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ORIGINAL PAPER

Evaluation of the performance of successive multispecies improved fishways to reconnect a rehabilitated river

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Abstract The equipping of barriers with fishways has useful applications for testing hypotheses of fish migration and connectivity in river networks, but multiple passage performance for potamodromous fish is poorly known to date. The aim of this study was to analyse the performance of new fishways installed in the river Vesdre (Belgium). Thirty-eight barbel (*Barbus barbus*; mean: 508 mm, 2133 g) and seven chub (*Squalius cephalus*; mean: 372 mm, 935 g) were captured by electric fishing and fish pass monitoring and were equipped by RFID-tags and/or radio-transmitters. They were translocated downstream of three different fishways (nature-like pool-type, block ramp, and technical pool-type) in the lower course of the Vesdre. Detection antennas connected to automatic receivers were placed downstream and upstream of each fishway to evaluate the approaching rate, the overall and adjusted passage efficiencies, the passage delays, temperature, dates and time period. The best passage performance and passage delays were observed for the block ramp fishway (88%; 9 h median time to pass) in comparison with pool structures (47 and 73%; 94 and 144 h median time to pass, respectively). The overall passage efficiency was 18.2 and 29.4% for two successive fishways, and 18.2% for three fishways. Passages occurred mainly during dark periods at median temperatures of 14 °C (barbel) and 12.3 °C (chub), and during highly variable flow conditions. This study provided evidence of the success rate of the reestablishment of the ecological continuity in the river Vesdre as a result of the construction of improved fish-passage structures.

Keywords River connectivity · Fishway performance · Fish telemetry · Potamodromous fish

Introduction

Rivers are considered as the quintessence of connectivity (Wiens 2002), corresponding to the extent to which a species or population can move among landscape elements in a mosaic of habitat types (Hilty et al. 2012). Longitudinal connectivity, in particular, is a critical factor influencing species distribution and viability and therefore structures spatial and temporal

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patterns in the composition of river biota (Rolls et al. 2013).

Few freshwater species complete their entire life cycle from birth to reproduction and death in a single patch of habitat (Lake and Bond Reich 2007). Potamodromous freshwater fish must disperse or migrate throughout the year to access breeding, feeding, and refuge habitats, and to complete their life cycle (Benitez et al. 2015). Spawning activity is one of the most common motivators for long-distance migration, but other movements may occur outside the spawning period for ontogenetic and trophic reasons (Lucas and Baras 2001; Sonny et al. 2006; Nunn and Cowx 2012; Benitez et al. 2015, 2018). Physical barriers represent one of the largest anthropogenic impacts on river ecosystems, affecting species' habitats and habitat connectivity on multiple spatial and temporal scales, leading to reduced distribution or population isolation (Ovidio and Philippart 2002; Geeraerts et al., 2007; Rolls et al. 2013; Fuller et al. 2015) with consequences of major reductions, or even the extinction, of fish species in different river basins (Fullerton et al. 2010).

When rivers are rehabilitated in terms of physical habitat quality, and biological and physicochemical water quality, the longitudinal reconnection would be another major step in the river restoration program (Bernhardt and Palmer 2007; Fullerton et al. 2010; Tummers et al. 2016). Correspondingly, the continuity of rivers constitutes an indispensable element for the assessment of river water bodies according to the European Water Framework Directive (EU-WFD) (Reyjol et al. 2014). In this context, fish assume a major indicator function based on their life cycle, complex species- and stage-specific movement patterns, as well as on their distinct habitat requirements (Jungwirth et al. 2000).

Barriers reduce watershed longitudinal connectivity and when their removal is not possible, the use of different fishway models represents a measure for countering the inaccessibility of functional habitats and to increase the ecological connectivity of rivers (Silva et al. 2012). The reestablishment of the longitudinal connectivity with fishways will enhance biodiversity by facilitating metapopulation processes and restore gene flow among populations (Lake and Bond Reich 2007; Pelicice and Agostinho 2008). Former fishways were mostly adapted for diadromous migratory fish species. However, in the past decade, efforts have been made to design new fishways that could be used by a wider variety of fish species. These multispecies and multistage characteristics imply that the fishways must be efficient throughout the seasons for species with various swimming and leaping capacities, as well as different motivational states for migration. However, it is thus critical to improve the design of the fishway and to collect standardized performance data from a wide range of structure type, in a wide variety of rivers and regions to find successful and more integrative solutions for the future (Ovidio et al. 2017).

Relatively little is known about the effect of restoration of extended longitudinal corridors for riverine fishes (but see Tummers et al. 2016). The use of individual tagging and further detection by telemetry devices (e.g. Radio Frequency Identification [RFID], radio telemetry) make it possible to measure individual behaviour of fishes (Lucas and Baras 2001; Lennox et al. 2017) and the passage performance associated to fishways (Ovidio et al. 2017). Studies on the successive uses and performance of fishways are scarce, mainly monospecific, and have essentially focused on diadromous species (Gowans et al. 2003; Calles and Greenberg 2005; Lucas et al. 2009; Castro-Santos et al. 2017) and rarely on potamodromous species (but see: De Leeuw and Winter 2008; Tummers et al. 2016; Benitez et al. 2018). Analyses of successive and cumulative performance of fishways are however essential to better apprehend the reestablishment of longitudinal corridors at a scale which is more in alignment with the biological requirements of fish.

In Belgium, most of the rivers were highly degraded by a wide variety of anthropogenic pressures since the mid-eighteenth century. Due to recent environmental awareness and in order to implement European and Benelux Directives and/or Recommendations, river restoration, which is defined as the process of returning a river section to a near-natural state (Woolsey et al. 2007) has become a priority for water authorities and river managers, as in many other European countries. Before the eighteenth century, the River Vesdre was a highly prolific river with important populations of rheophilic species, including Atlantic salmon, sea trout and European eel. Until the end of the nineteenth century, the river was fragmented and highly polluted due to the development of wool industries. The fish population drastically shifted as a result, to the extent that it was finally composed of resilient, ubiquitous species with poor ecological exigences. In the beginning of the year 2000, important efforts have been done to improve the water quality through the construction of new wastewater treatment plants, and the restoration of some functional habitats. Recolonization of fish species that are highly sensitive to water quality and habitat is still however difficult due to the presence of physical barriers in the lower course of the river. In early 2000, a plan to restore of the longitudinal connectivity was established, and new multi-specific fishways were progressively constructed.

We sought to characterize the cumulative passage performance of fishways. We use RFID and radio telemetry detection systems applied to rheophilic cyprinid species, the European barbel (*Barbus barbus*) and the chub (*Squalius cephalus*) as biological models. These species are known to move long distances between functional habitats (Baras 1995; Fredrich et al. 2003; Ovidio et al. 2007) in undisturbed sites. We analyze (1) the single and cumulative passage efficiency of the new fishways (2) the environmental variables (flow, temperature) associated to passage success and (3) the delay necessary to pass the fishways. We interpret the results in terms of potential of recolonization of the rehabilitated River Vesdre by these patrimonial rheophilic fish species.

Materials and methods

The studied fishways are situated in the lower course of the River Vesdre; a tributary of the River Ourthe in Belgium. The Vesdre is a gravel-bed river with a median inter-annual flow of 11.4 m^3/s and a 702 km^2 drainage basin (Fig. 1). The Vesdre is 72 km long, and its source is situated at 626 m above sea level, with a mean slope of 7.8‰ (Fig. 1). The mean annual water temperature is 11.1 °C, with a minimum mean monthly temperature in January (5.1 °C) and maximum in July (17.4 °C). The main course of the Vesdre is fragmented by twenty-seven several artificial barriers and one reservoir dam. In the entire river, the physicochemical parameters and prevailing macroinvertebrate communities are currently indicative of good water quality (Public Service of Wallonia—AQUABIO).

Up to 22 native fish species are potentially present in the Vesdre basin, including the diadromous European eel (*Anguilla anguilla*), the restocked Atlantic salmon (*Salmo salar*), and potamodromous fish species representative of river in good ecological conditions such as the brown trout (*Salmo trutta*), the European grayling (*Thymallus thymallus*), the European barbel, the nase *(Chondrostoma nasus*), the chub, and the dace (*Leuciscus leucisus*). The study area is located in a mixed barbel/grayling zone (Huet 1949) on the lower course of the river. The barbel and the chub were considered as biological models for this study because they are exigent and considered as priority species in terms of restoration for ecological continuity and potential colonisation from the Ourthe River, and are known to have very poor clearing capacities of obstacles during their spawning migration (Ovidio and Philippart 2002; Baudoin et al. 2015). They mainly realize their spawning migration between April and June in Belgium (Benitez et al., 2015).

The three investigated fishways (FW1: nature-like pool-type, FW2: block ramp, FW3: technical pool-type) were recently constructed (between 2014 and 2016), and though they were designed to be adapted for a wide diversity of fish species, their typologies and configurations are quite different (Fig. 1; Table 1). FW1 is the first physical obstacle encountered by fish entering the Vesdre, located 0.9 km from the Ourthe. FW2 is situated 2.3 km from FW1, and FW3 another 1.8 km upstream from FW2. Two obstacles not yet equipped with fishways are situated between FW1 and FW2 (obstacle IW1, height 1.7 m; Fig. 1) and between FW2 and FW3 (obstacle IW2, height 1.6 m; Fig. 1).

In order to encourage the fish to move upstream in the Vesdre by homing and/or spawning upstream, we decided to carry out intra- and inter-river translocations and to tag the fish before their spawning season. Two electric fishing samplings (walking in the river by sampling effort with a Generator EFKO FEG 5000 model placed in a boat) were performed upstream of three studied weirs in the Vesdre on 17th April and 3rd May 2018, where n = 33 barbel, and n = 4 chub were captured (Fig. 1; Table 2). On 24 April 2018, n = 5 barbel and n = 3 chub were captured in a fish pass between the Meuse and Ourthe Rivers (location C3 in Fig. 1), providing a total of n = 45 individual fish from the two species for the study.

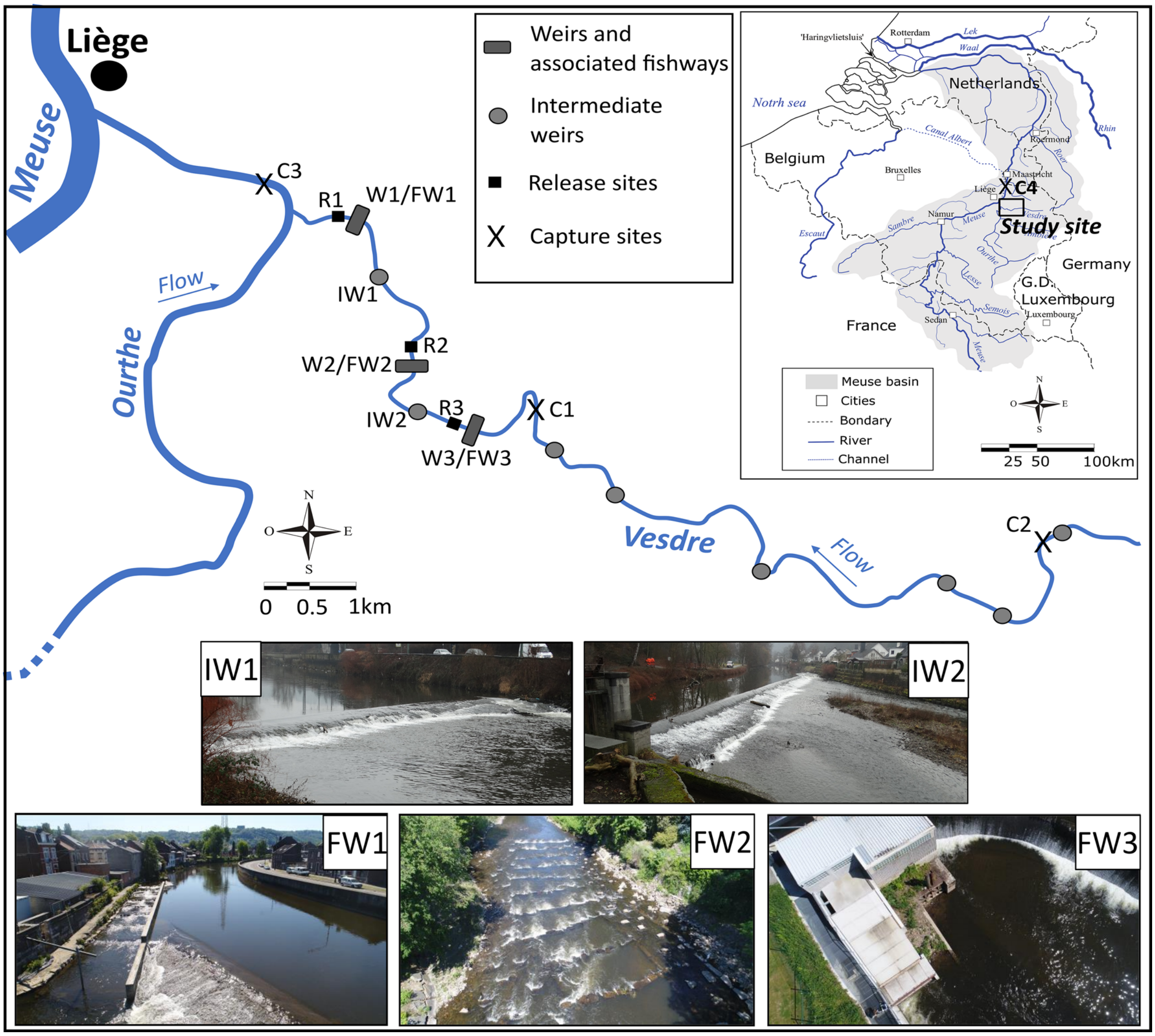

Fig. 1 Map of the study area in the river Meuse basin in Belgium, with the locations of the three studied fishways, the intermediate obstacles, the capture sites and the release sites. Photographic representations of the fishways and the intermediate obstacles are also presented (*Fw* fishway, *D* dam associated with fishway, *IW* intermediate weir, *C* capture site, *R* release site)

A total of 14 fish (n = 12 barbel, n = 2 chub) were double-tagged with an RFID transponder (23 mm, 0.8 g), and a radio transmitter (Sigma Eight®, Pisces 26 mm, 4.5 g, 310 mm antenna, 150 MHz, pulse rate 1.5 s). A total of 26 fish (n = 21 barbel, n = 5 chub) were single-tagged with a radio-transmitter. Finally, a total of five fish (n = 4 barbel, n = 1 chub) were single-tagged with an RFID transponder (Table 2). The fish were surgically tagged following the procedure described by Ovidio et al. (2017) and Benitez et al. (2018).

The captured fish were translocated the same day as the tagging to three different sites (R1, R2, R3; Fig. 1) downstream of the weirs FW1 (n = 11), FW2 (n = 17), and FW3 (n = 17) (Table 2). RFID and/or radio antennas were placed in order to analyse the passage performance of the tagged fish. At FW1, an aerial radio antenna (A0) was placed near the entrance of the fish pass on the right bank and one RFID antenna (A1) was placed in the upstream part of the fish pass between the seventh and eighth basin to confirm the fish passage. At FW2, two aerial radio antennas were

Table 1 Typological characteristics of the three studied fishways

Characteristics	FW1	FW2	FW3
Height of dam (m)	1.4	1.7	4.4
Fishway type	Nature-like pool-type	Block ramp	Technical pool-type
Construction year	2014	2015	2016
Length (m)	52	75	35
Width (m)	4.5	30	3.2
Discharge (m^3)	0.3 $m^3 s^{-1}$	River discharge	0.5 $m^3 s^{-1}$
Range Dissipated Energy (Wm^3)	97–147	87–200	150
Pool length (m)	2.8	10	3.3
Pool width (m)	1.8	4.6	1.6
Number of pools	9	12	8
Height between pools (m)	0.13	0.13	0.2

placed; one (A0) 50 m downstream of the fish pass entrance, and the other (A1) 300 m upstream of the fish pass to confirm the fish passage. The directions and the distance interval of these antennas have been selected to avoid any detection range overlapping. At FW3, one aerial radio antenna (A0) was placed downstream of the pass to detect fish approaching the weir, and another (A1) was placed 80 m upstream of the weir to confirm the fish passage.

The data from the radio and RFID antenna enabled definition of four passage metrics (Dam approaching rate; Overall passage efficiency; Adjusted passage efficiency; Passage delay) that could be quantified in order to determine fish behaviour in relation to the fishway attractiveness and performance (Table 3).

The water temperature (°C) of the Vesdre was recorded at the position of FW3 (Hobo Data Logger Onset, hourly measures, precision 0.1 °C) and the water flow data (m^3/s; hourly measures) was recorded in the Vesdre in Chaudfontaine using automatic and calibrated level meter (Aqualim, SPW).

A Chi square test was used to compare proportions of passage efficiencies between fishways and to test if the repartition of passage time during dark or light period was different from a theoretical population. As data of flow and temperature conditions during passage and passage delays violated normality assumptions (Kolmogorov–Smirnov, $p < 0.05$), non-parametric tests were used. Kruskal–Wallis and Wilcoxon tests were used to test differences between flow conditions during passage as well as differences between passage delays of the three fishways. The level of significance was set at 0.05 and tests were carried out using the R statistical program (The R Foundation for Statistical Computing, Vienna, Austria, version 3.1.1.).

Results

During the study period (17 April–3 May 2018), the mean flow of the Vesdre was 8.5 m^3/s and varied between 4.9 m^3/s (28 April 2018) and 36.6 m^3/s (30 April 2018) and the mean water temperature was 13.2 °C and exceed 14 °C only between 19 and 23 April 2018. The $n = 40$ studied fish survived after tagging and $n = 38$ were detected by at least one of the antennas of the detection systems at the studied fishways (FW1 to FW3), representing a detection rate of 95%. Of the five fish tagged with RFID, three were detected by the RFID antenna place at W1, representing a detection rate of 60%.

The dam approaching rate was high and reached mean values of 82 (FW1) to 100% (FW2). The overall passage efficiency was highest for FW2 with 100 and 86% for chub and barbel, respectively. FW1 and FW3 were not passed by the chub, but barbel reached 73 and 47% of overall passage efficiencies, respectively (Table 4). The proportion of passages are differently distributed between FW1 and FW2 (Chi square test: df1, $p < 0.05$), and FW2 and FW3 (Chi square test:

Table 2 Biometric characteristics, as well as capture dates and sites of the fish tagged for this study

Species	LF (mm)	Weight (g)	Sex	Tag	Capture-release site and date
Barbel	642	3784	F	Radio	C1-R2/17 April 2018
Barbel	642	4123	F	Radio	C1-R2/17 April 2018
Barbel	444	1215	M	Radio	C1-R2/17 April 2018
Barbel	464	1781	F	Radio	C1-R2/17 April 2018
Barbel	597	3263	F	Radio	C1-R2/17 April 2018
Barbel	459	1511	F	Radio	C1-R2/17 April 2018
Barbel	526	2245	F	Radio	C1-R2/17 April 2018
Barbel	465	1568	–	Radio	C1-R2/17 April 2018
Barbel	419	1111	–	Radio	C1-R2/17 April 2018
Chub	248	206	–	Radio	C1-R2/17 April 2018
Barbel	493	1766	–	Radio	C1-R3/17 April 2018
Barbel	571	3177	F	Radio	C1-R3/17 April 2018
Barbel	484	1618	–	Radio	C1-R3/17 April 2018
Barbel	582	3425	F	Radio	C1-R3/17 April 2018
Barbel	470	1700	F	Radio	C1-R3/17 April 2018
Barbel	379	828	–	Radio	C1-R3/17 April 2018
Barbel	392	836	–	Radio	C1-R3/17 April 2018
Barbel	458	1450	–	Radio	C1-R3/17 April 2018
Barbel	370	695	–	Radio	C1-R3/17 April 2018
Chub	554	554	–	Radio	C1-R3/17 April 2018
Chub	352	684	–	Radio	C4-R1/24 April 2018
Barbel	564	2340	F	Radio	C3-R1/23 April 2018
Barbel	557	2341	F	RFID	C3-R1/23 April 2018
Barbel	585	3816	F	RFID	C4-R1/24 April 2018
Chub	341	752	M	Radio	C4-R2/24 April 2018
Barbel	552	2219	F	Radio	C3-R2/23 April 2018
Chub	402	992	F	Radio	C4-R3/24 April 2018
Barbel	562	2670	F	Radio	C3-R3/23 April 2018
Barbel	465	1452	F	Radio-RFID	C2-R3/3 Mai 2018
Barbel	387	764	F	Radio-RFID	C2-R3/3 Mai 2018
Barbel	497	1780	F	Radio-RFID	C2-R3/3 Mai 2018
Barbel	556	2610	F	Radio-RFID	C2-R3/3 Mai 2018
Chub	462	1680	F	Radio-RFID	C2-R3/3 Mai 2018
Barbel	517	2140	–	Radio-RFID	C2-R2/3 Mai 2018
Barbel	434	1224	F	Radio-RFID	C2-R2/3 Mai 2018
Barbel	419	1138	M	Radio-RFID	C2-R2/3 Mai 2018
Barbel	578	3200	F	Radio-RFID	C2-R2/3 Mai 2018
Chub	462	1680	F	Radio-RFID	C2-R2/3 Mai 2018
Barbel	380	774	M	Radio-RFID	C2-R1/3 Mai 2018
Barbel	391	971	M	Radio-RFID	C2-R1/3 Mai 2018
Barbel	474	170	F	Radio-RFID	C2-R1/3 Mai 2018
Barbel	611	3408	F	Radio-RFID	C2-R1/3 Mai 2018
Barbel	608	3306	F	RFID	C2-R1/3 Mai 2018
Barbel	577	3288	–	RFID	C2-R1/3 Mai 2018
Barbel	575	3804	–	RFID	C2-R1/3 Mai 2018

Table 3 Definitions of the behavioural metrics used in the study

Behavioural metrics	Definitions
Dam approaching rate	Percentage of radio-tagged individuals that were detected by A0 after being released in the river
Overall passage efficiency	Percentage of individual fish that made a fishway passage compared with those released downstream
Adjusted passage efficiency	Percentage of individual fish that made a fishway passage compared with the amount detected at A0
Passage delay	Time (in hours) between the release date and the passage of the fish pass (last detection in A1)

Table 4 Performance of passage at the scale of a single for multiple fishway

Behavioural metrics	Species	Single fishways passage		
		FW1	FW2	FW3
Dam approaching rate	Barbel	90% (9/10)	100% (14/14)	100% (14/14)
	Chub	0% (0/1)	100% (3/3)	33% (1/3)
	Mean	82% (9/11)	100% (17/17)	88% (15/17)
Overall passage efficiency	Barbel	80% (8/10)	86% (12/14)	57,1% (8/14)
	Chub	0% (0/1)	100% (3/3)	0% (0/3)
	Mean	73% (8/11)	88% (15/17)	47% (8/17)
Adjusted passage efficiency	Barbel	89% (8/9)	86% (12/14)	57,1% (8/14)
	Chub	–	100% (3/3)	0% (0/1)
	Mean	89% (8/9)	88% (15/17)	53% (8/15)

Behavioural metric	Species	Multiple fishways passage		
		FW1–FW2	FW2–FW3	FW1–FW2–FW3
Overall passage efficiency	Barbel	20% (2/10)	28.5% (4/14)	20% (2/10)
	Chub	0% (0/1)	33.3% (1/3)	0% (0/1)
	Barbel + chub	18.2% (2/11)	29.4% (5/17)	18.2% (2/11)

df1, $p < 0.05$). The mean adjusted passage efficiency varied from 53 (FW3) to 89% (FW1).

The overall passage efficiency was on average 18.2% for the successive passage of FW1 and FW2, and 29.4% for the successive passage of FW2 and FW3 (Table 4). The mean overall passage efficiency for the successive passage of FW1, FW2 and FW3 was 18.2%. The distribution of the proportion of passage is differently distributed between the combined passage of FW1–FW2 and FW2–FW3 (Chi square test: df1, $p < 0,05$).

Passage took place at a median temperature of 14.0 °C (min 8.9 °C, max 15.2 °C) for barbel, and 12.3 °C (min 10.4 °C, max 13.6 °C) for chub. The passage mainly occurred during crepuscular and dark periods for the barbel, and during the daytime and crepuscular periods for the chub (Fig. 2). The repartition of passage time for barbel and chub combined is significantly different from a theoretical reparation (Chi square test: df1, $p < 0.001$), indicating a preference for dark conditions. The passage of fish at fishways (Fig. 3) took place under flow conditions measured between 31.4 and 94.6% (mean = 50.6%), corresponding to flow values between 5.1 and 29.1 m^3/s (mean = 8.4 m^3/s). The passage water flows were significantly different between fishways (Kruskal–Wallis: $H = 12.9$; $p = 0.001$); they were significantly higher for FW1 (mean = 12.8 m^3/s) compared to FW2 (mean = 7.0 m^3/s) and FW3 (mean = 7.1 m^3/s) (Wilcoxon: $p < 0.05$).

The median passage delay was 9 h for FW2, 94 h for FW3, and 144 h for FW1 and we observed significantly different passage delays between fishways (Kruskal–Wallis: $H = 6.059$; $p < 0.05$), with

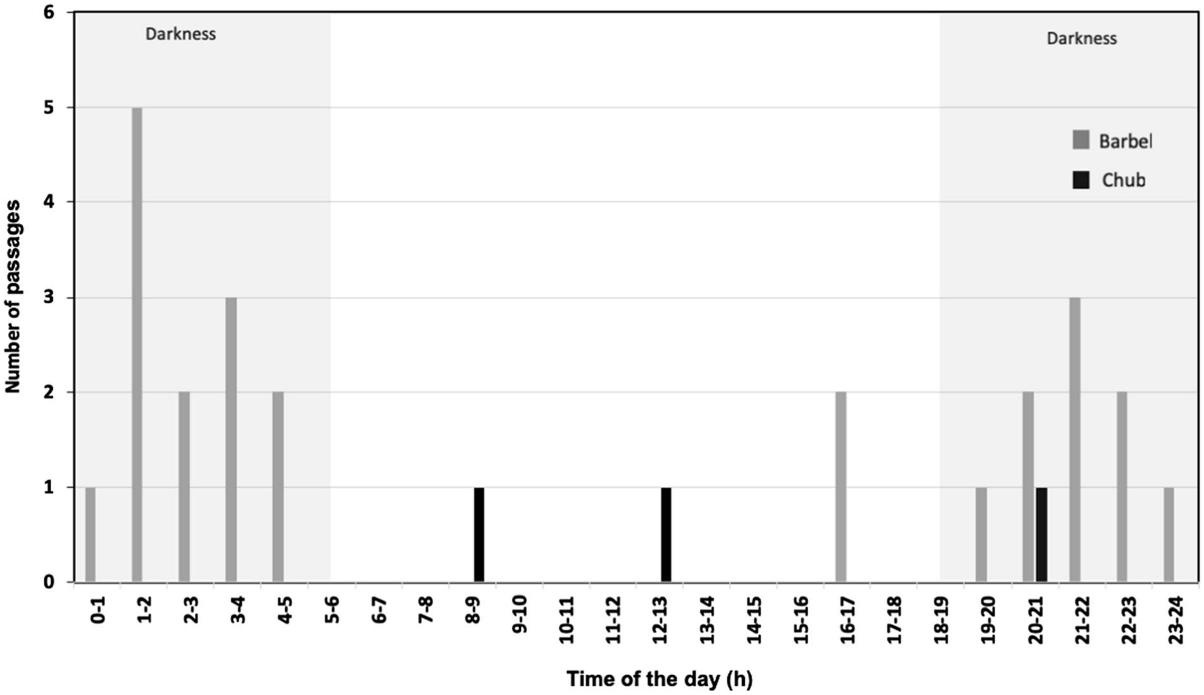

Fig. 2 Hourly passage time of fishways (FW1, FW2 and FW3) for chub and barbel

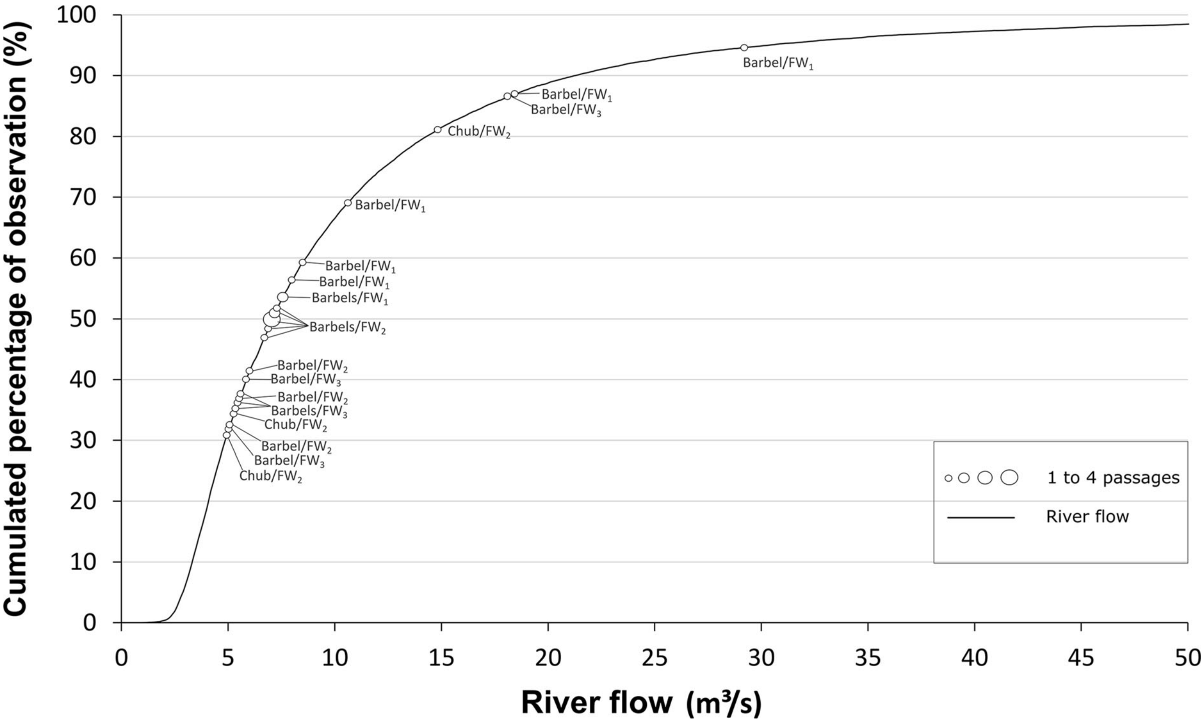

Fig. 3 Number of passages of the studied fishways in relation with the graded flow curve of the Vesdre for a period of 46 years (1972 to 2018)

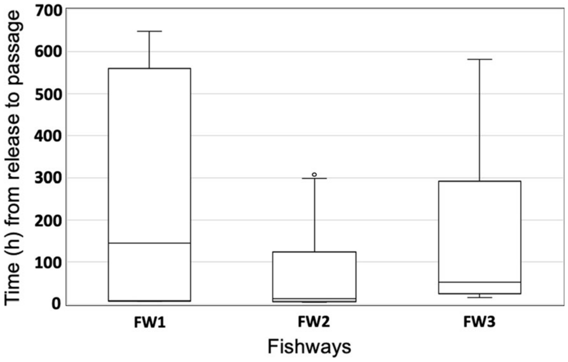

Fig. 4 Box-plot representation of the passage delay for FW1, FW2, and FW3

FW2 crossed the quickest (Fig. 4). The two barbels that succeeded to pass FW1, FW2, and FW3 successively took less than 48 h.

Discussion

This study provided evidence of the success rate of reestablishment of the ecological continuity in the River Vesdre, thanks to the construction of improved fish-passage structures adapted both for diadromous and potamodromous fish species. We used rheophilic cyprinids as biological models, because they are characterized by important requirements in terms of high-quality spawning and trophic habitats, but also because they are known to have limited clearing capacities of physical obstacles (Ovidio and Philippart 2002, 2008; Baudoin et al. 2015). Such species required well-designed and adapted fish-passage structures (Amaral et al. 2018). The utilisation of multiple fixed radio and RFID antennas was adequate to combine information on both approaching rate and passage efficiency for three successive fishways along a 4.1 km stretch of river. The choice to perform an intra-river translocation was successful as barbel and chub mostly moved upstream after being released downstream of the fishway, confirming the conservation of the inferred motivational state to migrate and making the evaluation of efficiency more accurate. Other authors used the technique of capturing fish at the top of fishways and subsequently evaluating re-ascension (Pont et al. 2009; Thiem et al. 2013; Harty et al. 2016). Our intra- and inter-river translocation method did not affect their spawning migration behaviour, as was already observed with the rheophilic cyprinid nase (Ovidio et al. 2016), the trout, and the grayling (Ovidio et al. 2017). It also has the advantage of avoiding habituation behaviour due to the recurrence of the passage and the associated possibility of learning, which may influence the ability of individuals to find the entrance of the fishway more rapidly.

When considering the evaluation of the restoration of the free movements of fish at a single site, by combining the two species, we obtained results of overall passage efficiencies of 47 (FW3), 73 (FW1), and 88% (FW2). The best result in terms of the proportion of passage was obtained for the block ramp fish pass (FW2) that has the advantage to occupy the entire width of the river and that functions with the total river flow, in comparison to more technical structures (FW1, FW3) with limited functioning flow. The passage efficiencies reported in this study are the best ever obtained in comparison with a variety of fishways at barriers for rheophilic and ubiquitous cyprinids in natural or laboratory conditions (Table 5). The performance observed also exceed almost all of those reported for the brown trout (Table 5) and are much higher than the means of efficiencies reported by Noonan et al. (2011) in a review of the world literature for migratory and non-migratory fish species (61.7% in mean for Salmonids and 21.1 for non-Salmonids). Passage performance estimation may be partly affected and underestimated by the capture, tagging, transport, and translocation of the fish that may alter their natural behaviour. Considering this possible bias, the achieved performance rates obtained in this study at the scale of a single fishway were quite acceptable. It seems evident that an ideal passage performance rate of 90% per site proposed as a target by Lucas and Baras (2001) is very challenging to reach, but maybe achievable in limited cases. When considering the clearing of two successive fishways, the overall efficiencies dropped and were evaluated at 18.2 (FW1–FW2) and 29.4% (FW2–FW3). Evaluation of two successive passage clearances is very scarce in the literature for potamodromous cyprinid species. Benitez et al. (2018) observed rates of 8.3 and 15.8% for two successive fishways in the Meuse (Belgium). Calles and Greenberg (2005) observed 50% of cumulative passage efficiency for two nature-like fishway in the River Eman is Sweden for brown trout (*Salmo trutta*). Finally, we observed that 18.2% of fish succeeded to pass three successive fishways over the

Table 5 Summary of passage efficiency for different types of fishways for potamodromous species (Brown trout-*Salmo trutta*; Barbel—*Barbus barbus*, Iberian Barbel-*Luciobarbus bocage*; Carpathian barbel—*Barbus carpathicus*; chub-*Squalius cephalus*; Iberian Chub-*Squalius pyrenaicus*; Nase-*Chondrostoma nasus*; Northen Straight Mouth Nase-*Pseudochondrostoma duriense*; Dace-*Leuciscus leuciscus*, and roach-*Rutilus rutilus*, as reported in the literature and in the present study

Fishway type	Brown trout	Species									Authors
		Barbel	Iberian Barbel	Carpathian Barbel	Chub	Iberian Chub	Nase	NSM Nase	Dace	Roach	
Nature like	–	89%	–	–	–	–	–	–	–	–	This study
	–	–	–	–	86%	–	–	–	–	50%	Calles and Greenberg (2007)
	91%	–	–	–	–	–	–	–	–	–	Calles and Greenberg (2005)
	55%	–	–	–	–	–	–	–	–	–	Aarestrup et al. (2003)
Block ramp	–	86%	–	–	100%	–	–	–	–	–	This study
	58%	–	–	10%	–	–	–	–	–	–	Plesinski et al. (2018)
	–	–	–	–	–	–	–	–	–	–	Weibel and Peiter (2013)
Low head ramped	79%	–	9 to 45%	–	–	–	–	–	–	–	Amaral et al. (2019a)
	–	–	48%	–	–	–	–	–	–	–	Amaral et al. (2019b)
	–	–	81%	–	–	–	–	–	–	–	Amaral et al., 2019c
Vertical slot	–	57.1%	–	–	–	–	–	–	–	–	This study
	–	66.7%	–	–	94.3%	–	77.8%	–	–	–	Benitez et al. (2018)
	–	–	15.5%	–	–	31.5%	–	–	–	–	Romão et al. (2019)
Pool and weir	86.9%	7.1%	–	–	–	–	–	–	–	–	Ovidio et al. (2017)
	–	–	60%	–	–	–	–	25%	–	–	Pedescoll et al. (2019)
	–	–	50%	–	–	–	–	–	–	–	Bravo Cordoba et al. (2018)
	–	–	39%	–	–	61%	–	–	–	–	Romão et al. (2017)
	–	–	28 to 68%	–	–	–	–	–	–	–	Silva et al. (2012)
	79 to 86%	–	–	–	–	–	–	–	–	–	Forty et al. (2016)
	–	–	–	–	–	–	–	–	–	29%	Knaepkens et al. (2016)
Baffle	–	52.8%	–	–	40%	–	–	–	50%	30%	Lothian et al. (2019)
	–	–	–	–	55.6%	–	–	–	57. %	66.1%	Coe and Rana (2014)
	68%	–	–	–	–	–	–	–	–	–	Forty et al. (2016)
	–	–	–	–	45%	–	–	–	81%	10%	Piper et al. (2018)
	–	–	–	–	25.8%	–	–	–	10%	16.7%	Lucas et al. (2000)
	64 to 91%	–	–	–	–	–	–	–	–	–	Dodd et al. (2018)
Flat V weir	–	40%	–	–	–	–	–	–	–	–	Lucas and Frear (1997)

4.1 km stretch, which is to our knowledge the only existing cumulative observation of more than two passage clearances to date for rheophilic cyprinids. These results indicate that cumulative passage rates of multiple fishways cannot be theoretically considered as proportional to the addition of a single intrinsic performance. However, in our study, it's not excluded that spawning habitat exist between the fishway that would limit their needs to pass them successively. Passage efficiency of multiple fishways must be in relation with spawning migration ranges of target species in regards to the fish population of the concerned fish zonation. Both deductions are important warnings for the management of the longitudinal connectivity in rivers.

The delay to pass the fishway varied from median values of 9 to 144 h. This delay did not represent the real passage time to cross the structure (Ovidio et al. 2017) as the number of antennas was not sufficient to analyse this metric, but instead represents the delay since the fish release. The block ramp fishway (FW2) was passed quicker than the pool-types (FW1 and FW3) that required the fish to find the entrance, which is a supplementary step to cross a fishway. The passage delay is an interesting metric and rapid passages are the sign of best performances. As the fish were translocated several weeks before their spawning period, some probably first adopted a residency position and have waited to start their migrations at photoperiods and temperatures that correspond to their requirements in terms of spawning migration (Benitez et al. 2015). The passage delays observed seem adapted to authorize a good timing of migration to reach the spawning site at the right moment in the Vesdre, which is also a key element to evaluate success of longitudinal restoration (van Leeuwen et al. 2016). Interestingly, the individuals that succeeded to pass two or three successive fishways did it in a very limited time period (< 48 h), which can be a result of the expression of behavioural personalities, with the potential existence of more proactive/intrepid individuals (Conrad et al. 2011; Renardy et al. 2020) and/or simply reflect a higher physiological motivation to reach the spawning area. In terms of diel passage activities for the barbel, most of them occurred at night and crepuscular periods, with some during dawn and daytime, which is in relatively good accordance with the observations of Benitez et al. (2018). The fishways were used during a wide range of river flow, with many passages occurring during low to medium flow rates. This is encouraging in terms of performance, as during high flow, the weir can be partially erased, and the fish are not obliged the use the fishway to move upstream (Ovidio and Philippart 2002). FW1 was used during higher flow than FW2 and FW3, perhaps reflecting a lower attractiveness at reduced flow.

Degraded aquatic communities can recover from past environmental impacts only if recolonization opportunities are provided from adjacent population sources (Langford et al. 2009). The relationship between the cost and the ecological benefit is an important consideration point for river restoration projects, but one question is difficult to ask: how many individuals need to get through a fishway to meet ecological objectives and to ensure population viability (Birnie-Gauvin et al. 2019)? We can reasonably think that low or medium passage performances constitute an improvement (gene flow effects, metapopulation reconnection) in comparison with the absence of connections, but it is still complicated to assess the demographic gain for a population from fish passage improvement or restoration. Relatively little is known about the effect of longitudinal continuum restoration for river fishes, especially in degraded and rehabilitated habitats, despite its crucial importance for species distribution, species turnover, and recolonization (Tummers et al. 2016). In the Nepean River estuary (Australia), Rourke et al. (2019) observed an increase in species richness and expanded distributions of fishes in the two years following the construction of fishways. In the case of the Vesdre, past pollution has eliminated the patrimonial rheophilic fish species and the actual recovery of the water quality has authorized their recolonization settlement and breeding in the newly-opened river stretches. As suggested by Radinger and Wolter (2014), studies of fish movement often find that a few individuals move long distances, even for species that do not have a migratory life-history. This colonization process may be largely facilitated and accelerated by new fishways. In a close study site, translocation tests upstream of an impassable barrier with some nase individuals enabled further reproduction and the reconstitution of a new juvenile population (Ovidio et al. 2016) which is an encouraging sign of potential emerging demographic gain after analogous migration routes are reopened. For further improvements of the distribution or status of the fish assemblage, efforts in improving longitudinal connectivity need to be accompanied by significant improvements of species' habitats (Radinger et al. 2018), that would increase the potential beneficial effects for populations.

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