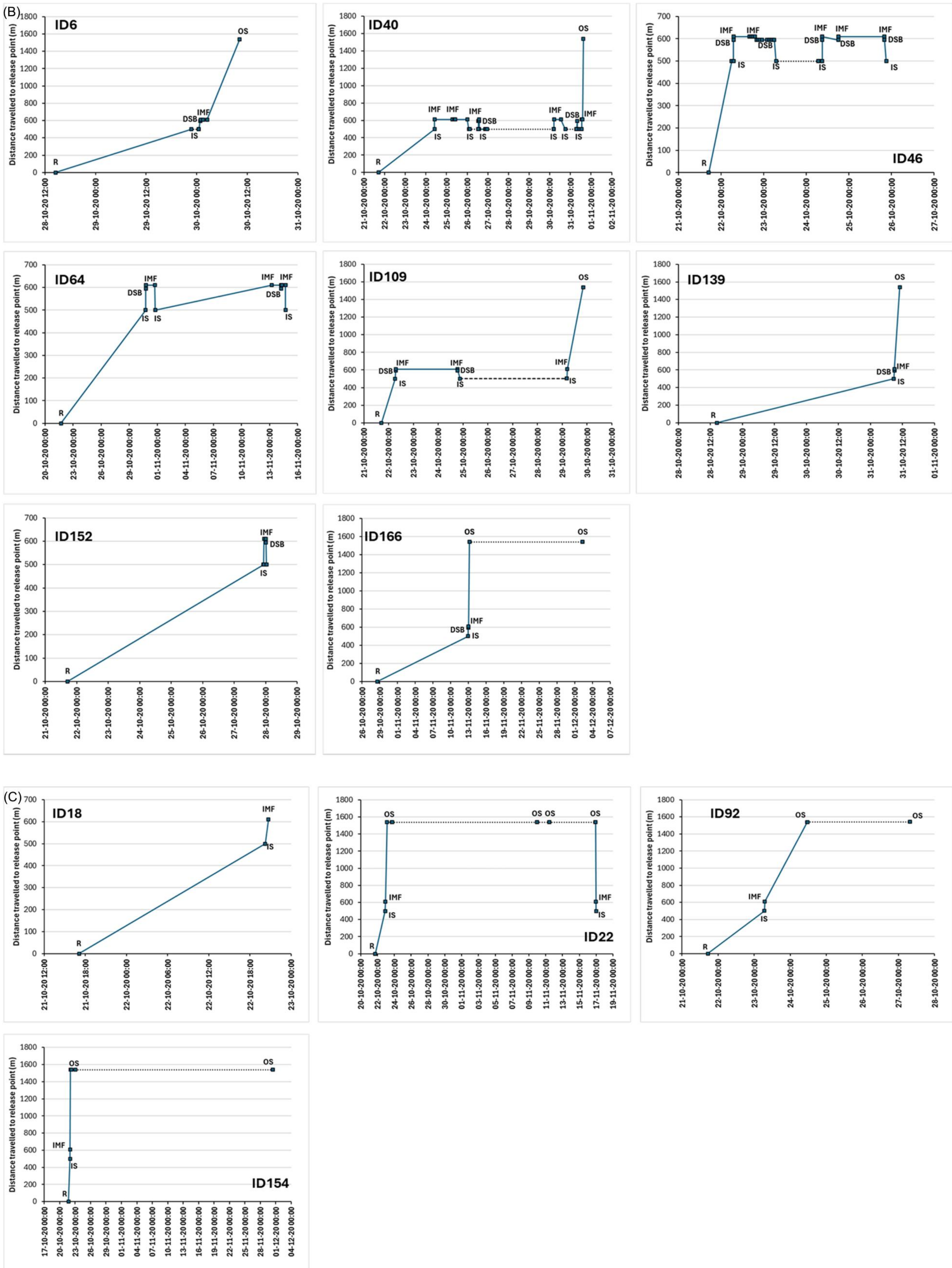

Figure 2. Continued.

4. Discussion

4.1. Assessment of mobility patterns

The movement ecology of fish by telemetry represents an emerging discipline crucial for the conservation and management of aquatic resources (Cooke et al. 2022). In our case, for a medium-sized river system, radio telemetry remains an optimal technique for studying fish behaviour (Radinger et al. 2019; Cooke et al. 2022). The radio telemetry

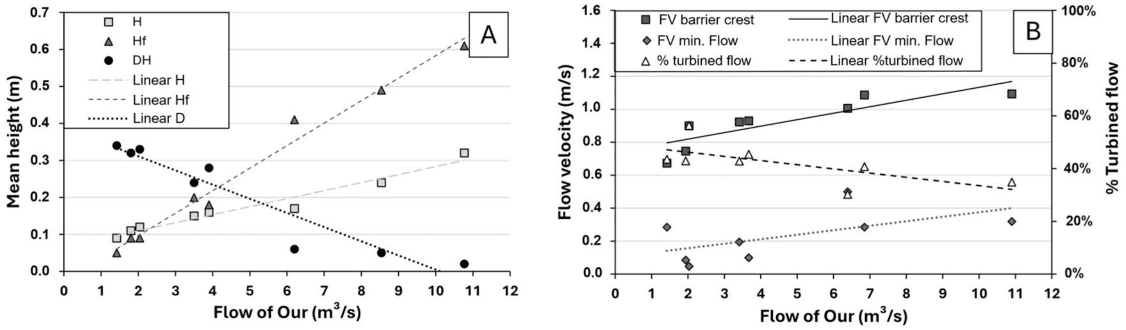

Figure 3. Relationship between the flow of the our River (m^3/s) and hydromorphological measurements (H, Hf, DH in metre) at the submerged barrier [A] or flow velocity (FV) and the percentage of turbined flow [B].

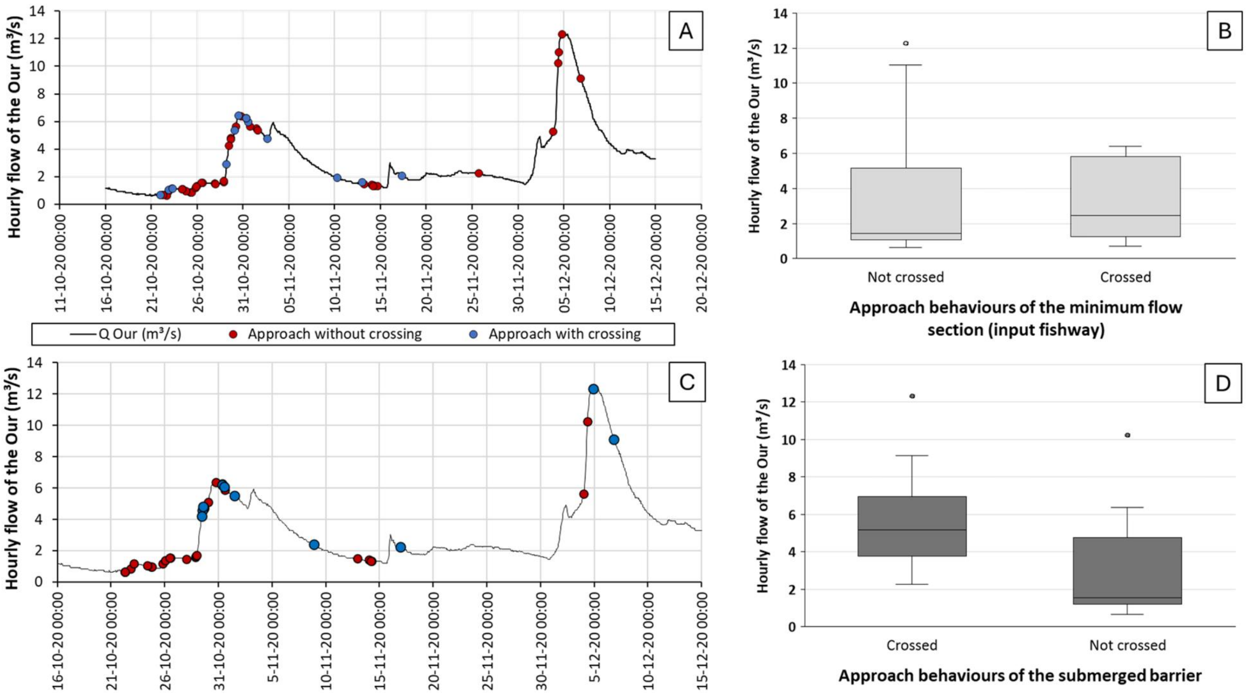

Figure 4. Approach behaviour at the minimum flow section, the fishway entrance (A), and the submerged barrier (C) as a function of the our River flow, with differentiation between individuals that successfully crossed (blue) and those that did not (red). Comparative flow conditions encountered during approaches to the fishway entrance (B) and the submerged barrier (D) are also presented.

Table 3. Results of best logistic models for the successful crossing of the submerged barrier and the fishway during the study period including coefficient estimates (β) for each variable together with standard errors (*SE*), odds ratios ($e\beta$), significance of the wald test (*p*) for each variable selected and the value of AIC. AUC and pseudo-R^2 statistics indicate the goodness-of-fit.

Tested device	Coefficient	β	SE	$e\beta$	p
Submerged barrier					
	Intercept	−27.21	0.81	−3.38	<0.001***
	River flow	0.39	0.16	2.46	0.013*
	AIC				*41.46*
	AUC				*0.81*
	Pseudo-R^2				*0.18*
Fishway					
	Intercept	−0.89	0.40	−2.26	0.024*
	Crossing the barrier	−10.99	0.73	−1.50	0.133
	AIC				*59.7*
	AUC				*0.62*
	Pseudo-R^2				*0.04*

detection system at the Weweler-Mühle site on the Our River was effective and provided coherent detection data that could be translated into movement profiles. The behaviour observed in trout was consistent with natural patterns during the spawning period in autumn (Ovidio et al. 2002) with a last detection on 7 December, showing a dual impulse for upstream migration: translocation/homing and spawning migration (Ovidio et al. 2017). The detection rate of tagged fish was relatively high (67%), with one-third of marked individuals (33%) not detected within the study area. Of these ten undetected individuals, 80% had been captured in the Ulf River before tagging. However, no biometric or tagging variables (such as tag weight/fish weight ratio) seemed to distinguish these undetected fish from those that were successfully tracked. Several hypotheses can explain the non-detections. It is possible that fish captured upstream of Weweler-Mühle experienced altered migratory behaviour due to the tagging procedure (Ovidio et al. 2020), although such behavioural alterations are rarely documented in other tagging studies. A previous successful passage through the fishway or early maturity in certain individuals may also have reduced their motivation to migrate. Predatory mortality on tagged individuals should not be excluded. The methodology used in this study was identical to that of previous mobile tracking studies, in which no mortality or aberrant behaviours linked to post-tagging mortality were observed (Ovidio et al. 2020; Renardy et al. 2020; Gelder et al. 2024). The study period only represents a few months of life for the individuals monitored due to the constraints of monitoring in the natural environment (budget, type of transmitter). Indeed, a long-term study would show more crossing behaviour at other times of the year. Nevertheless, the focus on the reproductive migration period represents the key movement in the trout life cycle (Ovidio et al. 2002).

4.2. Dissuasive effect of the behavioural barrier on upstream migration

In the context of restoring fish migration, the impact of obstacles is typically assessed to quantify fish passability (Ovidio and Philippart 2002; Branco et al. 2017). Behavioural barriers, generally used during downstream migration (Beck et al. 2020), induce avoidance behaviours to mitigate the impact of structures that induce damage to fish (e.g. turbines, pumping systems) (Stoilova 2024; Sonny et al. 2025), or to guide them towards safe passage routes (Coutant and Whitney 2000). However, the application of behavioural barriers during upstream movements remains largely unexplored. This study aimed to assess the deterrent effect of a concrete submerged barrier positioned at the entrance of a non-viable route, with the aim of diverting fish towards a safer upstream route. The adjusted attractiveness of this barrier was 80% of fish detected in the system (trout in categories 1 and 2 of mobility patterns). These results illustrate the strong attraction that an HPP output channel can exert, likely due to its higher flow velocities, its spatial positioning, and the proportion of discharge through it—all of which are factors known to attract fish (Silva et al. 2018). This migration route appears particularly attractive for fish that have an impulsion to move upstream for spawning. The installation of fishways should optimise passage through preferred routes while minimising time and exposure in unfavourable ones to enhance survival and reproductive success (Silva et al. 2018). The implementation of a behavioural barrier to redirect fish to a safer upstream route is therefore of considerable ecological interest.

During the study period, 50% of trout detected at DSB antenna successfully crossed the submerged barrier, with detections recorded 150 m upstream, near the turbines. No biometric or temporal indicators explained the success of these attempts. Indeed, our selected model to explain the success of crossing the behavioural barrier is based solely on river flow. It demonstrated good discriminatory power (AUC = 0.81) and a reasonable goodness of fit (Pseudo-R^2 = 0.18) (Fielding and Bell 1997; Menard 2001). However, the model results do not fully explain the success of the transition, which certainly illustrates a lack of crossing data and the intervention of other unmeasured factors. Flows exceeding 2.25 m^3/s, which were regularly observed upstream of the Weweler-Mühle weir, significantly increased fish passage by reducing the water level drop (Dh) below 30 cm, as evaluated by the relation between river flow and hydrodynamic measures. This threshold flow rate aligns with previous studies (e.g. Baudoin et al. 2015), which emphasize that moderate hydraulic conditions are crucial for enhancing the passage of small- to medium-sized fish across barriers, particularly for the brown trout (Ovidio and Philippart 2002). Above 10 m^3/s, the estimated turbined flow ratio would fall to 50%, which could explain the greater attraction of the minimum flow near the fishway. This finding confirms that attraction and crossing conditions are favourable for the non-viable route at an intermediate flow range between low and high flows. This incorrect choice of migration route leads to a delay in upstream migration during spawning period and a reduction in the probability of reaching spawning sites *via* the fishway. The emphasis on the autumn spawning migration of trout requires an assessment of fish behaviour under higher flow conditions, unlike in spring and summer. Indeed, to a lesser extent, trout also migrate upstream during spring (Ovidio et al. 1998; Benitez et al. 2015), when flow levels are generally lower, which is likely to reinforce the dissuasive effect of the behavioural barrier.

The proportion of fish that avoided using the outlet channel was 60%, suggesting the behavioural barrier had a dissuasive effect on studied fish. This is particularly relevant as fish that successfully crossed the behavioural barrier may spend several hours in the output channel, further exacerbating delays in the migratory process. The response to fragmentation and therefore to an obstacle is very species-specific, with size playing a key role (Blanchet et al. 2010), as well as jumping capacity (Baudoin et al. 2015). Among the species present in the Our River, the biological model (i.e. the brown trout) represents the species with the best swimming and jumping abilities (Ovidio et al. 2007), and therefore the best ability to pass through the submerged barrier. In addition, the observed flow velocities (between 0.1 and 1.2 m/s) remained well below the maximum sprint capabilities reported for brown trout (Baudoin et al. 2015) and thus constituted favourable conditions for passage. This observation would have a greater deterrent effect on other species present in the river.

4.3. Restoration of free movement

The adjusted attractiveness of the fishway is high, with 95% of the fish in the system being detected at the IMF antenna. However, competition with the submerged barrier is strong, with 55% of the fish presenting themselves first at the submerged barrier, which confirms the existence of a choice between two potential migration routes, one of which is a non-viable route. The overall efficiency of the fishway is 37%. This value is well below the target of 90–100% set by (Lucas and Baras 2001). However, this variable is based on all released fish, some of which did not move upstream. This alteration in migratory behaviour can be compensated for by using the adjusted efficiency, which considers only fish expressing upstream behaviour detected at the entrance to the fishway (Ovidio et al. 2017) and is therefore more representative of the fishway's efficiency. This variable reaches a value of 55%, which corresponds to an average efficiency value compared to other efficiency measures (Noonan et al. 2012; Ovidio et al. 2023). However, 900 m of the river has minimum flow conditions that need to be covered before reaching the effective entrance to the fishway, and there are certainly potential breeding habitat areas on this stretch. In fact, according to the migratory profiles of the trout, it was found that some trout had decided to stay in this section of the minimum flow section. This observation is due to the probability of having habitats suitable for trout life cycles, so it is important to maintain a sufficient minimum flow in order to offer a maximum number of available habitats (Gibson et al. 2005; Moreira et al. 2019). The influence of the minimum flow rate of 900 m is also evident in the relatively long crossing time of the fishway, with a median value of 43 h. This time illustrates a slowed transit of trout compared to other observations (Ovidio et al. 2023, 2017) and suggests that the fishway is only partially effective (Silva et al. 2018). In terms of the influence of the Our River's flow on the fishway's efficiency, the model selected to explain the success of crossing the fishway, did not consider flow rate as a determinant factor for successful fish passage. Although the passage data from the fishway did not allow a robust model to be defined, the lack of consideration of flow would indicate that the fishway is continuously passable at all flows and all times (Benitez et al. 2015).

In contrast to flow rate, the optimal model for predicting fish passage through the fishway included only the binary variable indicating prior passage through the submerged barrier, with previous passage negatively affecting the likelihood of successful crossing. However, this variable was not significant, and the model showed poor goodness of fit, with a pseudo-R^2 value of 0.04. These results indicate that success is likely influenced by other external factors. Finally, some downstream behaviour in search of a migration route for breeding habitats was frequent during the study, as already observed for other species and these behaviours could illustrate a lack of efficiency in the systems put in place (Ovidio et al. 2016; Gelder et al. 2024). Indeed, fish naturally migrate upstream to reproduce (Benitez et al. 2015). Choosing a downstream habitat is therefore a suboptimal choice that could reduce genetic exchange (Silva et al. 2018).

5. Conclusion

This study shows that the dissuasive effect of a submerged barrier installed on the Our River at the Weweler-Mühle site is sufficient for 50% of the trout monitored during their breeding period and detected at the submerged barrier. Nevertheless, long-term studies are essential for understanding the real impacts in the environment with climate change and human disturbances (Matley et al. 2022). Although the output channel of the HPP shows a highly competitive attractiveness (first approach rate = 55%; adjusted attractiveness = 80%) compared to the main river section leading to the fishway, 60% of the individuals detected in the study system used the fishway as a migration route without entering the output channel. Therefore, it is essential to ensure a sufficient flow within the minimum flow in order to increase the attractiveness of this section and at the same time maintain sufficient habitat availability for the fish (Lamouroux et al. 2015). Although the dissuasive effect is not total, the installation of a fixed submerged barrier like the one installed at the Weweler-Mühle site appears to be a satisfactory option for meeting this objective, bearing in mind that the intrinsic constraints of the site have limited the height of the structure. This solution is potentially transferable to other sites in similar contexts. However, reducing the attractiveness of the turbined flow by managing the ratio of turbined flow to available flow and reducing the obstacle's passability by optimising the design (e.g. increasing H) could improve the dissuasive effect of this type of behavioural barrier. Finally, the biological model (i.e. the brown trout) represents the species with the best swimming and jumping abilities, and therefore the best ability to pass through the submerged barrier. Conversely, for the fishway, the crossing results could be worse for species with poorer swimming abilities.

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