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Assessment of the effectiveness and efficiency of two fishways with vertical slot openings in an Alpine River (Toce River, northern Italy)

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A R T I C L E I N F O

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Fish pass efficiency

A B S T R A C T

Weirs and dams impede the longitudinal connectivity of rivers and create obstacles to free fish migrations. Blue infrastructures, such as fishways, have been implemented to restore river connectivity over the last 20 years. However, after construction, issues regarding the functionality and effectiveness of fishways often remain. In this study, we investigated the effectiveness and efficiency of two step-pool fishways with vertical slot openings (i.e., Tana and Prata fishways), in the Toce River, an Alpine River tributary of Lake Maggiore. We carried out this investigation over two years by using combined technologies: PIT tag telemetry and video monitoring, taking into account the fish size and river discharge. Fishways were suitable and utilized by trout (*Salmo* spp.), barbels (*Barbus* spp.), chub (*Squalius squalus*) and dace (*Telestes muticellus*), but not for bullhead (*Cottus gobio*). Additionally, we PIT tagged both wild and hatchery-reared trout, to compare the use of the fishways by wild and hatchery fish. The passage efficiency was 65.4 % for the Tana fishway and 60.0 % for the Prata fishway, corresponding to values within the range found in the literature. On the other hand, attraction efficiency was very low. Our observations suggest that finding and entering the fishways was more challenging than completing the passage. Most passages occurred in autumn and spring, in relation to spawning migration and high-flow periods. Slight differences were recorded between the two fishways, with longer transit times for the Tana fishway and better performance for adult wild trout at the Prata fishway. The combination of telemetry and video monitoring provided important information to guide future river defragmentation projects in the area and for similar water basins.

1. Introduction

River fragmentation caused by dams and weirs is one of the main threats to river biocenosis (Birnie-Gauvin et al., 2019; Reid et al., 2019). This is particularly true for fish fauna, and within this group of animals, for obligate migratory species (Nilsson et al., 2005). Fish movements within a river and across different critical habitats and environmental conditions throughout their lifetime are crucial for their survival and to mitigate the risk of metapopulation extinction (Pompeu et al., 2012). The re-establishment of longitudinal river connectivity is attained through the implementation of fishway structures, which act as blue corridors in the river restoration programmes to achieve good ecological status for all water bodies as foreseen in the European Union Water Framework Directive (EU WFD, 2000/60/CE). Initially, fishways were developed in the Northern Hemisphere for migratory adult diadromous fish, such as salmon and trout, due to their significant economic and iconic value. Therefore, fishways were designed to meet the needs of fish species with strong swimming capabilities, without considering non-salmonid species (OTA, 1995; Larinier and Travade, 1998; Calles and Greenberg, 2005; Parsley et al., 2007; Schilt, 2007; Landsman et al., 2018). However, the operational functioning configured for salmonids could be challenging for non-salmonid species, resulting in lower

Abbreviations: R_o, *Overlap rate*; E_p, *Overall passage efficiency*; E_{pAdj}, *Adjusted passage efficiency*; E_a, *Attraction efficiency/Attempting passage*; T_t, *Time of transit*; S_t, *Delta height transit speed*; T_d, *Fishway passage time/Fishway delay time*; R_f, *Fallback rate*; RoR, Run-Of-River hydropower plants.

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passage efficiency (Noonan et al., 2012). Later on, fishways have been also studied and designed for non-salmonid fish species, such as those belonging to the Cyprinidae (e.g., barbel, chub and dace) and Cottidae (e.g., bullhead) families (Sanz-Ronda et al., 2016; Lothian et al., 2019; Wiegleb et al., 2023). Some of these species are small-bodied fish and weak swimmers with different ecological characteristics compared to salmonids, which are pelagic and rheophilic species. In contrast, barbel and chub are benthopelagic rheophilic, dace is benthopelagic and eurytopic, and bullhead is benthic rheophilic (following the classification by Hershey, 2021).

The assessment of the effectiveness and efficiency (effectiveness refers to a qualitative concept, while efficiency refers to a quantitative concept, following Larinier, 2008) of fish passages is a crucial step in the BACI (Before After Control Impact) approach of blue infrastructures but, so far, the results were focused primarily on salmonids whilst the non-salmonid group were less considered (Noonan et al., 2012; Sun et al., 2023). Many methods are employed to monitor fish movements and fishway usage and therefore to assess the effectiveness and efficiency of fish passages, such as video monitoring, fish capturing techniques, and biotelemetry (i.e., passive and active radio and acoustic telemetry). The data resulting from monitoring are used to calculate several metrics, such as attraction and passage efficiency (Cooke and Hinch, 2013). However, caution is needed when reviewing literature data, as they could not always be considered "gold-standards". Some studies have used different experimental designs: in some cases, fish are captured from distant locations and translocated inside or near fishways to compel them to pass through, which carries the risk of generating bias and erroneous estimates (Cooke and Hinch, 2013). Additionally, the number of tagged fish is often insufficient to support statistical analysis, hindered by challenges in field sampling activities and the cost of technical equipment. The monitoring period, often limited to the fish spawning period rather than the entire lifetime, is another critical factor, along with the focus on salmonids only (Cooke and Hinch, 2013). The studies on fishway effectiveness/efficiency should prioritize longer monitoring periods, include target species with different ecological behaviours, and consider lifetime movements comprehensively, avoiding unreal data responses. Biological and environmental conditions experienced by fish (e.g., physical ability, tendency to migrate, the motivation to find fishway entrance, water temperature and river discharge) can vary between species, as well as being influenced by technical conditions of the fishways and by the location of the entrance relative to other migratory routes such as spillways, channels, etc. (Larinier and Porcher, 2002; Roscoe and Hinch, 2010; Castro-Santos et al., 2013; Bravo-Córdoba et al., 2022; Sun et al., 2023). Therefore, the assessment of the fishway's effectiveness/efficiency should be site- as well as species-specific.

This study aims to assess the effectiveness and efficiency of two step-pool fishways with vertical slot openings in an Alpine River (Toce River, northern Italy) realized within an EU-funded LIFE project (LIFE15 NAT/IT/000823 IdroLIFE). The realization of these two fishways in correspondence to the Prata and Tana Dams allowed the reestablishment of free migration of fish up to Pontemaglio municipality, covering a total of 54.91 km, over more than 50 % of the Toce River's total length. Both PIT tag telemetry and video monitoring technologies were used. Fish were PIT tagged above and below the two dams where the fishways were located (i.e., Tana and Prata dams). Fish were tagged randomly, without any size or species selection throughout the entire study area. The fish were categorized by family (i.e., Salmonidae, Cyprinidae and Cottidae). Salmonids were also categorized by size (i.e., juvenile, subadult and adult) and by their origin (i.e., wild and hatchery-reared salmonids). Fish passages were monitored over two years. River discharge and season were considered due to their possible influence on the use of fishways by different target species. The study of fishway use at the local level is fundamental for evaluating the ability of fish to pass, thus guiding further river defragmentation projects. We expect that i) fishways are most suitable for rheophilic and pelagic species (i.e., salmonids) compared to benthic and weak swimmer species, such as *Cottus gobio*; ii) fishway usage is higher during the spawning period due to increased migratory motivation; iii) larger fish have better swimming performance; iv) the performance of the Tana fishway could be more challenging due to the location of its entrance, which is on the opposite riverbank and far from the main river discharge.

2. Material and methods

2.1. Study area

The Toce is a glacial river located in the North-Western Alps (Piedmont, Italy). It originates at 1740 m asl and flows throughout the Verbano-Cusio-Ossola valley into Lake Maggiore (Fondotoce, 193 m asl) (Fig. 1). It is 83.6 km long, has an average slope of 2.4 %, and drains a ~ 1784 km^2 watershed. The climate is temperate (latitudinal range: 45°55′ N – 46°28′ N) and the average rainfall is ~1400 mm/y (ADBPO, 2018), with a typical regime characterized by two maxima during spring and autumn, and two minima during summer and winter (Saidi and Ciampitiello, 2014). The Toce River mean annual temperature is ~9.5 °C and the mean annual streamflow is 69.9 m^3 s^{-1} at the confluence in Lake Maggiore (Regione Piemonte, 2007).

The Toce River watershed is affected by the presence of 24 hydropower plants and 19 reservoirs with an average installed power of over 300 MW and a maximum storage of 180 Mm^3 (Regione Piemonte, 2021; Regione Piemonte, 2007). 44.7 % of the watershed area belongs to the NATURA 2000 network (Site codes: IT114001; IT114003; IT114004; IT114006; IT114007; IT114011; IT114013; IT114016; IT114017; IT114018; IT114019; IT114020; IT114021) (see Supplementary Materials Fig. S1).

The Toce River is inhabited by 34 fish species: 24 are native and 10 non-native. Also, 10 species are listed in the Annexes of the Habitat Directive 92/43/EEC, such as marble trout (*Salmo marmoratus* Cuvier, 1829), Adriatic grayling (*Thymallus aeliani* Valenciennes, 1848), bullhead (*Cottus gobio* Bonaparte, 1839), Padanian barbel (*Barbus plebejus* Bonaparte, 1839), brook barbel (*Barbus caninus* Bonaparte, 1839), Italian riffle dace (*Telestes muticellus* Bonaparte, 1837), Po brook lamprey (*Lampetra zanandreai* Vladykov, 1955), Italian roach (*Rutilus pigus* Lacépède, 1803), Italian nase (*Chondrostoma soetta* Bonaparte, 1840).

Within the activities of the IdroLIFE project (LIFE15NAT/IT/000823), the Toce River connectivity (from the mouth to the first impassable natural obstacle located ca. 32.3 km from the mouth) was re-established by building two fishways (Fig. 2) located at the Tana and Prata Run-Of-River (ROR) hydropower plants which fragmented the river at Crevoladossola (302 m asl, 33.7 km from the Toce source) and Prata di Vogogna (226 m asl, 51.2 km from the Toce source). The building of the 2 fishways allowed to opening of 61 km of new habitat for fish migration.

2.2. Tana and Prata ROR hydropower plants, fishways characteristics and PIT tag detection system

The Tana Dam consists of three mobile iron gates and a concrete gate impounding the river and creating a small reservoir (dam head = 4.4 m). The Prata Dam instead consists of six iron gates impounding the river and creating a small reservoir (dam head = 4.0 m). The Tana fishway was built in 2019, whereas the Prata fishway, was built in the 70s but was not functional due to the erroneous position of the septa: for this reason, it was restored in 2019. The characteristics and a view of both fishways are summarized in Table 1 and Fig. 2.

The fishways consist of successive basins, which are generally divided by septa. The latter have two openings at the Tana fishway (i.e., basal and vertical openings) and only one at the Prata fishway (i.e., vertical opening). The dimensions of the vertical openings are consistent across all septa at the Tana fishway, while they vary at the Prata fishway, with a minimum heigth at the first and last septa (1.56 and 1.76 m) and

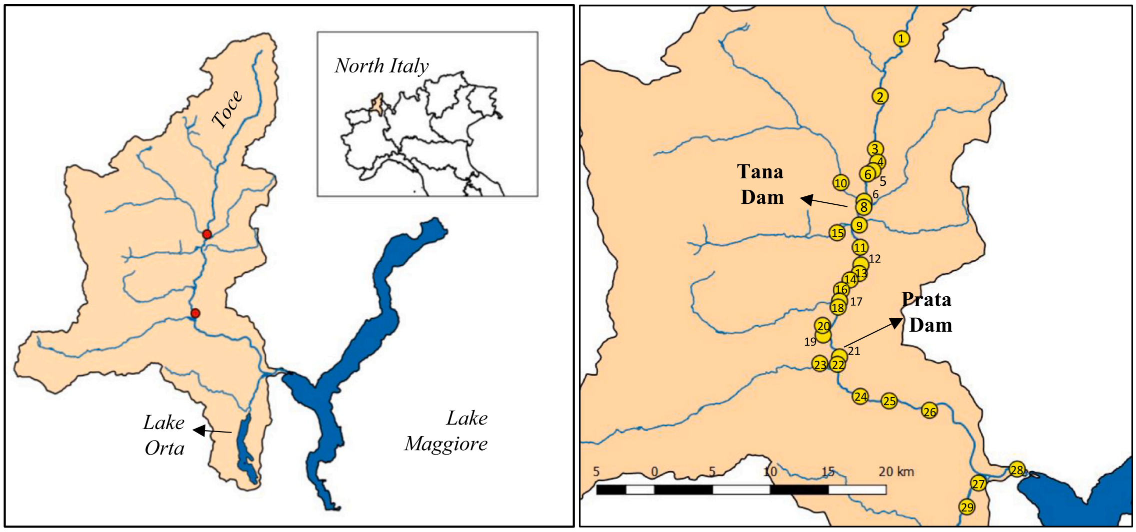

Fig. 1. Study area. The Toce watershed in northern Italy, including the Toce River and its main tributaries, flowing into Lake Maggiore. Fish sampling locations are shown by yellow circles. Prata and Tana dams are indicated by red dots (map on the left) and black arrows (map on the right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maximum height in the middle ones (from 1.8 to 2.32 m). (For more detailed information on the plans and sections of the fishways, refer to Supplementary Materials Fig. S2 and Fig. S3).

Both fishways were equipped with a pair of full-duplex passive integrated transponder (PIT) antenna systems (Biomark®, Boise, Idaho, USA) installed at the entry and outlet of the fishways (Tana fishway: downstream antenna = fourteenth septum; upstream antenna = fourth septum; Prata Fishway: downstream antenna = eighth septum; upstream antenna = second septum). Antennas were fixed by concrete anchors at the vertical slots of the selected fish pools so to detect any fish moving upstream or downstream in the fishways. During and after installation, a check of the tag reading distance and efficiency was carried out at the lumen of the antennas, particularly in the areas with weaker electromagnetic fields, such as the corners and the central part, by using the same PIT tags (Biomark APT12, 12 × 2 mm, FDX—B, 134.2 kHz tags) to mark the fish. The efficiency of the antenna was checked monthly and manual tuning was performed by an operator with the Biomark® Device Manager Software. Furthermore, the antennas were configured for automatic tuning and auto VVt (Virtual Test Tag) every 60 min, during which a new tag code was generated by the antenna for self-tuning. It was taken into account the possible external electromagnetic interference that could affect the efficiency of PIT tag detection by the installed antennas. As for communication by the manufacturer, a noise (Electro Magnetic Interference or EMI) of more than 20 % can reduce the antenna efficiency. The average noise EMI registered during the 2 years monitoring period never exceeded 15 % as registered by the antenna reader's internal memory as a confirmation of the good operation of the PIT tag monitoring system. The water head drop between the two antennas is 2.68 m for the Tana fishway and 1.55 m for the Prata fishway. The monitoring starts as soon as the construction of the fishway was completed and the systems operated continuously from 1st March 2021 to 8th May 2023.

In proximity to the Tana fishway, also a monitoring room with a video camera system connected to a computer (Tecnifish 2.0 software) was installed. We started monitoring the fishway with a video recording system approximately at the same time as the installation of the fish passage and PIT tag antenna, to compare the two systems. Due to issues related to cleaning of the window glass that allows viewing of the passage and the system installation, the monitoring period spans from1st April 2021 to 14th March 2022. A total period of almost one year was chosen to ensure a good amount of data was collected, covering all seasons of the year.

2.3. *Fish sampling and handling*

Fish sampling was carried out by CNR-IRSA personnel by electrofishing and by eleven selected anglers using fishing rods. To maximize the sampling area, including areas where electrofishing was impracticable, the aforementioned two sampling methods were employed. Electrofishing was conducted with DC (Direct Current) to avoid any damage to the fish stunned. The samplings were carried out during daytime, along transects in shallow water close to the riverbanks, with a built-in-frame EL64GII electrofishing device (Scubla aquaculture, 3.5 KW, 600 V, DC). The electrofisher has a copper cathode (width = 2 cm, length = 300 cm), a steel ring anode (thickness = 0.8 cm, diameter = 50 cm), and an effective electrical field of ~1 m^3 (Copp, 1995). The angler sampling was performed with flyfishing and spinning tackles. Both sampled reaches (CNR-IRSA) and capture sites (fishermen) were georeferenced with a GPS device. Garmin Basecamp v.4.7 and QGIS v.2.18 were used to analyse GPS data and calculate transect lengths. Thus, the sampling effort (sampled water volume for each surveyed meter) was calculated as L × 2 m^3, where L is the transect length, as described in (Polgar et al., 2023). The electrofishing device was swept by the operator on both sides of the path at depths of ~50–150 cm (median value = 100 cm) while other operators (usually 1 per site) were collecting stunned fish. The sampling locations are shown in Fig. 1 and their main characteristics are listed in Supplementary Materials (see Supplementary S1.1). The total or average fish density (plus standard deviation, when the sampling was done more than once) was calculated for most sampling sites (just in some cases sampling was not quantitative), along with the relative abundance of the most representative taxonomic groups. Trout belonging to the *Salmo trutta* complex (i.e., *Salmo marmoratus, Salmo trutta,* and *Salmo ghigii*) were merged into a unique *Salmo* spp. group since introgressive hybridization occurs among these taxa (Righi et al., 2023). The same holds for barbels. Therefore, all barbels captured were also merged in a single *Barbus* spp. group.

To facilitate data collection and taggging all fish captured by electrofishing were anaesthetized in a water volume of 10 L by adding 2 mL of a 1:5 emulsion of clove oil (eugenol) in 96 % ethanol. Each fish was positioned on an ichthyometer, photographed in lateral view, measured (TL: total length, in cm, to the nearest 1 mm; W: wet body mass, to the nearest 1 g), and a scale sample was collected for age determination. In addition, the fish was checked with a portable reader (Biomark HPR LITE) prior to the tagging procedure to verify if it had already been tagged before. This is also useful for recognizing recaptured fish and

Fig. 2. Photos of the Tana (a) and Prata (b) dams with fishways, showing antennas placements (i.e., yellow dots: U = upstream antenna; D = downstream antenna), and details of the fishways (respectively a_1 and b_1).

Table 1
Descriptive features of the two fishways are here reasumed.

Basin's general features	Tana Fishway	Prata Fishway
Length of the fishway (m)	47	24
Number of basins	18	9
Water head drop of each basin (m)	0.24	0.24
Length (m)	2.25	2.85
Width (m)	1.65	1.70
Height (m)	2.80	2.35
Water discharge (m^3 s^{-1})	0.350	0.424
Max Water discharge (m^3 s^{-1})	0.475	3.218
Min Water discharge (m^3 s^{-1})	0.156	0.066
Basal opening: width (m)	0.20	–
Basal opening: height (m)	0.20	–
Vertical opening: width (m)	0.30	0.25
Vertical opening: height (m)	1.55	1.56–2.32

mark/recapture information. Anaesthesia was unnecessary for fish sampled with fishing rod due to the reduction of their mobility for their physical stress after the capture. After data collection and tagging, fish were woke up in a fresh water tank, monitored for few minutes until full recovery and then released back in the River Toce.

2.4. Fish tagging

To evaluate fish passage efficiency and fish migration, selected fish were tagged from 2017 to 2022 with APT12 (12 × 2 mm, 0.1 g) and HPT8 (8 × 1.4 mm, 0.03 g), FDX-B tags 134.2 KHz (Biomark, Boise, USA), using pre-loaded needles and a Biomark implant gun (MK25 for 12 mm PIT tags, MK65 for 8 mm PIT tags).

Tag size is affected by fish size. As a rule of thumb, the ratio of tag size to body mass should not exceed 2 % (Winter, 1983). Even though it is considered as initial guide, it has been demonstrated that this value is species-specific and dependent on the life stages involved (Brown et al., 1999; Jepsen, 2004; Jørgensen et al., 2017; Watson et al., 2019). It was also suggested that the tag size should not exceed the 17.5 % of the total length of juvenile salmonids fish (e.g., 12 mm tag; minimum fish threshold length = 69 mm), with an expected mortality that does not exceed 5 % (Vollset et al., 2020). Moreover, some authors marked small species of cyprinids (e.g., *Telestes muticellus*) with PIT tag and recorded high survival rate (ca. 94.8 %) when the tag-to-fish length ratio ranged between 8.6 and 20 %, with no statistically significant differences in mortality between treatments (Schiavon et al., 2023). The development of microPIT tags (< 12 mm) allows the possibility to study small-sized fih and juveniles of larger fish species (< 100 mm, 5 g) (Watson et al., 2019). Considering all this information, and as a more conservative approach to minimize any potential damage related to handling small fish (Brown et al., 1999; PTAGIS, 2014), it was decided to tag salmonids and cyprinids larger than 70 mm, withouth exceeding the tag-to-mass ratio of 2 % and the tag-to-length ratio of 17.5 %, using smaller tags when necessary. At the same time, to avoid any detrimental effects on the survival, growth, and swimming performance of *Cottus gobio*, the tagging procedure was carried out using smaller tags (HPT8) and considering a minimum threshold size of 65 mm, which is higher than that reported in the literature (i.e., ≥ 50 mm), with an approximately 95 % survival rate (Knaepkens et al., 2007). Then, small-bodied and juveniles fish such as *Cottus gobio* (mean total length and weight ± SD, n = total number; TL = 12.8 ± 3.8 cm, W = 26 ± 32 g, *n* = 239), cyprinids (TL = 10.9 ± 2.6 cm, W = 16 ± 15 g, *n* = 106) and salmonids (TL = 11.6 ± 1.7 cm, W = 20 ± 32 g, *n* = 329), were preferentially tagged via intraperitoneal incision with preloaded needle and HPT8 tags. Moreover, fish were tagged in two different body parts depending on the size: fish smaller than 30 cm were tagged inside the body cavity (intraperitoneal cavity) while fish longer than 30 cm in the pelvic girdle. Taking into account this treshold size, salmonids (TL = 19.3 ± 5.4 cm, W = 86 ± 74 g, *n* = 1036) and cyprinids (TL = 15.6 ± 4.7 cm, W = 59 ± 74 g, *n* = 164) were tagged intra-peritoneal with APT12 tags, while larger salmonids (TL = 42.6 ± 10.6 cm, W = 1067 ± 879 g, *n* = 550) and cyprinids (TL = 48.1 ± 6.5 cm, W = 1294 ± 491 g, *n* = 105), were tagged in the pelvic girdle with APT12 tags. The tagging procedures were carried out taking into account best tag orientation, when fish are swimming through the PIT tag antenna detection system. Best PIT tag orientation for maximum reading distance and efficiency is the PIT tag perpendicular to the lumen of the antenna.

2.5. Tag-telemetry data collection and analyses

Tag-telemetry data were downloaded monthly by an operator from each antenna storage systems. Data were analysed to understand the direction of fish movement and the time spent by fish inside the fishway. Furthermore, each movement was classified as either upward or downward (i.e., successful passage), as well as each attempt to pass through the fishway (i.e., unsuccessful passage), and each fallback event. Fish movements were categorized on a daily basis. A passage was considered successful when a fish passed through both antennas. The location of antennas inside the passage and at the entrance allows us to determine the actual success of the passage. Moreover, unsuccessful passage was determined when a fish was recorded by only one antenna, and a fallback event when a fish attempt to pass (i.e., recorded at both antennas), but did not complete the passage and returned to the entrance antenna. When some movements spanned two days and were continuous, they were considered as a single movement. The time of the day when fish began and ended their migration in the fishway was also determined.

Additionally, river discharge was included in the data analysis to assess the flow conditions under which fish used the fishways. The analysis aimed to determine the range of water discharge associated with fishways usage and to explore possible correlations between successful fish passage and water discharge levels. Then, fish were grouped into "passed" and "not-passed". The data on Toce River discharge were free downloaded from the portal service ANTARES of the Environmental Protection Agency of Piedmont Region (https://secure.regione.piemonte.it). Two measurement stations were included in the dataset: Candoglia station, close to the Prata dam and Pontemaglio station, close to the Tana dam.

Only for trout, whose number of detections was higher compared to other fish, data on fish passage detections were analysed also considering three fish size classes since reproductive fish exhibit higher motivation to pass, and larger fish generally have better swimming performance. According to Polgar et al. (2023) and the analysis of fish scales, trout were divided into juveniles or young of the year (TL < 15 cm), subadults (15 cm ≤ TL < 30.7 cm) and adults (TL ≥ 30.7 cm).

The classification was based on two different criteria:

1. For the juveniles, the discrimination factor was the age of trout. We estimated the age counting the number of annual rings on the scales and assessed their biometrics by measuring the mean TL of the two cohorts (0+ = 10.8 ± 1.5 cm; 1+ = 21 ± 4.1 cm). Considering the mean TL and the upper and lower limits, we set a threshold size of 15 cm.
2. For the discrimination between subadults and adults, the mean TL at first maturity calculated by Polgar et al. (2023) was used ($TL_m = 55$ cm; PI = 30.7, 96.8). For a more conservative approach, a lower value of this parameter (TL = 30.7 cm) was chosen.

In addition to the size, we also considered the spawning period, which lasts from October to December (Ielli and Duchi, 1990; Giuffra et al., 1996; Zerunian, 2003; Kottelatt and Freyhof, 2007; Vincenzi et al., 2011; Moro, 2019).

2.6. Fishway efficiency metrics calculation

To determine the efficiency and effectiveness of the two fishways, eight metrics were calculated.

The R_o is the percentage of passing target species (i.e., $N_{pass\ Target}$ = number of target species that successfully passed through the fishway; N_{Target} = number of target species) (Bao et al., 2019) (eqs. 1).

$$\textit{Overlap rate}\ (R_o) = N_{pass\ Target}/N_{Target}{}^{*}\ 100 \quad (1)$$

The E_p is the percentage of fish that passed the fishway compared to those released in the river reach downstream of the dam (i.e., N_{passed} = fish that successfully passed the dam upstream or downstream; $N_{released}$ = fish that were tagged and released in the river reach downstream of the dam) (Bao et al., 2019; Ovidio et al., 2017) (eqs. 2).

$$\textit{Overall passage efficiency}\ (E_p) = N_{passed}/N_{released}{}^{*}\ 100 \quad (2)$$

The E_{pAdj} is the percentage of fish that passed the fishway (i.e., N_{passed}) compared to the number of fish detected at only one antenna (i.e., $N_{approach}$ = fish which has only one detection at one of the two antennas) (Bao et al., 2019; Bravo-Córdoba et al., 2022; Keefer et al., 2021; Lothian et al., 2020; Lothian et al., 2019; Ovidio et al., 2017) (eqs. 3).

$$\textit{Adjusted passage efficiency}\ (E_{pAdj}) = N_{passed}/N_{approach}{}^{*}\ 100 \quad (3)$$

The E_a is the proportion of radio-tagged fish that were detected at the fishway entrance (i.e., $N_{approach}$) divided by the total number of fish tagged (i.e., $N_{released}$) (Bravo-Córdoba et al., 2022; Bunt and Jacobson, 2019; Lothian et al., 2019) (eqs. 4).

$$\textit{Attraction efficiency/Attempting passage}\ (E_a) = N_{approach}/N_{released}{}^{*}\ 100 \quad (4)$$

The T_t is the time required for upward or downward passage (reported in minutes), measured based on the time elapsed from the last detection at the fishway entrance to the first detection at the fishway exit (i.e., $T_{F\ exit}$ = first recording time at exit antenna; $T_{L\ ent}$ = last recording time at entry antenna) (Bravo-Córdoba et al., 2022; Bunt and Jacobson, 2019; Lothian et al., 2019; Ovidio et al., 2017) (eqs. 5).

$$\textit{Time of transit}\ (T_t) = T_{F\ exit} - T_{L\ ent} \quad (5)$$

The S_t is the transit speed as a function of the topographic difference in height between the two antennas (i.e., $m_{water\ head\ drop}$ = water head drop between the two antennas) (Bravo-Córdoba et al., 2022; Ovidio et al., 2017) (eqs. 6).

$$Delta\ height\ transit\ speed\ (S_t) = T_t / m_{water\ head\ drop}{}^{*}\ 100 \quad (6)$$

The T_d is the time from the first detection in the first antenna to the last detection in the last antenna (i.e., Ent_F = the first detection by an antenna inside a fishway opening; $Exit_L$ = the last detection at a top-of-ladder fishway exit) (Bao et al., 2019; Keefer et al., 2021) (eqs. 7).

$$Fishway\ passage\ time/Fishway\ delay\ time\ (T_d) = Exit_L – Ent_F \quad (7)$$

The R_f is the percentage of individuals that fell back from an antenna or that passed back downstream via spillways relative to the total number of individuals reaching that antenna (i.e., $N_{approach}$; $N_{fallback}$ = total number of fish that experience fallback event). Fallbacks were determined exclusively from telemetry records (Bao et al., 2019; Boggs et al., 2004) (eqs. 8).

$$Fallback\ rate\ (R_f) = N_{fallback/}N_{approach}{}^{*}\ 100 \quad (8)$$

The fish were grouped based on the requirements of the metrics. For the evaluation of the overlap rate (R_o), a metric that defines the effectiveness of the fishway (i.e., qualitative concept), all fish taxa were included, considering the merged *Salmo* spp. and *Barbus* spp. groups (i.e., see sub-chapter on “Fish sampling and handling”). For all the other metrics, the fish were first grouped by family as follows: Salmonidae, Cyprinidae, and Cottidae. The design of both fishways was tailored to the requirements of Salmonidae and Cyprinidae, but Cottidae was not included. A further subdivision was carried out for Salmonidae fish based on their origin: hatchery-reared and wild salmonids.

2.7. Video monitoring data collection and analyses

The video monitoring system at the Tana fishway was remotely monitored daily, and the camera was cleaned if necessary. The software recorded each fish passage. The following information was obtained: the number of fish species using the fishway, the number of observed fish passages, the direction of the passage, and the date and time of the day of the passage.

2.8. Statistical analyses

The correlations between the number of fish recaptured and the number of samplings carried out with electrofishing, and between fish recordings by biotelemetry and water discharges, were assessed using the Pearson correlation test.

Three analyses were carried out using the Mann-Whitney *U* test due to the non-normal distribution of the data: the comparison of fish density recorded for the Toce River and its tributaries, the comparison of the water discharges at which the fish passed or did not pass the fishways, and the comparison of the metrics related to the time required to pass (i.e., $\mathbf{T_t}$, $\mathbf{T_d}$, $\mathbf{S_t}$) across the fishway type. The Kruskall-Wallis test was performed to analyse the time required to pass in relation to fish size classes, specifically for the Prata fisway.

To assess significant differences in the metrics $\mathbf{E_a}$, $\mathbf{E_p}$ and $\mathbf{E_{pAdj}}$ between the types of passages (i.e., Tana and Prata) and fish size classes per fishway (i.e., video and telemetry-systems), the Chi-square test was performed. When the assumptions for Chi-square test were not met, Fisher’s exact test was performed. This applies to the evaluation of differences in the metrics $\mathbf{E_a}$, $\mathbf{E_p}$, and $\mathbf{E_{pAdj}}$ across size classes (i.e., juveniles, subadults and adults) for each fishway. Chi-square test was also used to investigate the differences in fish recordings obtained through video and biotelemetry monitoring across different seasons. In this case, a post hoc test with Bonferroni correction was applied to determine which seasons were significantly different from the other. Further investigations with the same test were performed to compare the recordings and fish recorded during the trout spawning period. All statistical analyses were performed using Past Software (Hammer, 2001).

3. Results

3.1. Fish sampling

The fish density and relative abundances of the main taxa were calculated for most sampling sites (Fig. 3). The total fish density ranged from 176 ind ha^{-1} to 3356 ind ha^{-1} (average of 1635 ind ha^{-1}). No significant differences were observed in fish density recorded between the Toce River and its tributaries ($U = 819$, $Z = 0.721$, $p > 0.05$), although the Toce River had a slightly higher value (Toce River mean ± S.D. = 1769 ± 1499; Tributaries = 1602 ± 1480). The *Salmo* spp. group was generally the most abundant taxa sampled, with a mean density of 879 ind ha^{-1} (± 795), ranging from 0 to 4134 ind ha^{-1}. The higher density was recorded upstream of the Tana Dam, with 1322 ind ha^{-1} (± 1079), ranging from 21 to 4134 ind ha^{-1} ($U = 391.5$, $Z = 2.45$, $p = 0.013$), followed by the presence of *Cottus gobio* and *Telestes muticellus*. On the lower stretch of the river, the fish community is more diverse, and the contribution of non-salmonid species is higher.

3.2. Fish tagging

A total of 2547 fish were tagged (Fig. 4). Among these, 1788 fish were captured by electrofishing (92 sampling surveys), 303 by anglers (181 fishing events), and 456 fish were provided by local hatchery. Proportionally to the fish density in the study area, a higher number of *Salmo* spp. specimens (1909) was tagged, followed by *Cottus gobio* (240), *Barbus* spp. (161), *Telestes muticellus* (142), *Squalius squalus* (68), and *Oncorhynchus mykiss* (27). Most fish were tagged downstream of the two dams: 337 fish at site 7 (Tana Dam), and 201 and 251 at sites 21 and 22 (Prata Dam), respectively.

3.3. Fish recapture

Only 106 tagged fish (4 %) were recaptured during the entire study period. Among these, 99 *Salmo* spp., 4 *Oncorhynchus mykiss*, 2 *Cottus gobio*, 1 *Barbus* spp. (Fig. 5). The fish recaptured by angling and electrofishing were respectively 12 (11 %) and 94 (89 %). A positive and significant correlation between the number of fish recaptured and the number of samplings carried out with electrofishing was detected ($r = 0.79$; p-value $= 0.001$). Thus, the greater the number of monitoring surveys, the greater the chance of recapturing a fish.

Percentages ranging from 3 % to 10 % were detected at the downstream sites closest to the two studied dams whilst 20 % of the fish was recaptured in the channel upstream of the Tana Dam.

3.4. PIT tag telemetry

Seventy individual fish (2.6 % of the total fish PIT tagged) were recorded by at least one of the two antennas at both fishways. Forty-two fish belonging to 6 taxa were recorded at the Prata fishway and 28 fish belonging to 4 taxa were recorded at the Tana fishway. Out of the 70 individuals, 56 were *Salmo* spp., 3 *Barbus* spp., 3 chub, 6 Italian riffle dace, and 2 unknown individuals (i.e., fish detected by antennas but not recorded in the database due to an error by the operators during the tagging activities) (Table 2). A total of 2 % of fish tagged with a rod were also recorded by fixed antennas, i.e., a number not very different from that of fish tagged during electrofishing campaigns (3 %).

If we consider the tagged trout, on average the time of their first detection in one of the antennas was 69 days, with a minimum of 33 min (the fish was captured and released below the Tana dam) and a maximum of 568 days. The longest distance covered is 14.4 km by a trout tagged on 29th November 2017 (TL = 50 cm, estimated age 6 years old) and released below the Prata fishway (near Albo municipality). This trout was later detected by fixed antennas at the Prata fishway on 14th

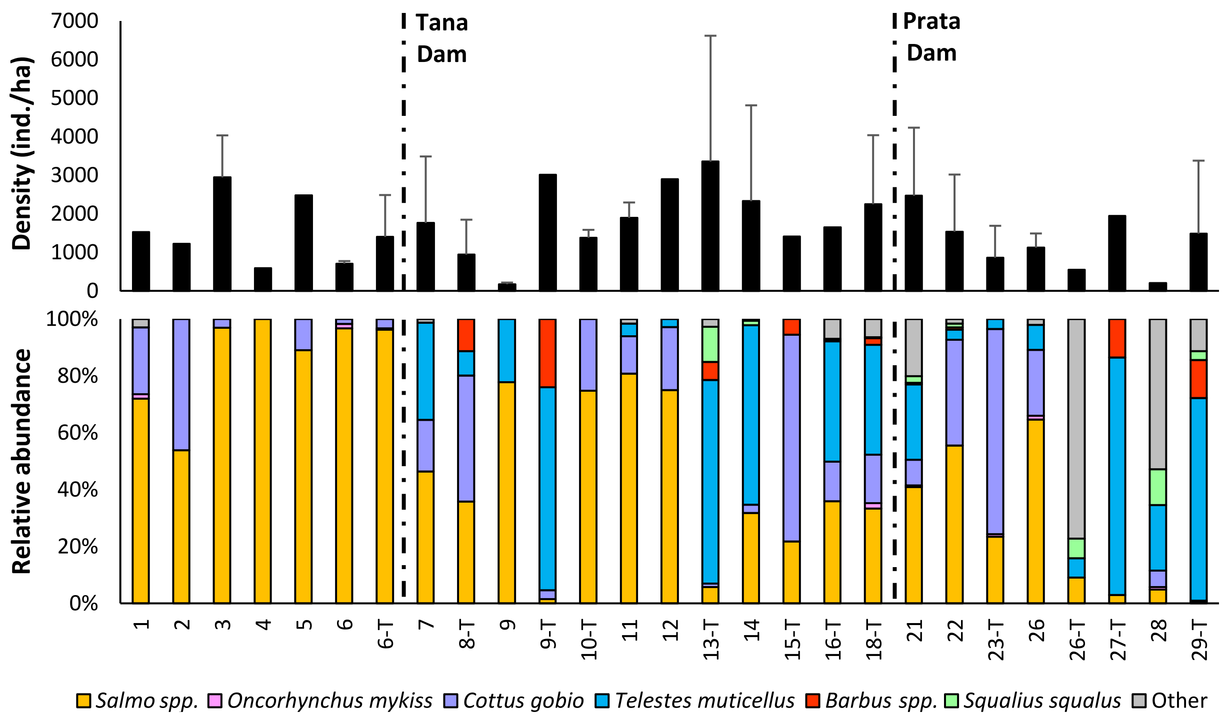

Fig. 3. Total or mean (plus standard deviation) fish density calculated along the Toce River sampling sites (Other = *Gasterosteus aculeatus*, *Perca fluviatilis*, *Scardinius hesperidicus*, *Lota lota*, *Esox lucius*, *Rutilus rutilus*, *Salaria fluviatilis*, *Thymallus thymallus*, *Lethenteron zanandreai*).

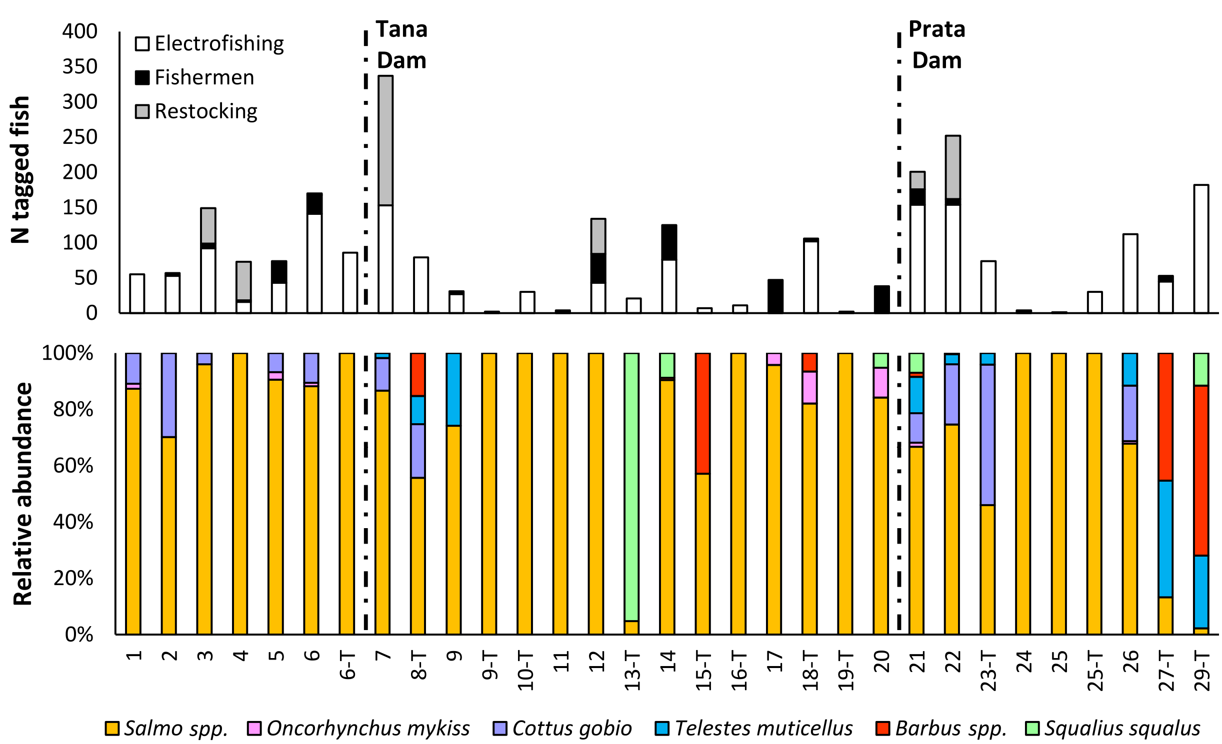

Fig. 4. Total number of fish tagged for each site, and relative abundance of each taxon. The sampling methodology (electrofishing, fishermen, or restocking) is also highlighted.

November 2021, approximately 4 years later, with an estimated age of 10 years old.

The analysis of the temporal pattern of fish detection by the antennas showed that trout approached the fishways mainly during two periods: autumn and spring (Fig. 6). Out of 167 fish recordings, 62 occurred in autumn (23 at the Tana fishway and 39 at the Prata fishway, respectively) and 41 in spring (27 at the Tana fishway and 14 at the Prata fishway, respectively). As for the number of fish recorded, out of 35 fish that successfully passed and were detected in both fishways, 19 were recorded in autumn (6 at the Tana fishway and 13 at the Prata fishway, respectively), 8 in spring (7 at the Tana fishway and 1 at the Prata fishway, respectively) as well as in summer (3 at the Tana fishway

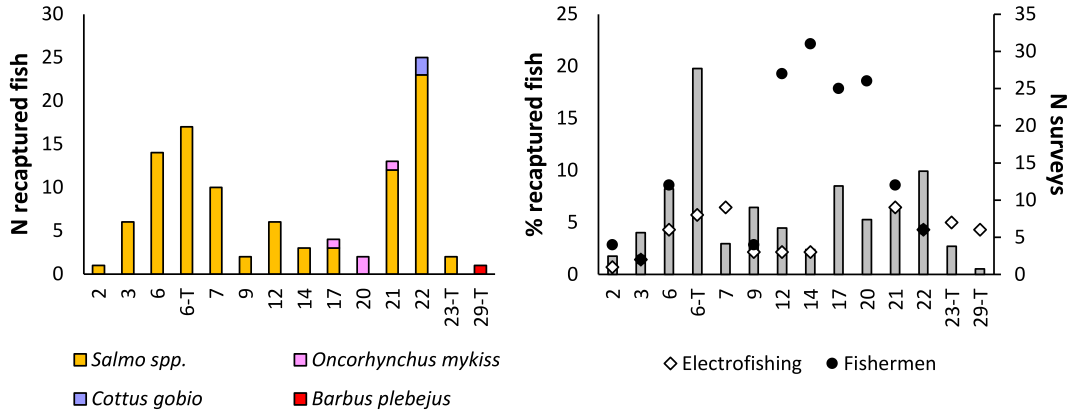

Fig. 5. Number and percentage of recaptured fish at some sampling sites. The taxonomic attribution along with the number of sampling surveys performed by electrofishing and fishermen are specified.

Table 2
Descriptive statistics for the fish species and their stage (Juvenile, Subadult and Adult) tagged (a) and recorded (b) by PIT tag monitoring system located at the Tana and Prata dams. TL = total length, SD = standard deviation, MIN = minimum total length, MAX = maximum total length. The results for wild and hatchery-reared Salmonidae are represented by indicating the latter in brackets.

a) Species	Tana Fishway			Prata fishway		
	N fish	TL ± SD (cm)	Min, Max TL	N fish	TL ± SD (cm)	Min, Max TL
Salmo spp.						
Juveniles	36	12.9 ± 1.6	9.9–14.9	45	13.3 ± 1.1	11.0 ± 14.9
	(0)	(–)	(–)	(–)	(–)	(–)
Subadults	66	21.3 ± 4.4	15.0–29.9	89	20.1 ± 4.3	15.0 ± 30.3
	(17)	(28.0 ± 2.1)	(22.3–30.6)	(29)	(27.3 ± 2.1)	(22.1–30.6)
Adults	30	44.0 ± 11.8	30.7–71.7	54	43.5 ± 10.2	31.0 ± 66.5
	(167)	(47.2 ± 9.2)	(31.2–73.0)	(86)	(39.5 ± 5.4)	(31.0–53.0)
Telestes muticellus	6	11.4 ± 1.4	9.5–13.7	35	11.1 ± 2.2	7.4–19.8
Cottus gobio	23	10.5 ± 1.2	8.2–13.1	75	12.3 ± 2.0	7.6–21.4
Barbus spp.	0	–	–	4	16.6 ± 4.1	11.3–20.3
Squalius squalus	0	–	–	12	19.1 ± 3.9	14.4–26.2
Oncorhynchus mykiss	0	–	–	2	27.6 ± 4.8	24.2–31.0

b) Species	Tana Fishway			Prata fishway		
	N fish	TL ± SD (cm)	Min, Max TL	N fish	TL ± SD (cm)	Min, Max TL
Salmo spp.						
Juveniles	7	12.0 ± 2.0	9.9–14.3	4	13.5 ± 1.0	12.5–14.6
	(0)	(–)	(–)	(0)	(–)	(–)
Subadults	5	23.0 ± 6.1	15.8–29.8	6	23.5 ± 7.2	15.0–30.0
	(0)	(–)	(–)	(0)	(–)	(–)
Adults	11	37.9 ± 7.8	15.8–29.8	19	46.6 ± 10.9	31.0–66.5
	(3)	53.3 ± 8.5	47.0–63.0	1	50.0	50.0
Telestes muticellus	2	10.9 ± 0.1	10.8–11.0	4	10.7 ± 1.5	9.1–12.6
Cottus gobio	0	–	–	0	–	–
Barbus spp.	0	–	–	3	18.3 ± 2.6	15.4–20.3
Squalius squalus	0	–	–	3	20.2 ± 5.5	15.3–26.2
Oncorhynchus mykiss	0	–	–	0	–	–

and 5 at the Prata fishway, respectively). The lowest number of recordings and fish passages were consistently recorded during winter, with only 3 specimens (2 at the Tana fishway and 1 at the Prata fishway, respectively).

A total of 35 out of 56 trout were able to migrate through the fishways and completing the upward passage (i.e., 62 %). Three trout moved downstream (Tana fishway), one of which was a hatchery-reared marble trout. The downstream migration through the gates of the dams was recorded for twelve fish, all from the trout group, representing the 19.2 % at the Tana fishway (i.e., 5 fish out of 26) and 23.3 % at the Prata fishway (i.e., 7 fish out of 30) of the Salmonidae recorded. These fish were either tagged above the dams and later recorded at the downstream antennas in the fishways (so on the way to move upstream again) or they were tagged below the dams and, after an upstream passage, were detected again at the downstream antennas few days later. Twelve fish approaching the fishways belonged to the Cyprinidae family, of which six were able to pass through the fishways (*Squalius squalus* = 1; *Telestes muticellus* = 5). Even in this case, the success rate of the passage was roughly 50 %, and 100 % of the movements were upstream. Only two tagged hatchery-reared trout were able to pass the Tana fishway out of 184, and none out of 115 for the Prata fishway.

3.5. *Water discharge and spawning period*

To investigate if there was an optimal water discharge for which the fishways were most effectively used, we compared the water discharge when the fish successfully passed through the fishway versus when they failed in the attempt for both fishways. The Mann-Whitney test showed

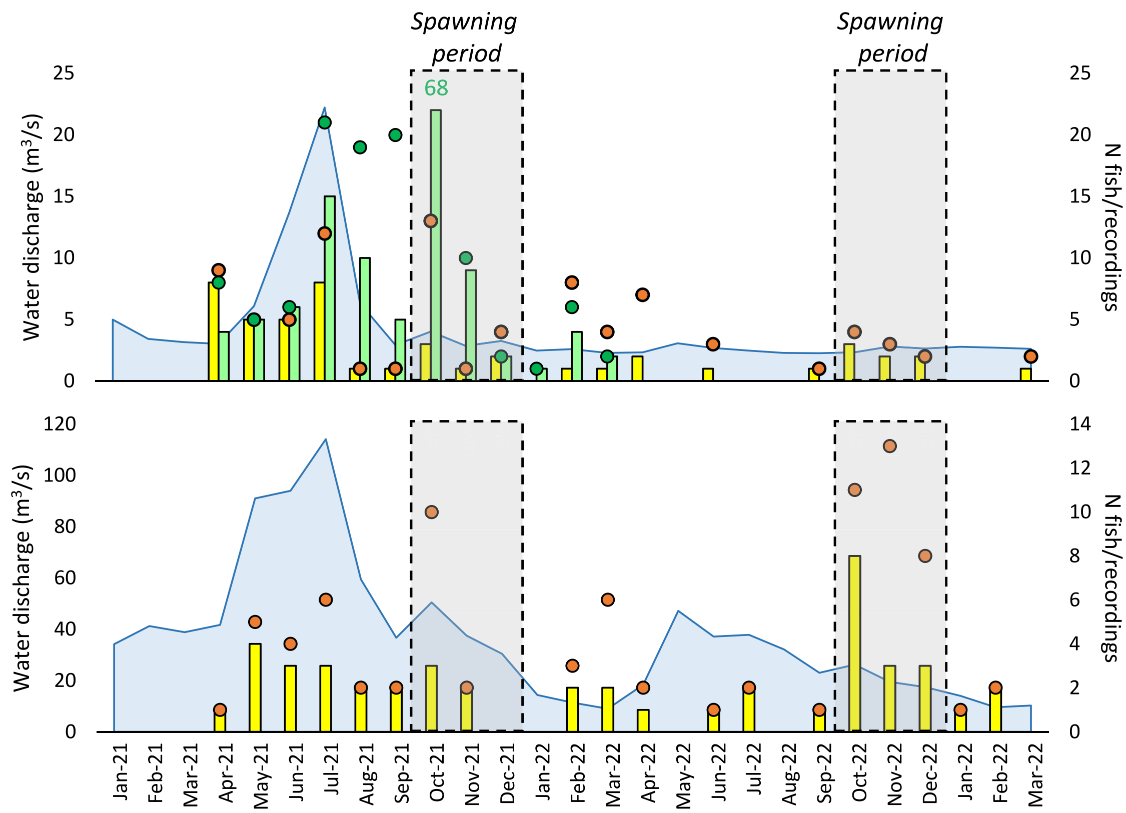

Fig. 6. The number of fish (yellow and green histograms for telemetry and video-monitoring data respectively) and recordings (orange and dark green dots for telemetry and video-monitoring data respectively) are plotted along with the spawning period (grey rectangles) and water discharge per fishway and month during the entire monitoring period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

no significant differences for both fishways (Tana: U = 408, Z = 1.614, $p > 0.05$; Prata: U = 678, Z = 0.224, $p > 0.05$).

In addition, the relationship between the mean monthly water discharge and the number of fish recorded, as well as the total number of fish recordings, was analysed using Pearson correlation test. At the Tana fishway, an increase in water discharge was significantly associated with higher usage of the fishway, both in terms of the number of fish recorded ($r = 0.66$; $n = 24$; $p = 0.0003$) and the total number of recordings ($r = 0.48$; n = 24; $p = 0.0174$). Similarly, a positive relationship was observed at the Prata fishway, but it was not statistically significant for either the number of fish recorded ($r = 0.27$; n = 24; $p > 0.05$) or the total number of recordings ($r = 0.11$; n = 24; $p > 0.05$).

Further investigations were carried out to evaluate whether the higher number of both fish recordings and fish recorded during the trout spawning period (i.e., from October to December) was statistically significant. The Chi-square test revealed a significant difference in the number of recordings and fish recorded only at the Prata fishway (Fish recordings: $\chi^2 = 29.5$, $p < 0.001$; Fish recorded: $\chi^2 = 9.73$, $p = 0.001$). In contrast, no significant differences were observed at the Tana fishway (Fish recordings: $\chi^2 = 1.70$, $p > 0.05$; Fish recorded: $\chi^2 = 1.00$, $p > 0.05$).

3.6. Fishway efficiency

In order to evaluate the fishway efficiency, only the fish tagged within a range of approximately 850 m below the dams (Tana $_{\text{fish tagged}} = 345$; Prata $_{\text{fish tagged}} = 431$) since a larger number of fish was tagged at these sites due to the inaccessibility of the uppermost sites for tagging activities (e.g., presence of reservoirs and higher water discharge), and considering that about 80 % of the fish recorded by the antennas came from these areas, in proximity to the fish passages. The fishway usage is very low for hatchery-reared trout, contrary to the wild type, which were more able to find and use the fishways (Table 3). The overlap rate (R_o) was 66.7 % of target species successfully using the fishways, with bullhead never being recorded at either fishway, and therefore not included in the summarized data table (Table 3). The attraction and passage efficiencies were higher for the Tana fishway (i.e., $\mathbf{E_a} = 16.7$ %; $\mathbf{E_p} = 11.4$ %) compared to the Prata fishway (i.e., $\mathbf{E_a} = 10.6$ %; $\mathbf{E_p} = 6.4$ %), relative to the wild fish. However, this difference was not significant (i.e., Chi-squared test: χ^2 ($\mathbf{E_a}$) = 2.47, $p > 0.05$; χ^2 ($\mathbf{E_p}$) = 2.49, $p > 0.05$). The $\mathbf{E_{pAdj}}$ was quite similar for the two passages, 65.2 % for Tana and 62.1 % for Prata, with no significant differences (χ^2 ($\mathbf{E_p}$) = 0.05, $p > 0.05$). More in detail, for all the metrics, wild and larger trout (i.e., adults) seem to perform better compared to smaller ones (i.e., juveniles and subadults). Only the Tana fishway shows higher percentages of $\mathbf{E_{pAdj}}$ metric relative to the subadult size class. Accordingly, the attraction efficiency was significantly different among fish size classes at the Tana (Chi-squared test: χ^2 ($\mathbf{E_a}$) = 12.56, $p = 0.001$) and Prata fishways (Chi-squared test: χ^2 ($\mathbf{E_a}$) = 15.34, $p = 0.0004$). Fisher's exact test did not reveal a significant association for the utilization rate by the three size classes at the Tana fish passage (i.e., ($\mathbf{E_p}$) $p > 0.05$; ($\mathbf{E_{pAdj}}$) $p > 0.05$). Conversely, significant differences were found for Prata fishway (i.e., ($\mathbf{E_p}$) $p = 0.0001$; ($\mathbf{E_{pAdj}}$) $p = 0.0079$), indicating that there is a size selection in the fishway use. No juvenile fish were recorded passing through the Prata fishway. The time required for fish to pass over the two fishways was on average lower for the Prata fishway than for the Tana fishway (Table 4). Due to the low number of observations (i.e., <5) for the hatchery-reared trout and Cyprinidae, the analysis focused only on Salmonidae. The time required for Salmonidae to bypass Tana fishway was significantly different from that of the Prata fishway as suggested by $\mathbf{T_t}$, $\mathbf{T_d}$ and $\mathbf{S_t}$ metrics ($\mathbf{T_t}$: U = 134.5, Z = 3.84, $p = 0.0001$; $\mathbf{T_d}$: U = 193.5, Z = 2.79, $p = 0.005$; $\mathbf{S_t}$: U = 204.5, Z = 2.59, $p = 0.009$). Moreover, there were no significant differences between the different size classes and the time calculations for each metric, both for Tana ($\mathbf{T_t}$:

Table 3

Attraction and passage efficiencies (i.e., E_p, E_{pAdj} and E_a) for the Salmonidae and Cyprinidae families are reported for the different size classes (i.e., Juvenile, Subadult and Adult) and the two fishways (i.e., Tana and Prata). In addition, the total number of fish released (**N** **released**), those that passed (**N** **passed**), and those that approached (**N** **approach**) the fishways are included. The metrics marked with an asterisk (*) were calculated using a small number of specimens or observations. The results for wild and hatchery-reared Salmonidae are represented by indicating the latter in brackets.

Family	Tana Fishway			Prata fishway		
	E_p	*N passed*	*N released*	E_p	*N passed*	*N released*
Salmonidae	11.4 % (0.0 %)	15 (0)	132 (184)	6.4 % (0 %)	12 (0)	188 (115)
Juveniles	11.1 %	4	36	0 %	0	45
Subadults	7.6 % (0 %)	5 (0)	66 (17)	2.2% (0 %)	2 (0)	89 (29)
Adults	20.0 % (0 %)	6 (0)	30 (167)	18.5 % (0 %)	10 (0)	54 (86)
Cyprinidae	33.3 %*	2	6	7.8 %	4	51
	E_{PAdj}	***N passed***	***N approach***	**E_{PAdj}**	***N passed***	***N approach***
Salmonidae	65.2% (66.7 %)	15 (2)	23 (3)	62.1 % (0 %)	18 (0)	29 (1)
Juveniles	57.1 %	4	7	0 %	0	4
Subadults	100.0 %	5	5	50.0 %	3	6
Adults	54.5 % (66.7 %)	6 (2)	11 (3)	78.9 % (0 %)	15 (0)	19 (1)
Cyprinidae	100 %*	2	2	40 %	4	10
	E_a	***N approach***	***N released***	**E_a**	***N approach***	***N released***
Salmonidae	16.7 % (0.5 %)	22 (1)	132 (184)	10.6 % (0 %)	20 (0)	188 (115)
Juveniles	16.7 %	6	36	8.9 %	4	45
Subadults	7.6 % (0 %)	5 (0)	66 (17)	3.4 % (0 %)	3 (0)	89 (29)
Adults	36.7 % (0.7 %)	11 (1)	30 (167)	24.1 % (0 %)	13 (0)	54 (86)
Cyprinidae	33.3 %*	2	6	19.6 %	10	51

Table 4

Transit time (**T_t**), delay transit time (**T_d**) and delta height transit speed (**S_t**) are shown for fish that passed through the fishway. The metrics represent the time spent by fish for the passage, per group (i.e., family and size class) and were expressed in minutes. The metrics marked with an asterisk (*) have a small number of specimens or observations. The results for wild and hatchery-reared Salmonidae are represented by indicating the latter in brackets.

Fishway		Transit Time (T_t) Mean ± SD	Min	Median	Max	N obs
Tana	**Salmonidae**					
	Total	144 ± 248 (61 ± 58*)	20 (3)	50 (60)	1020 (120)	27 (3)
	Juveniles	284 ± 349	26	120	1020	8
	Subadults	127 ± 232	20	48	780	10
	Adults	40 ± 12 (61 ± 58*)	21 (3)	42 (60)	60 (120)	9 (3)
	Cyprinidae	90 ± NA*	60	90	120	2
Prata	Salmonidae					
	Total	53 ± 161	2	15	840	26
	Subadults	114 ± 272	3	19	840	9
	Adults	21 ± 21	2	10	60	17
	Cyprinidae	65 ± 77*	14	34	180	4

Fishway		Delay Time (T_d) Mean ± SD	Min	Median	Max	N obs
Tana	Salmonidae					
	Total	203 ± 290 (81 ± 67*)	21 (3)	60 (120)	1200 (120)	27 (3)
	Juveniles	322 ± 317	27	240	1020	8
	Subadults	230 ± 356	24	90	1200	10
	Adults	68 ± 87 (81 ± 67*)	21 (3)	44 (120)	300 (120)	9 (3)
	Cyprinidae	180 ± NA*	180	180	180	2
Prata	Salmonidae					
	Total	110 ± 219	2	23	900	26
	Subadults	143 ± 288	7	43	900	9
	Adults	92 ± 180	2	11	720	17
	Cyprinidae	79 ± 68*	27	54	180	4

Fishway		Delta height transit speed (St) Mean ± SD	Min	Median	Max	N obs
Tana	Salmonidae					
	Total	54 ± 92 (22 ± 21*)	7 (1)	18 (22)	380 (44)	27 (3)
	Juveniles	106 ± 130	9	44	380	8
	Subadults	47 ± 86	7	18	291	10
	Adults	15 ± 4 (22 ± 21*)	7 (1)	15 (22)	22 (44)	9 (3)
	Cyprinidae	33 ± NA*	22	33	44	2
Prata	Salmonidae					
	Total	34 ± 104	1	10	545	26
	Subadults	74 ± 177	1	12	545	9
	Adults	14 ± 13	1	6	38	17
	Cyprinidae	42 ± 50*	9	22	116	4

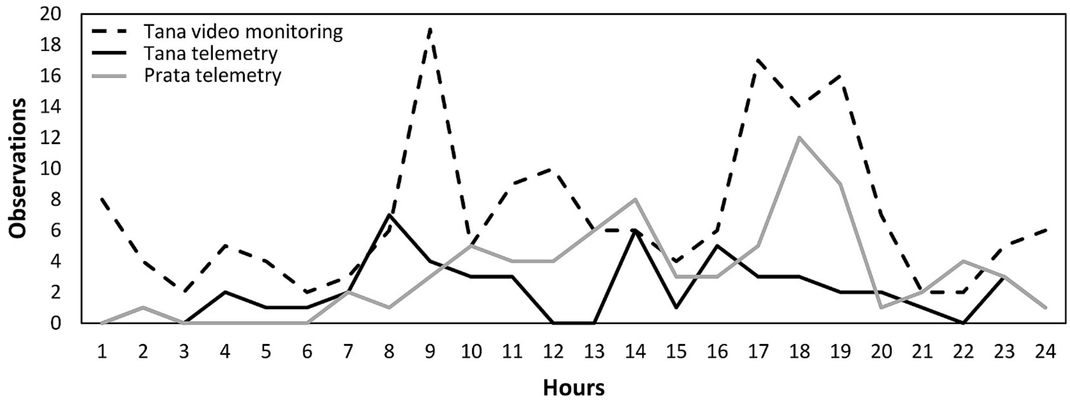

Fig. 7. Comparison of the time during a day (24 h) when the observations of fish passages were recorded by video monitoring and/or telemetry at Tana and Prata fishways. Each observation corresponds to a specimen, either through its tag code for telemetry or through visual identification in case of video monitoring. Observations are time-based, with separate instances occurring at least 1 h apart and corresponding to the end of the recorded movement.

H = 4.78, $p > 0.05$; $\mathbf{T_d}$: H = 3.76, p > 0.05; $\mathbf{S_t}$: H = 4.78, p > 0.05) and for Prata ($\mathbf{T_t}$: U = 62, Z = 0.75, p > 0.05; $\mathbf{T_d}$: U = 57, Z = 1.02, p > 0.05; $\mathbf{S_t}$: U = 62, Z = 0.75, p > 0.05). The percentages of fallback events were 30 % for Salmonidae (i.e., 8 specimens out of 26 recorded) and 0 % for Cyprinidae (i.e., 0 specimens out of 2 recorded) at the Tana fishway. In contrast, at the Prata fishway, the percentages were 20 % for Salmonidae (i.e., 6 specimens out of 30 recorded) and 10 % for Cyprinidae (i.e., 1 specimen out of 10 recorded).

3.7. Comparison between telemetry and video monitoring

The video monitoring system worked for 312 days and 7488 h, with a few interruptions due to power outages, covering 90 % of the total period. A total of 168 fish passages were observed, and 84 fish were detected. The number of observed fish was lower than the number of total observations because some fish were recorded more than once. Out of the 84 fish recorded at the Tana fishway, 82 were Salmonidae (i.e., 81 *Salmo* spp., 1 *Oncorhynchus mykiss*), while only 2 Cyprinidae (i.e., *Telestes muticellus*). In the same period, the antenna recorded only 22 fishes: 20 *Salmo* spp. and 2 cyprinids (i.e., *Telestes muticellus*) (Fig. 6). The direction of the movement was mostly upward (88 % of the observations).

A comparison between the number of fish passages recorded by the two different monitoring systems across the seasons was performed using the Chi-square test. The result showed a dependency between the two categorical variables, indicating that the number of fish recorded by the different monitoring systems varied across the seasons (Chi-squared test: $\chi^2 = 32.7$, $p < 0.001$). Post-hoc pairwise comparisons using the Bonferroni correction indicated a significant difference for the autumn season when compared to spring (p < 0.001), summer ($p = 0.033$) and winter (p < 0.001).

Moreover, the video observations of the time of fish movements throughout 24 h are reported in Fig. 7, along with those recorded by PIT tag telemetry for comparison. Results show that the fishways were used continuously throughout the daytime with two main peaks of activity close to sunrise and sunset. On the contrary, a lower use during nighttime was recorded, in agreement with telemetry data at both fishways.

4. Discussion

This study aimed to assess the effectiveness and efficiency of two step-pool fishways with vertical slots in a large Alpine River in northern Italy. The fish used for this study included both wild and hatchery-reared trout, cyprinids (e.g., barbel, chub and minnow) and bullhead inhabiting the Toce River, and that were PIT tagged throughout the river course. The two fishways were different since only one had holes at the base of each septum. Two different monitoring systems were used (PIT tag telemetry and videorecording) to maximize the data collection with the ultimate goal of improving the knowledge on the functionality of these structures for conservation purposes.

4.1. Fishway effectiveness

The data gathered from both monitoring systems indicate that salmonids and cyprinids could use the fishways. This is not surprising, as these fish groups were target species considered when designing the two fishways (G.R.A.I.A, 2018). A specific power dissipation value of less than 150 W/m^3 was used for the basin, in accordance with Larinier et al. (1994). Among the fish species inhabiting the river, bullhead did not use the fishways, even though one of them (Tana dam) was built including holes at the base of each septum. It can be argued that the absence of detection is due to the low number of bullheads tagged ($n = 23$). However, no passages have been recorded by the video monitoring system, thus corroborating PIT tag telemetry results.

Wiegleb et al. (2023) found a passage probability reduction of 39.29 % for bullhead when the water discharge increases from 0.080 m^3 s^{-1} to 0.130 m^3 s^{-1}. Consistently, under normal functioning conditions, the water discharge at the Tana fishway is 0.350 m^3 s^{-1} (0.475 and 0.156 m^3 s^{-1} during maximum and minimum operation) (G.R.A.I.A, 2018), while that computed for the Prata fishway is 0.424 ± 0.384 m^3 s^{-1} (MIN = 0.066 m^3 s^{-1}, MAX = 3.218 m^3 s^{-1}) (Poleni et al., 1717), and can be found in Supplementary Material S1.2. Therefore, within this range of water discharge, bullheads have a few chances to swim through the fishways. The vertical slots without holes at the base of each septum would oblige bullheads to leave their typical habitat (i.e., the riverbed) and swim up into the water column to complete the passage. This could be problematic in the artificial habitat, which lacks natural sheltering zones (i.e., cobbles and boulders) used by the fish to escape from unfavourable water flow conditions (Carlson and Lauder, 2011). As suggested by some authors, flow conditions inside the fishways are an important factor for fish passage success (Wiegleb et al., 2022, 2023). Guaranteeing variable flow conditions is crucial to allow the passage of different fish species and sizes, thereby achieving biodiversity conservation purposes. Adaptive technical solutions can then be implemented, such as the use of spoiler baffles and macroroughness (i.e., substratum with embedded gravel or cobbles, staggered rows of rectangular-shaped baffles) or the insertion of additional structures (e.g., vertical cylinders) at the bottom of the fishway. These modifications could create suitable variable flow conditions for fish, particularly for benthic and small species (Franklin and Bartels, 2012; Calluaud et al., 2014; Peter et al., 2022). A retrofitting alternative and cost-effective option is the use of permeable brush blocks, which could be installed in a short-time (Kucukali et al., 2023).

4.2. Fishway efficiency

Different metrics were used to assess the efficiency of the two fishways. In most of fish passage studies, the main metrics investigated are usually $\mathbf{E_a}$ (i.e., attraction efficiency) and $\mathbf{E_p}$ (i.e., passage efficiency). As suggested by some authors (Cooke and Hinch, 2013), the metrics should be informative both for the upstream and the downstream passage within the fishway. However, in this study, only the upstream passage was investigated due to the unsuitability for field activities of the sites located upstream of the dam, resulting in a low number of fish tagged. According to reviews available in the literature (Noonan et al., 2012; Bunt et al., 2016; Sun et al., 2023), the mean values of $\mathbf{E_p}$ and $\mathbf{E_a}$ for Salmonidae are 61.7–70.0 % (total range from 0 % to 100 %) and 65.1–69.9 % (total range from 14 % to 100 %), respectively. In our study, the values for $\mathbf{E_p}$ (i.e., $\mathbf{E_{pAdj}}$) for Salmonidae (i.e., 65.4 % at the Tana fishway and 60.0 % at the Prata fishway) were within the ranges aforementioned. In contrast, the $\mathbf{E_a}$ values (i.e., 7.2 % at the Tana fishway and 6.6 % at the Prata fishway) were much lower compared to the average and minimum values found in the literature. If only wild Salmonidae were considered, the $\mathbf{E_a}$ values were slightly higher (i.e., 16.7 % at the Tana fishway and 9.5 % at the Prata fishway). At the same time, the attraction efficiency appears to be very low.

However, it is necessary to consider additional factors about the terms used for different efficiency metrics, which are typically divided into three phases: approach, entrance, and passage (Castro-Santos et al., 2009). Some authors (Kemp, 2016) have suggested that discrepancies exist in the definitions and methods used to evaluate fishway performance. This is particularly true for attraction and entrance efficiency metrics, which can be assessed either by the number of fish recorded by antennas located at the tailrace or at the entrance of the fish passage (Bunt et al., 2012; Lothian et al., 2020; Keefer et al., 2021), or by using inner antennas in other cases (Bunt and Jacobson, 2019; Lothian et al., 2019; Bravo-Córdoba et al., 2022). In this study, attraction efficiency was evaluated using inner antennas. To some extent, the values we calculated for attraction efficiency may actually better reflect the metrics related to entrance efficiency. Noonan et al., 2012 showed that overall mean attraction efficiency (i.e., $\bar{x} = 65.1$ %, SE = 7.6; $N_{paper} = 12$) is usually higher than the mean entrance efficiency (i.e., $\bar{x} = 39.6$ %, SE = 8.1; $N_{paper} = 11$). However, Hershey (2021) reported high entrance efficiency for Salmonidae (i.e., $\bar{x} = 60.0$ %, SE = 29; Min = 0 %; Max = 100 %; $N_{paper} = 62$). In both cases, our results are lower than those documented, suggesting that finding and entering the fishways by fish was more challenging rather than completing the passage.

Hatchery-reared salmonids were unable to use the fishways as effectively as the wild fish. Out of 299 fish tagged at the hatchery and released from last summer to winter (Number of fish released; August = 15, September = 52, October = 117, November = 90, February = 25), only 4 specimens (0.013 %) approached the fishways and only 2 (0.006 %) passed. It is known that wild fish have higher swimming abilities (Johnsson et al., 1996; Domenici and Batty, 1997; Faucher et al., 2006; Lefrançois and Domenici, 2006), higher fitness in the natural environment (Berejikian et al., 2001) and better cognitive abilities (Rodewald et al., 2011) than hatchery-reared fish. In this study, fish were released in the river after three or four years of hatchery rearing. Therefore, the inability of hatchery-reared fish to use the fishway is likely related to the domestication process and behavioural trait selection in the hatchery (e.g., loss of migratory behaviour, becoming resident when released into the natural environment), which can be altered in only one generation of captive rearing (Bégout-Anras and Lagardère, 2004; Huntingford, 2004).

4.3. Efficiency comparison between studied fishways

The overall passage efficiency was the same for both fishways (i.e., 66.7 %). In addition, both fishways revealed the same problems for *Cottus gobio*. The passage (both overall and adjusted) and attraction efficiency for the wild salmonid group were slightly higher for the Tana fishway, but not significantly different, indicating that there is no substantial difference between them, contrary to our expectations. The previous results for the hatchery-reared trout were quite similar across all the metrics and fishways, highlighting their lack of ability to use the fishway structures.

The only difference detected between the two fishways relates to trout size. Larger individuals (i.e., adult fish; TL $\geq$ 30.7 cm) exhibited better passage performance in terms of usage and transit time at the Prata fishway, while at the Tana fishway, no differences were detected except for attraction efficiency. The longer time required to pass is likely due to the size of the fishway, with the Tana fishway being longer and steeper.

4.4. Successful combination of telemetry and videorecording results

Overall, video monitoring appears to represent fishway usage more accurately and helps address a gap related to the low number of tagged fish, which may not be representative of the population size. This method was effective in estimating the use of the fishway for downstream migration, but it did not accurately measure the attraction efficiency. Indeed, video monitoring can present challenges when it comes to distinguish individual fish from the footage (Cooke and Hinch, 2013). The direction of the recorded passages by video monitoring was almost all upward (88 %), with a few passages recorded downward (12 %). The two types of monitoring (i.e., telemetry and video monitoring) showed comparable results, indicating a problem in the downward use of the fishway. Under other circumstances, some authors argued that there were no differences between upward and downward passage efficiency (Noonan et al., 2012). In addition, our findings indicate that 21.4 % (12 out of 56) of the trout recorded by the antennas were able to migrate downstream through the dam spillways. Generally, downstream migration occurs as fish follow the bulk flow of water, with salmonids generally exhibiting a surface orientation (Coutant and Whitney, 2000). Fish migrating downstream have less time to assess environmental conditions compared to those migrating upstream. On the other hand, the main flow typically guides the fish through turbines or other routes rather than bypass channels (Williams et al., 2012). Downstream passage via spillways can be influenced by high run-off events and the partial or total opening of the gates. In summary, the fishways appear to be inefficient in guiding fish to locate and enter the fishway from upstream sites, posing a risk to different species and life stages. This includes highly economically valuable migratory iteroparous species, such as lacustrine marble trout, which migrate from the lake to upstream waters for spawning, as well as small-bodied fish of less interest, like bullhead (*Cottus gobio*) (Knott et al., 2023). Therefore, there is a need to find technical solutions to guide fish safely into the fishways. Nowadays, mechanical (e.g., bar or mesh screens), behavioural (e.g., acustic and electric), and hybrid barriers (e.g., a combination of the two) are used as guidance structures, taking into account costs, target species, and hydrological characteristics (Schwevers and Adam, 2019). However, due to the high costs of these structures, low-cost alternatives can be considered. In some contexts, the use of behavioural barriers (e.g., bubble curtains, ligth systems and acoustic barriers) and their combinations is regarded as an efficient method for guiding multiple fish species, including migratory fish (e.g., smolts and kelts of salmonids), by preventing downstream access to channels and turbines and steering fish toward fishways, thereby improving their survival rates (Noatch and Suski, 2012; Flammang et al., 2014; Leander et al., 2024; Stoilova, 2024). Motivation to migrate is one of the fish biological drivers influencing efficiency estimates (Cooke and Hinch, 2013; Bunt et al., 2016; Bunt et al., 2012). Our results show that the periods with a greater number of fish recordings were mainly autumn and spring, which are associated with higher water discharges. Additionally, the fishways were used more frequently during the spawning period which occurs in autumn. These findings are in agreement with other studies indicating that high water discharge has an overwhelming influence on some fish species' movements (Piper et al., 2013; Bultel et al., 2014) as well as that the motivation of fish to migrate upstream of a barrier is associated with levels of reproductive hormones (Thiem et al., 2013), increasing just before or during the spawning period.

5. Conclusions

In this study, we reported and discussed the results of a two year study that combined PIT tag telemetry and video-monitoring to assess the effectiveness and efficiency of two fishways built along an Alpine River to mitigate habitat fragmentation. The fishways allow the upstream passage of wild salmonids and cyprinids, but not bullheads, which have never been recorded by either telemetry or video monitoring. Hatchery-reared salmonids did not use the fishways as effectively as wild fish, suggesting deficient performances due to alteration of behavioural traits after a few years of captive rearing. Statistical analyses of fishway efficiency metrics did not show significant differences between the two fishways, except for the transit time metrics, with shorter passage times and better performance for larger individuals observed for the Prata fishway. Finally, our results indicate that video monitoring is a useful tool that can be effectively combined with PIT tag telemetry to estimate fishway usage, and that both fishways are mainly used during spring and autumn, in correspondence with high water discharge and with spawning period.

The comparison of our results with those found in the literature was challenging due to differences in experimental design, technical aspects of the fishways, study sites, and target fish species. Nevertheless, our results showed that the passage efficiency is within the range of values reported in the literature, while the attraction efficiency is instead very low. In general, the total efficiency of a fishway should be summarized by the product of the probability of attraction efficiency (i.e., number of fish tagged that can locate the fishway), entrance efficiency (i.e., number of fish tagged that can enter the fishway), and passage efficiency (i.e., number of fish tagged that enter the fishway and pass through). However, due to the inconsistency in the terms used in the literature and methodological constraints, the metric of attraction efficiency calculated in this work is well adapted to the entrance efficiency only. Based on our data, we suggest that implementing technical structures, such as sheltering zones and permeable brush blocks near the fishway's bed, could help guide the bullhead into the vertical opening to complete the passage. Furthermore, the use of guidance structures (e.g., bubble gas barrier) is needed to prevent downstream migration through channels and turbines. These actions are essential to avoid the fragmentation of the Toce River and to support the ecological functions of key habitats for all species, achieving biodiversity conservation goals. Further data and additional technological equipment are needed to enhance our understanding of the real attraction efficiency and so the total efficiency of both fishways. For instance, the use of supplem*ent*ary antennas at the entrance of the fishways, along with temperature and water discharge sensors below the dams, could help determine the real attraction efficiency and the driving forces behind it.

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CRediT authorship contribution statement

Mattia Iaia: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Silvia Quadroni:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Stefano Brignone:** Writing – review & editing, Methodology. **Armando Piccinini:** Writing – review & editing, Methodology, Conceptualization. **Roberta Bettinetti:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Pietro Volta:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

All the authors have nothing to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2025.107535.

Data availability

Main data are provided whithin the manuscript and Supplementary informtion file. Further information is available from the corresponding author upon reasonable request.

References

ADBPO, 2018. Linee generali di assetto idrogeologico e quadro degli interventi-Bacino del Fiume Toce. Available at https://pai.adbpo.it/index.php/linee-generali-di-assetto-idraulico-e-idrogeologico/. Accessed (May 2023).

Bao, J., Li, W., Zhang, C., Mi, X., Li, H., Zhao, X., Cao, N., Twardek, W.M., Cooke, S.J., Duan, M., 2019. Quantitative assessment of fish passage efficiency at a vertical-slot fishway on the Daduhe River in Southwest China. Ecol. Eng. 141, 105597. https://doi.org/10.1016/j.ecoleng.2019.105597.

Bégout-Anras, M.L., Lagardère, J.P., 2004. Domestication et comportement chez les poissons téléostéens. INRAE Product. Anim. 17, 211–215. https://doi.org/10.20870/productions-animales.2004.17.3.3594.

Berejikian, B.A., Tezak, E.P., Park, L., LaHood, E., Schroder, S.L., Beall, E., 2001. Male competition and breeding success in captively reared and wild coho salmon (Oncorhynchus kisutch). Can. J. Fish. Aquat. Sci. 58, 804–810. https://doi.org/10.1139/f01-039.

Birnie-Gauvin, K., Franklin, P., Wilkes, M., Aarestrup, K., 2019. Moving beyond fitting fish into equations: Progressing the fish passage debate in the Anthropocene. Aquat. Conserv. Mar. Freshwat. Ecosyst. 29, 1095–1105. https://doi.org/10.1002/aqc.2946.

Boggs, C.T., Keefer, M.L., Peery, C.A., Bjornn, T.C., Stuehrenberg, L.C., 2004. Fallback, Reascension, and Adjusted Fishway Escapement estimates for Adult Chinook Salmon and Steelhead at Columbia and Snake River Dams. Trans. Am. Fish. Soc. 133, 932–949. https://doi.org/10.1577/T03-133.1.

Bravo-Córdoba, F.J., Fuentes-Pérez, J.F., García-Vega, A., Peñas, F.J., Barquín, J., Sanz-Ronda, F.J., 2022. Brown Trout Upstream Passage Performance for a Fishway with Water Drops between Pools beyond fish Passage Design Recommendations. Water 14, 2750. https://doi.org/10.3390/w14172750.

Brown, R.S., Cooke, S.J., Anderson, W.G., McKinley, R.S., 1999. Evidence to Challenge the "2% rule" for Biotelemetry. N. Am. J. Fish Manag. 19, 867–871. https://doi.org/10.1577/1548-8675(1999)019<0867:ETCTRF>2.0.CO;2.

Bultel, E., Lasne, E., Acou, A., Guillaudeau, J., Bertier, C., Feunteun, E., 2014. Migration behaviour of silver eels (*Anguilla anguilla*) in a large estuary of Western Europe inferred from acoustic telemetry. Estuar. Coast. Shelf Sci. 137, 23–31. https://doi.org/10.1016/j.ecss.2013.11.023.

Bunt, C., Jacobson, B., 2019. Rainbow Trout Migration and use of a Nature-like Fishway at a Great Lakes Tributary. N. Am. J. Fish Manag. 39, 460–467. https://doi.org/10.1002/nafm.10285.

Bunt, C.M., Castro-Santos, T., Haro, A., 2012. Performance of fish Passage Structures at Upstream Barriers to Migration. River Res. Appl. 28, 457–478. https://doi.org/10.1002/rra.1565.

Bunt, C.M., Castro-Santos, T., Haro, A., 2016. Reinforcement and Validation of the Analyses and Conclusions Related to Fishway Evaluation Data from Bunt et al.: 'Performance of Fish Passage Structures at Upstream Barriers to Migration'. River Res. Appl. 32, 2125–2137. https://doi.org/10.1002/rra.3095.

Calles, E.O., Greenberg, L.A., 2005. Evaluation of nature-like fishways for re-establishing connectivity in fragmented salmonid populations in the River Emån. River Res. Appl. 21, 951–960. https://doi.org/10.1002/rra.865.

Calluaud, D., Pineau, G., Texier, A., David, L., 2014. Modification of vertical slot fishway flow with a supplementary cylinder. J. Hydraul. Res. 52, 614–629. https://doi.org/10.1080/00221686.2014.906000.

Carlson, R.L., Lauder, G.V., 2011. Escaping the flow: boundary layer use by the darter Etheostoma tetrazonum (Percidae) during benthic station holding. J. Exp. Biol. 214, 1181–1193. https://doi.org/10.1242/jeb.051938.

Castro-Santos, T., Cotel, A., Webb, P.W., 2009. Fishway evaluations for better bioengineering – an integrative approach. In: Challenges for Diadromous Fishes in a Dynamic Global Environment, pp. 557–575.

Castro-Santos, T., Sanz-Ronda, F.J., Ruiz-Legazpi, J., 2013. Breaking the speed limit — comparative sprinting performance of brook trout (Salvelinus fontinalis) and brown trout (Salmo trutta). Can. J. Fish. Aquat. Sci. 70, 280–293. https://doi.org/10.1139/cjfas-2012-0186.

Cooke, S.J., Hinch, S.G., 2013. Improving the reliability of fishway attraction and passage efficiency estimates to inform fishway engineering, science, and practice. Ecol. Eng. 58, 123–132. https://doi.org/10.1016/j.ecoleng.2013.06.005.

Copp, G.H., 1995. Evaluating microhabitat use of fish larvae and juveniles with Point Abundance Sampling. Copp, G.H. & Garner, P. 1995. Folia Zool. 44, 145–158.

Coutant, C.C., Whitney, R.R., 2000. Fish Behavior in Relation to Passage through Hydropower Turbines: a Review. Trans. Am. Fish. Soc. 129, 351–380. https://doi.org/10.1577/1548-8659(2000)129<0351:FBIRTP>2.0.CO;2.

Domenici, P., Batty, R.S., 1997. Escape behaviour of solitary herring (Clupea harengus) and comparisons with schooling individuals. Mar. Biol. 128, 29–38. https://doi.org/10.1007/s002270050065.

Faucher, K., Fichet, D., Miramand, P., Lagardère, J.P., 2006. Impact of acute cadmium exposure on the trunk lateral line neuromasts and consequences on the "C-start" response behaviour of the sea bass (*Dicentrarchus labrax* L.; Teleostei, Moronidae). Aquat. Toxicol. 76, 278–294. https://doi.org/10.1016/j.aquatox.2005.10.004.

Flammang, M.K., Weber, M.J., Thul, M.D., 2014. Laboratory Evaluation of a Bioacoustic Bubble Strobe Light Barrier for reducing Walleye Escapement. N. Am. J. Fish Manag. 34, 1047–1054. https://doi.org/10.1080/02755947.2014.943864.

Franklin, P.A., Bartels, B., 2012. Restoring connectivity for migratory native fish in a New Zealand stream: effectiveness of retrofitting a pipe culvert. Aquat. Conserv. Mar. Freshwat. Ecosyst. 22, 489–497. https://doi.org/10.1002/aqc.2232.

G.R.A.I.A, 2018. Relazione generale e tecnica. Action A.3 - Progettazione degli interventi di deframmentazione - Planning of interventions of longitudinal connectivity restoration, p. 87.

Giuffra, E., Guyomard, R., Forneris, G., 1996. Phylogenetic relationships and introgression patterns between incipient parapatric species of Italian brown trout (Salmo trutta L. complex). Mol. Ecol. 5, 207–220. https://doi.org/10.1046/j.1365-294X.1996.00074.x.

Hammer, Ø., 2001. PAST : paleontological statistics software package for education and data analysis. Palaeontol. Electron. 4, 9.

Hershey, H., 2021. Updating the consensus on fishway efficiency: a meta-analysis. Fish Fish. 22, 735–748. https://doi.org/10.1111/faf.12547.

Huntingford, F.A., 2004. Implications of domestication and rearing conditions for the behaviour of cultivated fishes. J. Fish Biol. 65, 122–142. https://doi.org/10.1111/j.0022-1112.2004.00562.x.

Ielli, F., Duchi, A., 1990. Ielli: Indagini preliminari sulle caratteristiche... - Google Scholar [WWW Document]. URL. https://scholar.google.com/scholar_lookup?title=Indagini%20preliminari%20sulle%20caratteristiche%20morfologiche%20di%20alcune%20trote%20marmorate%20Salmo%20trutta%20marmoratus%20Cuv,%20pure%20ed%20ibride%20del%20torrente%20Avisio%20(Val%20di%20Fiemme,%20Trento)&author=Jelli&publication_year=1990 (accessed 9.5.24).

Jepsen, N., 2004. A brief discussion of the 2% tag/bodymass rule. In: Aquatic Telemetry: Advances and Applications.

Johnsson, J.I., Petersson, E., Jönsson, E., Björnsson, B.T., Järvi, T., 1996. Domestication and growth hormone alter antipredator behaviour and growth patterns in juvenile brown trout, Salmo trutta. Can. J. Fish. Aquat. Sci. 53, 1546–1554. https://doi.org/10.1139/f96-090.

Jørgensen, M.G.P., van Deurs, M., Butts, I.A.E., Jørgensen, K., Behrens, J.W., 2017. PIT-tagging method for small fishes: a case study using sandeel (*Ammodytes tobianus*). Fish. Res. 193, 95–103. https://doi.org/10.1016/j.fishres.2017.04.002.

Keefer, M.L., Jepson, M.A., Clabough, T.S., Caudill, C.C., 2021. Technical fishway passage structures provide high passage efficiency and effective passage for adult Pacific salmonids at eight large dams. PLoS One 16, e0256805. https://doi.org/10.1371/journal.pone.0256805.

Kemp, P.S., 2016. Meta-analyses, Metrics and Motivation: mixed Messages in the fish Passage debate. River Res. Appl. 32, 2116–2124. https://doi.org/10.1002/rra.3082.

Knaepkens, G., Maerten, E., Tudorache, C., De Boeck, G., Eens, M., 2007. Evaluation of passive integrated transponder tags for marking the bullhead (Cottus gobio), a small benthic freshwater fish: effects on survival, growth and swimming capacity. Ecol. Freshw. Fish 16, 404–409. https://doi.org/10.1111/j.1600-0633.2007.00231.x.

Knott, J., Mueller, M., Pander, J., Geist, J., 2023. Downstream fish passage at small-scale hydropower plants: Turbine or bypass? Front. Environ. Sci. 11. https://doi.org/10.3389/fenvs.2023.1168473.

Kottelatt & Freyhof, 2007. Handbook of European freshwater fishes | Wageningen University and Research Library catalog [WWW Document]. URL. https://library.wur.nl/WebQuery/titel/1862482 (accessed 9.5.24).

Kucukali, S., Alp, A., Albayrak, I., 2023. Retrofitting Vertical Slot fish Pass with Brush Blocks: Hydraulics Performance. Water 15, 1155. https://doi.org/10.3390/w15061155.

Landsman, S.J., McLellan, N., Platts, J., van den Heuvel, M.R., 2018. Nonsalmonid versus Salmonid Passage at Nature-like and Pool-and-Weir Fishways in Atlantic Canada, with special attention to Rainbow Smelt. Trans. Am. Fish. Soc. 147, 94–110. https://doi.org/10.1002/tafs.10019.

Larinier, M., 2008. Fish passage experience at small-scale hydro-electric power plants in France. Hydrobiologia 609, 97–108. https://doi.org/10.1007/s10750-008-9398-9.

Larinier, Travade, Porcher, 2002. Fishways: biological basis, design criteria and monitoring | Wageningen University and Research Library catalog [WWW Document]. URL. https://library.wur.nl/WebQuery/titel/1662988 (accessed 8.28.24).

Larinier, M., Travade, F., 1998. Petits aménagements hydroélectriques et libre circulation des poissons migrateurs. La Houille Blanche 84, 46–51. https://doi.org/10.1051/lhb/1998093.

Larinier, M., Porcher, J.P., Travade, F., Gosset, C., 1994. Passes a poissons. Expertise, conception des ouvrages de franchissement.

Leander, J., Hellström, G., Nordin, J., Jonsson, M., Klaminder, J., 2024. Guiding downstream migrating Atlantic salmon (Salmo salar) and brown trout (Salmo trutta) of different life stages in a large river using bubbles. River Res. Appl. 40, 107–115. https://doi.org/10.1002/rra.4209.

Lefrançois, C., Domenici, P., 2006. Locomotor kinematics and behaviour in the escape response of European sea bass, Dicentrarchus labrax L., exposed to hypoxia. Mar. Biol. 149, 969–977. https://doi.org/10.1007/s00227-006-0261-0.

Lothian, A.J., Gardner, C.J., Hull, T., Griffiths, D., Dickinson, E.R., Lucas, M.C., 2019. Passage performance and behaviour of wild and stocked cyprinid fish at a sloping weir with a Low cost Baffle fishway. Ecol. Eng. 130, 67–79. https://doi.org/10.1016/j.ecoleng.2019.02.006.

Lothian, A.J., Schwinn, M., Anton, A.H., Adams, C.E., Newton, M., Koed, A., Lucas, M.C., 2020. Are we designing fishways for diversity? Potential selection on alternative phenotypes resulting from differential passage in brown trout. J. Environ. Manag. 262, 110317. https://doi.org/10.1016/j.jenvman.2020.110317.

Moro, G.A., 2019. Osservazioni sull'attivita' riproduttiva di Salmo marmoratus Cuvier, 1829, in Friuli Venezia Giulia. Italian J. Freshwater Ichtyol. 5, 132–146.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and Flow Regulation of the World's large River Systems. Science 308, 405–408. https://doi.org/10.1126/science.1107887.

Noatch, M.R., Suski, C.D., 2012. Non-physical barriers to deter fish movements. Environ. Rev. 20, 71–82. https://doi.org/10.1139/a2012-001.

Noonan, M.J., Grant, J.W.A., Jackson, C.D., 2012. A quantitative assessment of fish passage efficiency. Fish Fish. 13, 450–464. https://doi.org/10.1111/j.1467-2979.2011.00445.x.

OTA, 1995. Fish Passage Technologies: Protection at Hydropower Facilities, OTA-ENV-641. U.S. Government Printing Office, Washington, DC.

Ovidio, M., Sonny, D., Dierckx, A., Watthez, Q., Bourguignon, S., de le Court, B., Detrait, O., Benitez, J.P., 2017. The use of behavioural metrics to evaluate fishway efficiency. River Res. Appl. 33, 1484–1493. https://doi.org/10.1002/rra.3217.

Parsley, M.J., Wright, C.D., Van Der Leeuw, B.K., Kofoot, E.E., Peery, C.A., Moser, M.L., 2007. White sturgeon (Acipenser transmontanus) passage at the Dalles Dam, Columbia River, USA. J. Appl. Ichthyol. 23, 627–635. https://doi.org/10.1111/j.1439-0426.2007.00869.x.

Peter, A., Schoelzel, N., Wilmsmeier, L., Albayrak, I., Bravo-Córdoba, F.J., García-Vega, A., Fuentes-Pérez, J.F., Valbuena-Castro, J., Carazo-Cea, O., Escudero-Ortega, C., Sanz-Ronda, F.J., Calluaud, D., Pineau, G., David, L., 2022. The Attractiveness of Fishways and Bypass Facilities. In: Rutschmann, P., Kampa, E., Wolter, C., Albayrak, I., David, L., Stoltz, U., Schletterer, M. (Eds.), Novel Developments for Sustainable Hydropower. Springer International Publishing, Cham, pp. 61–81. https://doi.org/10.1007/978-3-030-99138-8_5.

Piper, A.T., Wright, R.M., Walker, A.M., Kemp, P.S., 2013. Escapement, route choice, barrier passage and entrainment of seaward migrating European eel, *Anguilla anguilla*, within a highly regulated lowland river. Ecol. Eng. 57, 88–96. https://doi.org/10.1016/j.ecoleng.2013.04.030.

Poleni, G., Comino, G., PBL, 1717. Ioannis Poleni ... De motu aquae mixto libri duo. Quibus multa nova pertinentia ad portus, atque ad flumina continentur. Typis Iosephi Comini, Patavii.

Polgar, G., Iaia, M., Sala, P., Khang, T.F., Galafassi, S., Zaupa, S., Volta, P., 2023. Size-age population structure of an endangered and anthropogenically introgressed northern Adriatic population of marble trout (Salmo marmoratus Cuv.): insights for its conservation and sustainable exploitation. PeerJ 11, e14991. https://doi.org/10.7717/peerj.14991.

Pompeu, P.S., Agostinho, A.A., Pelicice, F.M., 2012. Existing and Future challenges: the Concept of successful fish Passage in South America. River Res. Appl. 28, 504–512. https://doi.org/10.1002/rra.1557.

PTAGIS, 2014. Pacific States Marine Fisheries Commission, p. 2014.

Regione Piemonte, 2007. Piano di Tutela delle Acque (D. C. R. n. 117-10731). Sottobacino: Ticino. AI33-Toce Regione Piemonte, Monitoraggio della fauna ittica.

Available at https://www.regione.piemonte.it/web/temi/agricoltura/tutela-della-fauna-caccia-pesca/monitoraggio-dellittiofauna-piemonte. Accessed (4 July 2023).
Regione Piemonte, 2021. Approvazione, con valenza ricognitoria, dell'elenco delle grandi derivazioni idroelettriche ricadenti sul territorio della Regione Piemonte (D. G.R. 28-2708/20).
Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd, K.A., MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., Cooke, S.J., 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. 94, 849–873. https://doi.org/10.1111/brv.12480.
Righi, T., Fasola, E., Iaia, M., Stefani, F., Volta, P., 2023. Limited contribution of hatchery-produced individuals to the sustainment of wild marble trout (*Salmo marmoratus* Cuvier, 1829) in an Alpine basin. Sci. Total Environ. 892, 164555. https://doi.org/10.1016/j.scitotenv.2023.164555.
Rodewald, P., Hyvärinen, P., Hirvonen, H., 2011. Wild origin and enriched environment promote foraging rate and learning to forage on natural prey of captive reared Atlantic salmon parr. Ecol. Freshw. Fish 20, 569–579. https://doi.org/10.1111/j.1600-0633.2011.00505.x.
Roscoe, D.W., Hinch, S.G., 2010. Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish Fish. 11, 12–33. https://doi.org/10.1111/j.1467-2979.2009.00333.x.
Saidi, H., Ciampitiello, Dresti, 2014. Il cambiamento climatico e le piogge: analisi dell'evoluzione delle piogge stagionali e degli eventi estremi negli ultimi 50 anni nella stazione di Pallanza§.
Sanz-Ronda, F., Bravo Córdoba, F., Fuentes, J., Castro-Santos, T., 2016. Ascent ability of brown trout, Salmo trutta, and two Iberian cyprinids - Iberian barbel, Luciobarbus bocagei, and northern straight-mouth nase, Pseudochondrostoma duriense - in a vertical slot fishway. Knowl. Manag. Aquat. Ecosyst. 2016, 1–9. https://doi.org/10.1051/kmae/2015043.
Schiavon, A., Comoglio, C., Candiotto, A., Hölker, F., Ashraf, M.U., Nyqvist, D., 2023. Survival and swimming performance of a small-sized Cypriniformes (Telestes muticellus) tagged with passive integrated transponders. J. Limnol. 82. https://doi.org/10.4081/jlimnol.2023.2129.
Schilt, C.R., 2007. Developing fish passage and protection at hydropower dams. Appl. Anim. Behav. Sci. Fish Behav. Welf. 104, 295–325. https://doi.org/10.1016/j.applanim.2006.09.004.
Schwevers, U., Adam, B., 2019. Fish Protection Technologies and Fish Ways for Downstream Migration. Springer.
Stoilova, V., 2024. Behavioural Guidance Systems for Downstream Migrating Fish: A Mini-review. In: Kalinowska, M.B., Mrokowska, M.M., Rowiński, P.M. (Eds.), Advances in Hydraulic Research. Springer Nature, Switzerland, Cham, pp. 385–396. https://doi.org/10.1007/978-3-031-56093-4_31.
Sun, J., Tan, J., Zhang, Q., Shen, Y., Shi, J., Zhang, H., Shi, X., 2023. Attraction and passage efficiency for salmonids and non-salmonids based on fishway: a meta-analysis approach. River Res. Appl. 39, 1933–1949. https://doi.org/10.1002/rra.4194.
Thiem, J.D., Hatin, D., Dumont, P., Van Der Kraak, G., Cooke, S.J., 2013. Biology of lake sturgeon (Acipenser fulvescens) spawning below a dam on the Richelieu River, Quebec: behaviour, egg deposition, and endocrinology. Can. J. Zool. 91, 175–186. https://doi.org/10.1139/cjz-2012-0298.
Vincenzi, S., Crivelli, A.J., Jesensek, D., Rossi, G., De Leo, G.A., 2011. Innocent until proven guilty? Stable coexistence of alien rainbow trout and native marble trout in a Slovenian stream. Naturwissenschaften 98, 57–66. https://doi.org/10.1007/s00114-010-0741-4.
Vollset, K.W., Lennox, R.J., Thorstad, E.B., Auer, S., Bär, K., Larsen, M.H., Mahlum, S., Näslund, J., Stryhn, H., Dohoo, I., 2020. Systematic review and meta-analysis of PIT tagging effects on mortality and growth of juvenile salmonids. Rev. Fish Biol. Fish. 30, 553–568. https://doi.org/10.1007/s11160-020-09611-1.
Watson, J.R., Goodrich, H.R., Cramp, R.L., Gordos, M.A., Franklin, C.E., 2019. Assessment of the effects of microPIT tags on the swimming performance of small-bodied and juvenile fish. Fish. Res. 218, 22–28. https://doi.org/10.1016/j.fishres.2019.04.019.
Wiegleb, J., Hirsch, P.E., Seidel, F., Rauter, G., Burkhardt-Holm, P., 2022. Flow, force, behaviour: assessment of a prototype hydraulic barrier for invasive fish. Hydrobiologia 849, 1001–1019. https://doi.org/10.1007/s10750-021-04762-z.
Wiegleb, J., Hirsch, P.E., Seidel, F., Rauter, G., Burkhardt-Holm, P., 2023. Impact of hydraulic forces on the passage of round goby (Neogobius melanostomus), gudgeon (Gobio gobio) and bullhead (Cottus gobio) in a vertical slot fish pass. Ecol. Freshw. Fish 32, 416–430. https://doi.org/10.1111/eff.12696.
Williams, J.G., Armstrong, G., Katopodis, C., Larinier, M., Travade, F., 2012. Thinking like a fish: a Key Ingredient for Development of Effective fish Passage Facilities at River Obstructions. River Res. Appl. 28, 407–417. https://doi.org/10.1002/rra.1551.
Winter, J.D., 1983. Underwater biotelemetry. Fisheries Techniques.
Zerunian, S., 2003. Piano d'azione generale per la conservazione dei Pesci d'acqua dolce italiani.

Glossary

R_o =: is the percentage of passing target species (i.e., $N_{pass\ Target}$ = number of target species that successfully passed through the fishway; N_{Target} = number of target species);
E_p =: is the percentage of fish that passed the fishway compared to those released in the river reach downstream of the dam (i.e., N_{passed} = fish that successfully passed the dam upstream or downstream; $N_{released}$ = fish that were tagged and released in the river reach downstream of the dam);
E_{PAdj} =: is the percentage of fish that passed the fishway (i.e., N_{passed}) compared to the number of fish detected at only one antenna (i.e., $N_{approach}$ = fish which has only one detection at one of the two antennas);
E_a =: is the proportion of radio-tagged fish that were detected at the fishway entrance (i.e., $N_{approach}$) divided by the total number of fish tagged (i.e., $N_{released}$);
T_t =: is the time required for upward or downward passage (reported in minutes), measured based on the time elapsed from the last detection at the fishway *ent*rance to the first detection at the fishway exit (i.e., $T_{F\ exit}$ =first recording time at exit antenna; $T_{L\ ent}$ = last recording time at entry antenna);
S_t =: is the transit speed as a function of the topographic difference in height between the two antennas (i.e., $m_{water\ head\ drop}$ = water head drop between the two antennas);
T_d =: is the time from the first detection in the first antenna to the last detection in the last antenna (i.e., Ent_F = the first detection by an antenna inside a fishway opening; $Exit_L$ = the last detection at a top-of-ladder fishway exit);
R_f =: is the percentage of individuals that fell back from an antenna or that passed back downstream via spillways relative to the total number of individuals reaching that antenna (i.e., $N_{approach}$; $N_{fallback}$ = total number of fish that experience fallback event);
$N_{pass\ Target}$ =: number of target species that successfully passed through the fishway;
N_{Target} =: number of target species;
N_{passed} =: fish that successfully passed the dam upstream or downstream;
$N_{released}$ =: fish that were tagged and released in the river reach downstream of the dam;
$N_{approach}$ =: fish which has only one detection at one of the two antennas;
$T_{F\ exit}$ =: first recording time at exit antenna;
$T_{L\ ent}$ =: last recording time at entry antenna;
$m_{water\ head\ drop}$ =: the water head drop between the two antennas;
Ent_F =: the first detection by an antenna inside a fishway opening;
$Exit_L$ =: the last detection at a top-of-ladder fishway exit;
$N_{fallback}$ =: total number of fish that experience fallback event;