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RESEARCH ARTICLE

Assessment of the effectiveness of fish passage through the vertical-slot fishway at the main dam on the longest Baltic River

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Abstract. In 1969, a dam was constructed on the Vistula River, the longest in the Baltic drainage basin, 276 km from its estuary, which resulted in the collapse of migratory fish populations throughout the drainage basin. The existing, ineffective fishway was rebuilt in 2014. Monitoring at the new fishway indicated that 24 fish species used it, and over a period of five years the number of individuals fluctuated from nearly 4,000 to over 23,000. Radio frequency identification (RFID) technology was used to investigate 12 fish species, mostly vimba and bream, passing through the fishway. Fish caught in a trap in the upper part of the fishway were tagged with PITs and then released below the dam. Returning fish were recorded by four loop antennas. Of the 877 fish that were tagged, 13% returned to the fishway mostly on the first and fourth days following release. Of the fish that returned, 30% turned back while passing through the fishway: 30% vimba and 52% bream. The transit time of vimba and bream did not depend on fish size or the time after which they returned. Overall, estimated fishway efficiency based on the migration of the tagged fish was high.

Keywords: fishway, RFID, fish passage, Vistula River

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Introduction

Europe has more heavily modified rivers than anywhere else in the world with very long history of fragmentation (Petts et al. 1989). New data indicate that there are well over one million hydrotechnical barriers in Europe (Belleti et al. 2020). In global scale, just one-third of the world's longest rivers (>1,000 km) remain free-flowing (Grill et al. 2019) and today, there are about 6000 existing or planned large hydropower dams (>15 m height) worldwide (Zarfl et al. 2014). River fragmentation by barriers always disturbance and interruption of its biological continuity (e.g. Jungwirth 1998). Dams affect and modify natural river sections but also block upstream and downstream fish migration and downstream flow and sediment transport (Schmutz and Moog 2018). Large and long rivers play a special role in the migration of fish, which constitute migration routes for many species, not only those considered as diadromous (Brink et al. 2018).

The Vistula is the longest Baltic Sea river at 1,047 km, and it has the second largest drainage basin of 194,000 km^2 (only that of the Neva River is larger) and a mean flow rate of 1,046 m^{3}s^{-1}. In 1969, a dam was constructed at km 267 in Włocławek, which created the largest dam reservoir in Poland with a surface area of approximately 70 km^2 and a drainage basin of 172,000 km^2, which means the dam cuts off 55% of the surface area of Poland from the Baltic Sea. A fishway was installed at the dam in 1970. It is located in a pillar between the weir and the hydropower plant. This technical fishway comprised 33 chambers (including three for resting) with a slope between chambers of 0.40 m, and a classic arrangement of alternating openings with overflow at the top (0.60 x 0.60 m), slots at the bottom (0.50 x 0.50 m), and a flow rate of 0.935 m^3 s^{-1} (Biegała 1972).

Research conducted in 1971–74 (Bontemps 1977) indicated that 19 fish species entered the fishway. These were mainly vimba, *Vimba vimba* (L.); barbel, *Barbus barbus* (L.); ide, *Leuciscus idus* (L.); and eel, *Anguilla anguilla* (L.). This experiment also indicated that an average of 50% of cyprinids were able to pass through to upper reservoir waters from several upper fishway chambers. A subsequent study conducted from 1998 to 2004 (Bartel et al. 2007) indicated that numerous fish of various species entered the fishway, but only 3.5% successfully passed through the entire fishway. In the meantime, the conditions of fishway operation deteriorated significantly: deep erosion of the riverbed below the outflow from the hydropower plant in the first two years following dam construction caused the bottom to drop by 2.5 m (Szupryczyński 1986), and erosion progressed in subsequent years (Woźniewski et al. 1999). Consequently, the location of the entrance to the fishway deteriorated progressively. Telemetry studies confirmed that sea trout, *Salmo trutta* L., had difficulty finding the fishway entrance (Linnik et al. 1998, Woźniewski et al. 1999). In 1998, an anti-erosion threshold was built below the dam, which was significant obstacle to fish migration (Dębowski 2017).

Damming the Vistula River and the loss of river continuity, which was not compensated for by the ineffective fishway, caused changes in the ichthyofauna of the river that were particularly drastic with regard to migratory fish. Before the construction of the dam, sea trout and vimba were a significant part of Vistula commercial fisheries (Jokiel and Backiel 1960, Morawska 1968, Wiśniewolski 1987), and a few years following dam construction, catches of them were many times lower (Backiel 1985, Wiśniewolski 1987, Bartel et al. 2007, Dębowski 2018a); however, catches of these species were still recorded (Bernaś et al. 2019).

In 2014, the chamber fishway was thoroughly reconstructed into a vertical-slot fishway without changing its location. The new fishway is equipped with a Riverwatcher VAKI fish counter located in chamber 49. Within five years, it registered 24 fish species, and the number of fish registered annually ranged from 3,882 to 23,028 (Dębowski 2016, 2017, 2018b, 2019, 2020). Counter records show that many fish turn back in the fishway (Dębowski 2016). The aim of this study was to estimate what proportion of fish enter the fishway without successfully passing through it, and how long it takes for the fish to pass through the entire fishway, which is necessary to assess the efficiency of fishway passage (Roscoe and Hinch 2010).

Material and Methods

Fishway

The fishway is located in the pillar between the dam abutment and the hydropower plant (52.656445 N, 19.132606 E) (Fig. 1). After reconstruction, it measures 195 m in length with a slope of 7.46%. It comprises 60 chambers measuring 2.8 x 2.4 m with a minimal depth of 1.08 m that are connected by single vertical slots with a width of 0.30 m. The water flow velocity in the fishway is 0.59 m^3 s^{-1} and the energy dissipation is 159 W m^{-3}. Additionally, the first, or bottom, chamber is supplied by a pipeline to create a water flow of 3.0 m^3 s^{-1} to attract fish to the fishway, which means the water flowing through the fishway is approximately 0.4% of the average outflow from the reservoir. The bottom of the fishway is covered with stones. According to measurements at different levels of impoundment, the water velocity flow in the slots was less than 2.0 m s^{-1}.

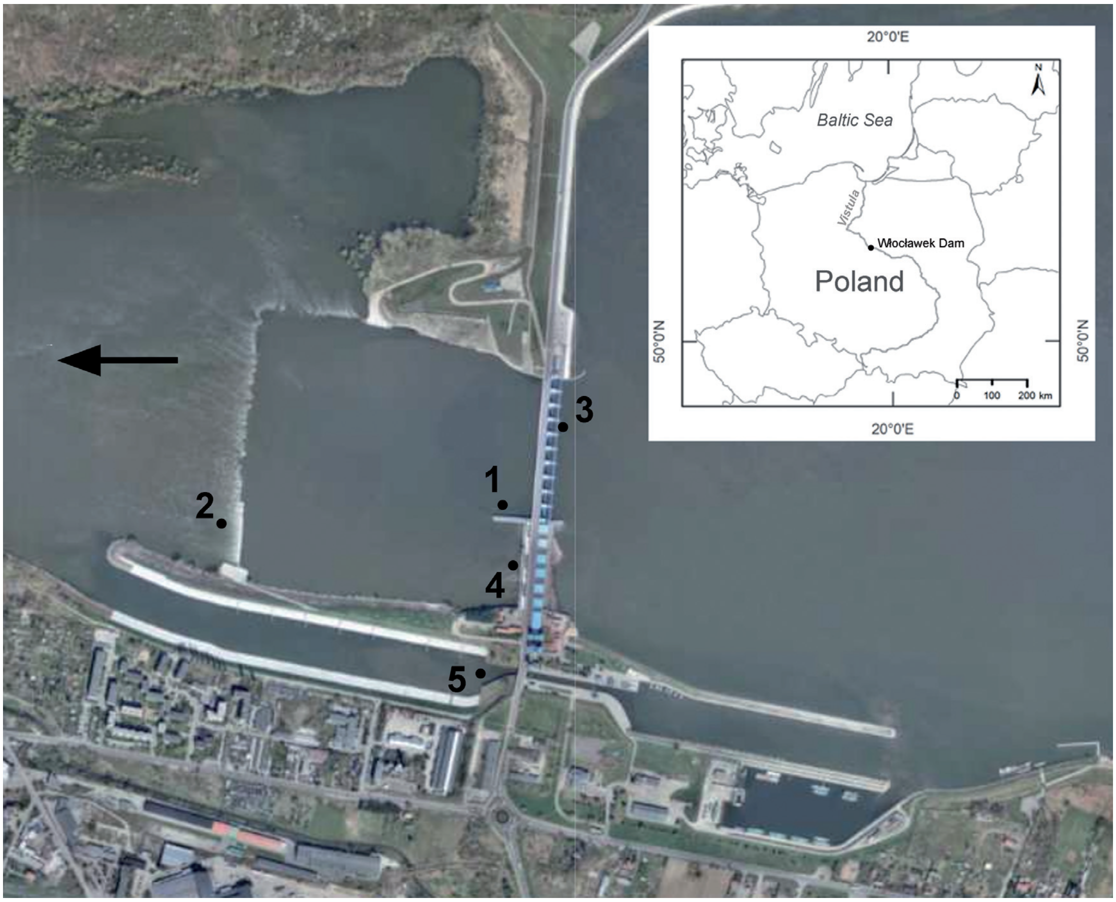

Figure 1. The location of the Włocławek Dam on the Vistula River. 1 = fishway, 2 = anti-erosion threshold, 3 = weir, 4 = turbine outlet, 5 = sluice, arrow = flow direction (orthophotomap under license from Head Office of Geodesy and Cartography, Poland).

Catches and fish tagging

The fish were caught in a metal trap set in the last, or top, chamber (Fig. 2), which means that these fish had passed through the entire fishway. The trap was set for periods of time ranging from 8 to 52 h. The fish caught were anesthetized in groups in a tank with etomidate (Propiscin, IFI). PIT tags (Oregon RFID HDX) of 12 mm (0.1 g), 23 mm (0.6 g), or 32 mm (0.8) were injected into the abdominal cavity according to fish length. After recovering from anesthesia, the fish were released into the water below the dam to the right of the middle pillar opposite the entrance to the fishway in an area without water flow (Fig. 1). The study was conducted five times from 2015 to 2019: three times in spring and two times in fall. A total of 877 fish from 12 species was tagged (Table 1).

Recording fish

The fish were recorded with Oregon RFID LF HDX readers connected to four loop antennas placed in gaps between the chambers (Fig. 2): 4 and 5 (A1), 18 and 19 (A2), 49 and 50 (A3), and 56 and 57 (A4). The antennas were fitted with test tags and powered by utility power.

Fish that were recorded by any of the antennas were considered to have entered the fishway. Since the lowest antenna (A1) was periodically not operating, the first antenna was often A2. This is why the transit time from antennas A2 to A4, or from chambers 18 to 57, was considered to be the transit time through the

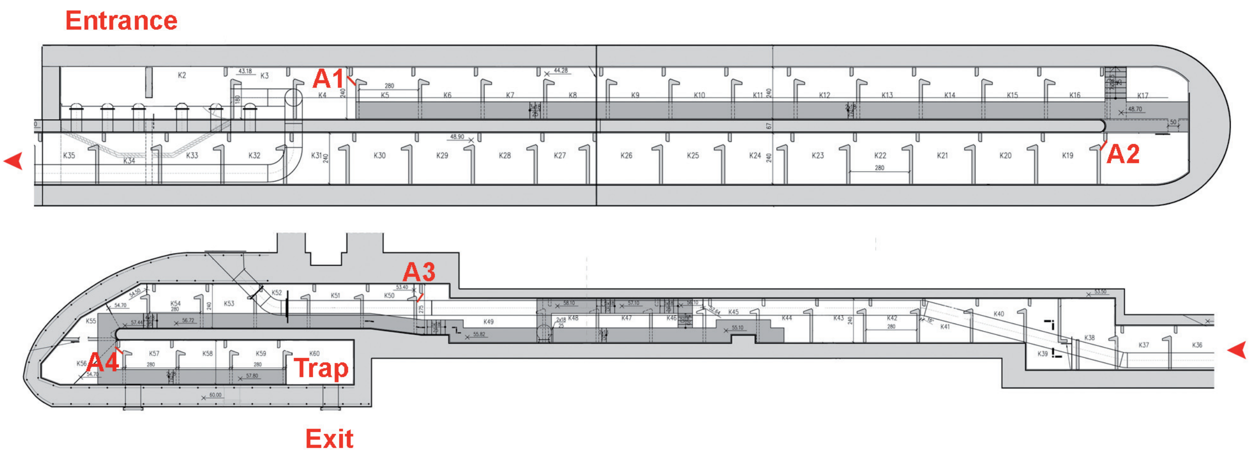

Figure 2. Diagram of the rebuilt fishway in Włocławek Dam with the location of antennas and trap.

Table 1
Dates of the sampling, species and numbers of tagged fish

Species	11-15 May 2015	2 Nov 2016	18 Sep 2017	24 Apr 2018	24 May 2019	Total
Asp *Aspius aspius*			6	1		7
Barbel *Barbus barbus*			20			20
Vimba *Vimba vimba*	40		27	2	577	646
Ide *Leuciscus idus*			2		3	5
Dace *Leuciscus leuciscus*			1			1
White bream *Blicca bjoerkna*					12	12
Bream *Abramis brama*	21		40	10	24	95
Roach *Rutilus rutilus*					18	18
White-eye bream *Ballerus sapa*			5		10	15
Nase *Chondrostoma nasus*					2	2
Sea trout *Salmo trutta* m. *trutta*	11	9				20
Bleak *Alburnus alburnus*	1		4	28	3	36
Total	73	9	105	41	649	877

fishway. The first recording was considered as the entry time, and the transit time through the fishway was that from the entry time on the lower antenna until the last recording on the upper antenna.

Statistical analysis

The t test was used to compare the groups of fish entering the fish pass depending on the length and species, as was the case with the comparison of fish that failed to pass and turned back ($P < 0.05$). The comparison of the significance of differences in the speed of transition between species was also performed using the t test ($P < 0.05$). Regression analysis was used to describe the relationships between fish length and transition time and returning decision. Statistical calculations were performed with Statistica 8.0 (StatSoft Inc., Tulsa, OK, USA).

Results

Of the 877 fish tagged, 115, or 13%, were recorded in the fishway. They belonged to seven species and were

Table 2

Fish species, N = number of tagged fish, 1 = length range of tagged fish (cm), 2 = number of fish entering the fishway, 3 = length range of fish entering the fishway (cm), 4 = percentage of fish entering the fishway, 5 = number of fish turning back in the fishway, 6 = percentage of fish turning back in the fishway, 7 = number of fish passing through the fishway, 8 = length range of fish passing through the fishway (cm), 9 = percentage of fish passing through the fishway

Species	N	1	2	3	4	5	6	7	8	9
Vimba	646	12.5-41.5	77	17.0-40.0	12	19	30	58	25.0-37.5	70
Bream	95	24.5-56.5	24	47.0-53.0	25	13	52	11	47.0-53.0	48
Bleak	36	12.5-17.0	2	14.0-14.0	6	0	0	2	14.0-14.0	100
Sea trout	20	54.0-92.0	4	65.0-92.0	20	0	0	4	65.0-92.0	100
Barbel	20	24.0-37.0	3	14.0-36.0	15	1	33	2	26.0-36.0	67
Roach	18	19.5-28.5	0							
White-eye bream	15	23.0-31.0	3	26.5-27.0	20	0	0	3	26.5-27.0	100
White bream	12	20.0-35.0	0							
Asp	7	55.0-65.0	2	58.0-60.0	29	1	50	1	60	50
Ide	5	13.0-46.0	0							
Nase	2	20.5-27.5	0							
Dace	1	20	0							
Total	877		115		13	34	30	81		70

mainly vimba and bream (Table 2). The first fish, a vimba, was recorded 2 h 18 min after release, while the last, a bream, was recorded ten days short of three years later. Most of the fish returned to the fishway on the first and fourth days following release (Fig. 3), but 17 vimba and nine bream returned over a period ranging from six months to three years. The vimba that entered the fishway did not differ in length from those that did not (t test, P = 0.3425), but this was not true for the bream as those that were recorded were larger at 55 vs 44 cm (t test, P = 0.0039).

Of the fish that returned to the fishway, 30% turned back and 70% passed through the entire fishway (Table 2). While all of the bleak, trout, and white-eye bream passed through the fishway, only single specimens of these species were recorded. Of

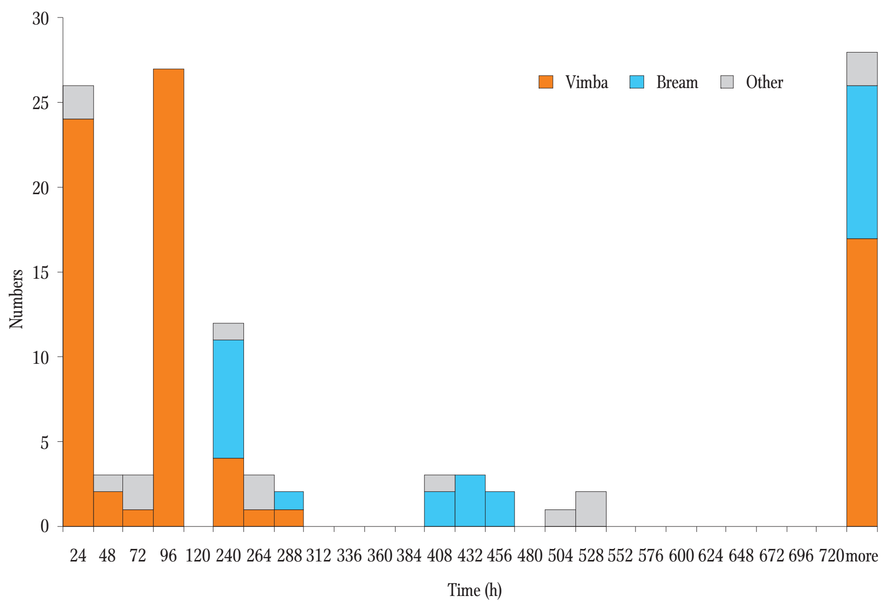

Figure 3. Return time of fish to the fishway.

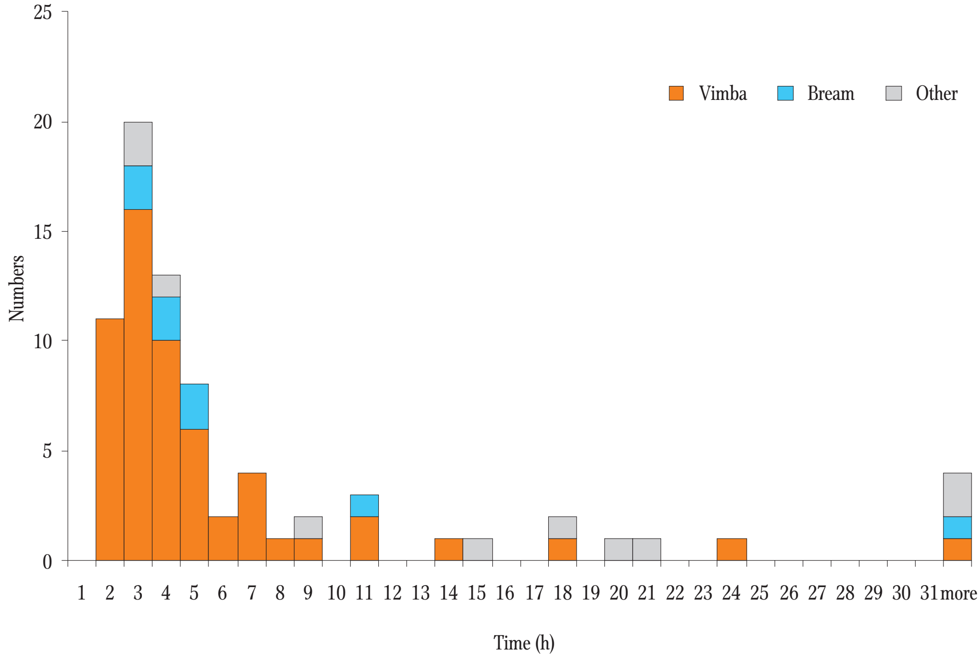

Figure 4. Transit time through the fishway.

the vimba, 70% passed through the fishway, while 48% of the bream did so. The vimba and bream that turned back did not differ in length from those that passed through the fishway (t test, P = 0.8139). Vimba passed through the fishway the fastest at 1 h 15 min and sea trout were the slowest at 16 days, while 72% of the fish required less than 6 h (Fig. 4).

Vimba required an average of 5 h 53 min to pass through the fishway, while bream required 8 h 48 min; however, this difference was not statistically significant (t test, P = 0.5286). Transit time did not depend on size for either vimba (r^2 = 0.0115, P = 0. 4273) or bream (r^2 = 0.0239, P = 0.7409). Length also had no impact on how long it took vimba (r^2 = 0.0366, P = 0.2247) or bream (r^2 = 0.0341, P = 0.6917) to return to the fishway. If we only consider the fish that returned with a period of 10 d, the average transit time of these fish did not differ from the transit times of those that returned after several months to three years.

Discussion

The results obtained regarding fish entering the fishway should be considered with great caution. In the present study, the fish were caught in the upper fishway similarly to comparable studies (e.g., Pon et al. 2009, Faller and Schwevers 2012, Thiem et al. 2013). Thus, we knew that these fish were able to locate the fishway entrance and wanted to pass through it, although, of course, we could not be sure if they would want to do it again and what role fatigue would play. However, fish used in research are often caught below barriers and sometimes at some distance from them (Forty et al. 2016, Bao et al. 2019, Lothian et al. 2019, 2020), so we can only speculate about their motivation to migrate upstream, and when assessing fish locating fishway entrances their motivation is crucial (Roscoe and Hinch 2010, Kemp 2012, Cooke and Hinch 2013). In studies of migratory fish, we usually assume that they are highly motivated, and we can predict their migration routes with great probability, but with fish that migrate voluntary or optionally (Lucas and Baras 2001), such assumptions are questionable. Therefore, quantitative assessments of the passage of these fish through fishways are significantly fewer (Noonan et al. 2011, Bunt et al. 2012). Another problem is the location where tagged fish are released. In some studies, they were released at fishway entrances or even in the lower parts of them (Thiem et al. 2013, Bao et al. 2019), while in other studies the fish were released where they were caught (Forty et al. 2016, Lothian et al. 2019, 2020). In the current study, the fish were released in an area of standing water far from the fishway entrance and from a presumed migration corridor (Faller and Schwevers 2012).

Of the 24 fish species recorded in the fishway over five years, only seven species were included in the study, but only two, vimba and bream, were recorded in sufficient numbers to permit analyzing their passage through the fishway. Vimba is a migratory fish that undertakes two migration runs in the Vistula in spring and in fall (Bontemps 1969). These runs are usually very concentrated, and, within a few days, several hundred or even more than 1,500 fish pass through the fishway daily (Dębowski 2018b, 2020); thus, this fish is a very determined migrant. The number of bream recorded in the fishway ranged from 200 to almost 6,000 in different years of the study, and it migrated almost exclusively in spring and usually in several runs that culminated over extended periods of time. If it did not encounter favorable hydrological conditions at that time, it did not migrate. Bream is therefore a non-obligatory migrant.

An additional element that hinders interpreting results could be the different levels of stress associated with the various fishing techniques and the necessity, for example, of transporting fish. It seems that fish stress levels in the current study were quite high, especially in spring 2019. The migration intensity meant that the fish were crowded in large numbers in the small trap. This could explain why, despite the intensity of the migration and their great determination, many vimba gave up trying to pass through the fishway again, and many did not attempt it until the next season. It is interesting that most of the vimba that returned to the fishway joined the next migration peak, which, in spring 2019, occurred four days later, which we know about thanks to the results from the counter (Dębowski 2020).

The number of fish that turned back while passing through the fishway could have been underestimated in the present study because the lower antenna was not located at the entrance to the fishway, but it was five chambers higher, and the fish that turned back earlier were not recorded. The fish that turned back were quite numerous, even among vimba, individuals of which passed through the fishway in under 2 h. Moreover, we know that all these fish had been able to pass through the fishway before. Turning back did not seem to be a matter of fatigue; transit time through the fishway did not depend at all on the rest period after the previous passage or the manipulations to which the fish had been subjected. Rather, this appeared to be a question of fish “circling” behavior (Lucas et al. 1999, Prchalova et al. 2006), although, on the other hand, hardly any of the returning fish made subsequent attempts. It is possible that passage through the fishway itself is a source of stress since fish of various species are often overcrowded in relatively small chambers where conditions are fundamentally different from those in the river with regard to both current velocity and distribution, as well as chamber dimensions and light conditions. Even slight increases in stress levels can induce fish to turn back, even if it is not too difficult for them to physically pass through subsequent slots. This issue is linked closely with fish transit time through the fishway. Interestingly, sea trout was among the fish with the longest transit times, and apparently the prevailing conditions in the fishway, namely turbulence, high water oxygenation, and twilight, were attractive to it.

Each fishway has its own specificities, as do the different fish species passing through it. Studies of the quantitative characteristics of vimba and bream passing through vertical-slot fishways is lacking in the literature. Benitez et al. (2018) found the effectiveness of this type of fishway for barbel to be 66.7% and for chub 94.3%, while for various fish species Bao et al. (2019) noted it to be 20.3%. Bunt et al. (2012) compared the efficiency of various slot fishways for different fish, which ranged from 0 to 100 % with a median of 43%. The mean for all fish noted in the present study at 70% seems to be relatively high.

Conclusions

Obtained results have revealed few facts that may prove important for fish pass studies. First, this type vertical slot fishway can be relatively effective even is located in the middle part of the large barrier, what is generally not preferred because of problems with access (Larinier 2002). This seems to be the case with the fish pass in Włocławek Dam. Our results also showed that in the case of a more motivated swimmer like the vimba, the determination to overcome the fish pass was higher than that of the bream. At the same time, the study showed that RFID telemetry is an effective method of testing the effectiveness of migration through large fish passes, especially in combination with fish counters.

Author contributions. P.D., and R.B. conceptualization; R.B., P.D., W.Ś., and G.R. building and setting up the RFID system; P.D., R.B., G.R. and W.Ś fish tagging and handling; P.D., and R.B. formal analysis and investigation; P.D., and R.B. writing and draft preparation; R.B. review and editing.

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Ethics approval. All methods were carried out in accordance with relevant guidelines and regulation. The study complies with the current laws of the Republic of Poland. All applicable international, national, and institutional guidelines for the care and use of animals were followed (Certificate no. 3798/2016 for Rafał Bernaś by Polish Laboratory Animal Science Association). Field protocols for the capture, handling, and release of fish were approved by the competent authority.

Availability of data and material. Data are available on request.

Conflict of interest. The authors declare no conflict of interest.

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