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An Efficiency Analysis of a Nature-Like Fishway for Freshwater Fish Ascending a Large Korean River

Jeong-Hui Kim [1], Ju-Duk Yoon [2], Seung-Ho Baek [1], Sang-Hyeon Park [3], Jin-Woong Lee [1], Jae-An Lee [4] and Min-Ho Jang [1,*]

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[1] Department of Biology Education, Kongju National University, Gongju 32588, Korea; ragman-k@hanmail.net (J.-H.K.); bell4555@naver.com (S.-H.B.); jinwoong0127@daum.net (J.-W.L.)
[2] Biological Resource Research Center, Kongju National University, Gongju 32588, Korea; zmszmsqkek@hanmail.net
[3] Bio Monitoring Center, Daejeon 34576, Korea; recall7719@naver.com
[4] Water Environment Research Department, Watershed Ecology Research Team, Incheon 22689, Korea; leejanier@korea.kr
* Correspondence: jangmino@kongju.ac.kr; Tel.: +82-41-850-8285; Fax: +82-41-850-8842

Abstract: Using traps and passive integrated transponder (PIT) telemetry, we investigated the effectiveness of the nature-like fishway installed at Sangju Weir on the Nakdong River, Korea. In 11 regular checks over the study period, 1474 individuals classified into 19 species belonging to 5 families were collected by the traps, representing 66% of the species inhabiting the main channel of the Nakdong River. PIT tags were applied to 1615 individuals belonging to 22 species, revealing fishway attraction and passing rates of 20.7% and 14.5%, respectively. Interspecific differences were also shown. For 63.2% of fishes, it took more than a day to pass through the fishway. Some individuals spent a longer time (>28 days) inside the fishway, suggesting the fishway was also being used for purposes other than passage. In this study, we verified species diversity of fish using a nature-like fishway installed in a large river in Korea. The results of this study provide a useful contribution to the development of fishways suitable for fish species endemic to Korea and for non-salmonid fish species worldwide.

Keywords: nature-like fishway; trap; PIT telemetry; attraction efficiency; passage efficiency

1. Introduction

A large number of structures such as dams and weirs have been constructed across rivers and streams for management of water resources. These structures alter the physical properties of rivers and riverine environments, and affects water quality by slowing down its flow. They also affect the movement of migratory fish by reducing the longitudinal connectivity of the river [1,2]. Adverse effects of such artificial structures across rivers have been reported for the local aquatic ecosystems, especially in relation to decreases in the number of anadromous fish communities, such as salmonid and lamprey fish, due to the obstruction of movement to their respective spawning habitats. For freshwater fish species, genetic discontinuity between the upstream and downstream populations can also occur [3,4].

Fishways (fish ladders, fish passes, or fish steps) are the most effective solution to the problems related to the blocked downstream and upstream movements of aquatic fauna caused by manmade structures in rivers [5]. Early fishway construction targeted only a few fish species with strong swimming abilities, such as adult salmonids [6], but recent trends are directed at making fishways available for the passage of all species in all life stages [7]. Among the various types of fishways, nature-like fishways are constructed with boulders, large wooden debris, and riparian vegetation to imitate natural environments, instead of concrete or steel, thus producing hydrodynamic and morphological properties similar to those of natural rivers [8,9]. Owing to these characteristics, unlike other fishways, nature-like fishways can be used by fish species with a wide range of sizes and swimming abilities [10]. Best-suited for the original purpose of fishways, nature-like fishways are being constructed across the world in increasing numbers [11]. In Korea too, nature-like fishways are attracting increasing amounts of attention, and 8 nature-like fishways have been constructed in large rivers since 2010.

By regularly monitoring the use of a fishway after its installation, not only can its attraction and passage efficiencies be checked, but useful data for its efficient management can also be obtained to better address fish movement issues. The most common conventional monitoring method, which is still frequently used [12], is to count the number of individuals passing through the exit of the fishway. In particular, customized traps are often used owing to their advantages in identifying the species, numbers, and sizes of individuals using fishways, and can also be used for collection purposes. On the other hand, fish telemetry using passive integrated transponder (PIT) tags, radio tags, or acoustic tags is mostly used for assessing the attraction and passage efficiencies of a fishway [7]. Such tagging methods deliver detailed information on fish behavior and movement, enabling an accurate quantitative evaluation of its attraction and passage efficiencies [13]. However, telemetry methods can only selectively monitor the tagged species, and thus cannot deliver the data for identifying all fish species using the fishway. These disadvantages can be overcome by the combined use of these two methods to obtain accurate high-quality information for fishway management.

This study aimed to obtain accurate data necessary for evaluating the efficiency of a nature-like fishway constructed on a large river by applying a refined method combining customized traps and a PIT telemetry system to both identify the species and sizes of fishes using the fishway and evaluate the attraction and passage efficiencies. Additionally, we presented measures to improve the efficiency of the fishway by analyzing the correlation between the upstream water level and fishway use data.

2. Materials and Methods

2.1. Study Site

The Nakdong River (525.15 km in length) is one of the longest rivers in Korea. Its main channel has a midstream width of at least 100 m and up to 1 km in some downstream areas. Eight large weirs have been constructed in the main channel to manage water resources and control water flow (Figure 1). Of the 8 weirs in the Nakdong River, Sangju Weir lies the furthest upstream. It is 335 m long and 11 m high, with a nature-like fishway installed on the right side and a small hydropower plant on the left side. The upstream water level is constantly maintained at its management water level of 47.00 m AMSL, except during the flooding season.

2.2. Fishway

The study site was the nature-like fishway installed on the right side of Sangju Weir (Figure 1). The fishway is 700 m long in total, at a slope of 1/100. It has a zigzag path designed to make optimal use of the narrow space. Its width ranges from 6 m to 18 m (mean = 7.4 m), with slight differences per section. Although the water depth of the fishway is maintained at an average of 50 cm, it fluctuates depending on the inflow rate into the fishway and the location within the fishway. The inflow rate into the fishway varies in accordance with the upstream water level. The fishway was thus designed to induce an optimal inflow rate, provided that Sangju Weir is maintained at its intended water level.

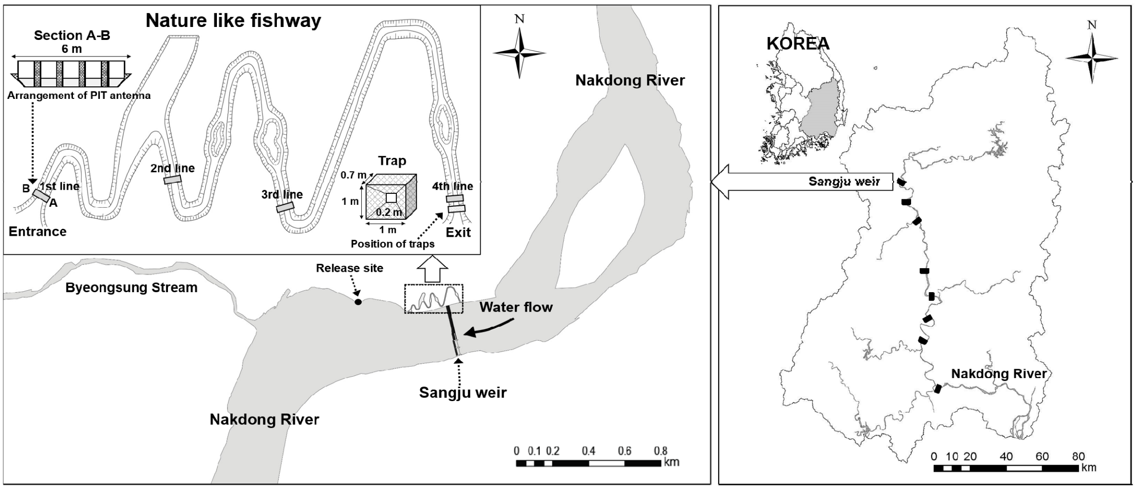

Figure 1. The location of Sangju Weir on the Nakdong River in Korea, the positions of the 4 PIT antenna lines along the fishway, and 6 traps at the exit of the fishway used during the sampling period.

2.3. Ichthyofauna of the Nakdong River

To determine the fish species that might use the fishway, the ichthyofaunal assemblages of communities found in the main channel of the Nakdong River were analyzed. Fish were collected at one upstream site and one downstream site, both at a 1 km distance from Sangju Weir. A cast net (mesh: 7 mm; area [πr^2]: 16.6 m^2) and a fyke net (mesh: 5 mm) were used as active and passive fishing gear, respectively. The cast net was thrown 15 times for each survey, and the fyke net was set for 48 h. After measuring the total length (TL, mm) of the collected fish on site, they were released back to the stream at the same point as collection. Surveys were carried out 4 times (July and October 2012, March and May 2013) at 2–3 month intervals, excluding the winter months.

2.4. Fishway Monitoring

2.4.1. Trap Monitoring

To identify the species and number of individuals using the fishway, 6 traps (dimensions: 1 × 1 × 0.7 m; mesh: 4 mm) were installed at the exit of the fishway (Figure 1), which blocked the entire fishway exit. All ascending fish were thus collected. The traps were installed for monitoring once per month for 11 months between June 2012 and July 2013. Due to the limited mobility of fish at low water temperatures, the winter months (December 2012 through February 2013) were excluded from monitoring. The traps were installed at 16:00 and collected after 24 h. According to the study by Lee *et al*. [14], which evaluated the same type of trap we used in this study, the installment of the trap did not significantly affect the water velocity within the fishway. Therefore, we assume the installment of the trap did not affect the fish using the fishway. However, when a trap is installed for a long period, it may come loose, or debris may accumulate. Therefore, we checked the status of the trap every 6 h following the installment. Before being released upstream of the weir, the number of collected individuals were counted per species and TLs were measured.

2.4.2. PIT Telemetry

We applied PIT telemetry to monitor the efficiency of the fishway from July 2012 to July 2013, on a total of 1615 individuals of 22 species from 8 families (Table 1). Samples were collected using a cast net (mesh, 7 mm) and fyke net (mesh, 5 mm) within 1 km downstream of the weir. Collected fish were immediately moved to an aerated plastic tank (1 × 1 × 0.7 m) and stabilized for 30 min prior to tag implantation. Each fish without visible injuries was subsequently anaesthetized using

0.1 g·L^{-1} ethyl 3-aminobenzoate methanesulfonate salt (Sigma-Aldrich, Munich, Germany), after which its TL and body weight (BW) were measured (Table 1). A 3-mm-long incision was made on the ventral body surface and a PIT tag (12 mm in length and 2.12 mm in diameter, FDX-B, Finfotech, Korea), was inserted into the abdominal cavity. A biological bond (Vetbond; 3M, Minnesota, USA) was used to prevent water from entering the cavity. After tag insertion, the fish was then moved to an aerated plastic tank (1 × 1 × 0.7 m) for recovery. Tagged fish were released at the release site 300 m downstream from the fishway entrance, and their fishway usage patterns were tracked.

The total length of the nature-like fishway installed at Sangju Weir is 700 m. With the first 50 m from the entrance (lower end) constantly immersed, the actual length used by the fish is 650 m. Four antenna lines (1st line at the entrance, 2nd and 3rd lines in the middle, 4th line at the exit) were installed at intervals of 200–230 m. We used rectangular PIT antennas (1 (w) × 0.4 (h) m, F-12030, Finfotech, Korea), and each antenna line comprised 5 antennas. Since a signal could be detected whenever a fish passes inside an antenna and up to 15 cm outside of it, the total detection range of each antenna was 130 cm. By installing them at 30 cm intervals to ensure detections free of inter-antenna interference, each antenna line consisting of 5 antennas had a signal detection range of 6.5 m. In other words, the antennas were arranged so that any signal emitted within the fishway at a given moment could be detected by one antenna. The 4 antenna lines were numbered from the entrance to the exit for easy identification. Tests were performed every 2 weeks to check the operation and detection range of each antenna in the following manner. Each antenna was connected to a reader (Finfotech, Korea), and readers were connected to a data logger (Finfotech, Korea). Detection data that was stored in a data logger was subsequently transferred to a database [15] by the code division multiple access (CDMA) method every 10 min. More detailed information about the PIT antenna are available in the study of Yoon *et al*. [16] using the same antenna system.

To determine the factors that affect the efficiency of the fishway, the water velocity in the fishway and the upstream water level were measured. Water velocity was measured with a handheld velocity meter (FP111, Global Water, TX, USA) at the exit of the fishway. The flow rate in the fishway was calculated on the basis of the water depth and velocity at the exit. The water velocity and flow rate were monitored 16 times during the study period in accordance with upstream water level variations. Upstream water levels were extracted from the data collected by the Nakdong River Flood Control Office at 10-min intervals.

Table 1. Information on the tagged and detected fish in the nature-like fishway at Sangju Weir. The "movement" of a detected fish indicates number of fishes that reached each antenna line. "Return" refers to the number of individuals that turned back from the exit after being detected by the 4th antenna line. "RA" means relative abundance.

Family	Species	Tagged Fish						Detected fish							
		N	RA (%)	TL (mm)		BW (g)		Attraction		Movement				Passing	
				Mean (SD)	Range	Mean (SD)	Range	N	Rate (%)	1st	2nd	3rd	4th (return)	N	Rate (%)
Cyprinidae	*Cyprinus carpio*	8	<1	189 (25.8)	149–228	96.2 (42.5)	42.8–166.9								
	Carassius auratus	16	<1	179 (54.2)	76–312	118.9 (98.8)	5.8–441.4	1	6.3	1					
	Carassius cuvieri [2]	20	1.2	159 (70.5)	86–346	104.4 (151.6)	10.4–554.9	2	10.0	1			1	1	50
	Acheilognathus lanceolatus	7	<1	71 (24.9)	60–131	6 (7.7)	2.2–24.8	2	28.6		1	1			
	Pungtungia herzi	2	<1	74 (8.0)	66–82	3.5 (1.2)	2.3–4.7								
	Squalidus chankaensis tsuchigae [1]	109	6.7	89 (9.4)	72–114	6 (2.2)	2.3–13.3	11	10.1	7	4				
	Hemibarbus labeo	28	1.7	212 (144.3)	92–488	191.1 (289.6)	6.6–866.4	11	39.3	4	1	4	2 (1)	1	9.1
	Hemibarbus longirostris	66	4.1	142 (40.1)	70–208	28.1 (19.0)	2.6–74.1	26	39.4	6	1	9	10	10	38.5
	Pseudogobio esocinus	212	13.1	153 (26.6)	80–214	29.5 (16.1)	3.7–117.1	33	15.6	7	10	6	10 (1)	9	27.3
	Zacco platypus	507	31.4	122 (23.1)	70–184	17.9 (12.1)	2.3–138	147	29.0	64	22	42	19 (2)	17	11.6
	Opsariichthys uncirostris amurensis	427	26.4	145 (67.7)	77–359	41.6 (62.2)	2.8–451.6	75	17.6	44	8	16	7 (2)	5	6.7
	Erythroculter erythropterus	11	<1	360 (83.9)	234–493	281.8 (200.8)	59.2–615.8	4	36.4	2	1		1	1	25
	Hemiculter eigenmanni [1]	84	5.2	114 (11.8)	92–150	8.8 (3.4)	4.1–24.8	2	2.4	2					
Bagridae	*Pseudobagrus fulvidraco*	41	2.5	195 (28.3)	132–241	75.9 (26.7)	25–121.3	9	22.0		3	4	2	2	22.2
	Leiocassis ussuriensis	2	<1	132 (6.5)	125–138	14.9 (1.6)	13.3–16.5	1	50.0				1	1	100

Table 1. *Cont.*

Family	Species	Tagged Fish						Detected fish							
		N	RA (%)	TL (mm)		BW (g)		Attraction		Movement				Passing	
				Mean (SD)	Range	Mean (SD)	Range	N	Rate (%)	1st	2nd	3rd	4th (return)	N	Rate (%)
Siluridae	*Silurus asotus*	23	1.4	291 (52.1)	203–425	145.9 (78.1)	46.1–346.9	3	13.0	2			1	1	33.3
Centropomidae	*Siniperca scherzeri*	20	1.2	173 (60.0)	112–310	86.4 (108.1)	16–394.3	1	5.0	1					
	Coreoperca herzi [1]	21	1.3	156 (15.9)	108–180	57.2 (15.0)	16.4–87.7	4	19.0	2		1	1	1	25
Centrarchidae	*Micropterus salmoides* [2]	6	<1	199 (26.5)	161–240	112.2 (32.9)	59.5–154.3	1	16.7	1					
Odontobutidae	*Odontobutis platycephala* [1]	3	<1	166 (6.4)	161–175	61.7 (7.9)	55.3–72.8	1	33.3		1				
Gobiidae	*Rhinogobius giurinus*	1	<1	70		4.1									
Channidae	*Channa argus*	1	<1	451		663.1									
	Total	1615		140 (59.0)	60–493	37.5 (72.1)	2.2–866.4	334	20.7	144	52	83	55 (6)	49	14.5

1: Endemic species; 2: Exotic species.

2.5. Data Analysis

To evaluate the efficiency of the fishway, the attraction rate, passing rate, passing time, and movement time were calculated for each species. Attraction rate was the percentage of all tagged individuals that were detected by antennas installed in the fishway. Passing rate was the percentage of the total number of individuals that were detected at the 4th antenna line and that did not move back to the range of the other (1st–3rd) antenna lines [13,17]. Additionally, we tracked fish movements inside the fishway and presented the distances covered by the individuals after entering the fishway. Passing time, which is the time taken for an individual to move from the entrance to the exit (650 m), reflects its swimming speed. The movement time between the antennas (3 sections) was calculated and compared by section (low section: 1st→2nd; middle section: 2nd→3rd; upper section: 3rd→4th). A Spearman's rank correlation analysis was carried out on *Zacco platypus*, which passed the fishway most frequently, to determine the correlation between passing time and TL. To investigate the interspecific differences in fishway usage, a one-way ANOVA test was performed to analyze the upstream water level at the time of fishway usage by the 4 most frequently passing species (*Z. platypus*, *Opsariichthys uncirostris amurensis*, *Pseudogobio esocinus*, and *Hemibarbus longirostris*). Additionally, the daily movement pattern of each species was compared and analyzed. All analyses were performed using SPSS ver. 20.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Species Assemblages of the Fish Collected in The Nakdong River and the Fishway Traps

Twenty-eight species from nine families were collected upstream and downstream in the Nakdong River's main channel. Of these, 19 species belonged to the Cyprinidae family, and their relative abundance was very high (97.8%) compared to other families. Nineteen species from five families were collected from the traps installed at the exit of the fishway. Hence, 66.0% of the fish species inhabiting the main channel of the Nakdong River used the fishway (Table 2). The species that used the fishway most frequently were *O. u. amurensis* (RA, 39.9%), followed by *Hemibarbus labeo* (39.2%), *Z. platypus* (8.1%), *P. esocinus* (4.2%), and *Squalidus chankaensis tsuchigae* (3.4%), which were also the dominant species among those collected in the Nakdong River's main channel. Four of the seven endemic species (57.0%) collected from the main channel were also collected in the fishway. Up to 11 species were found to be using the fishway on the same day (in July and August 2012).

The frequency of fishway usage decreased during the low water temperature season (none in November; two species in March). The TL distribution of fish species inhabiting the main channel of the Nakdong River demonstrated that individuals ranging in sizes from 50 to 100 mm accounted for approximately 50% of the total, and the ratio gradually decreased as the size of the individuals increased. The range of the TL distribution of fish that used the fishway was 39–550 mm. Moreover, the size distribution of individuals using the fishway was not limited to a certain size. Fish of various sizes utilized the fishway evenly. This differs from the main channel of the Nakdong River (Figure 2).

Table 2. Species assemblage of the fish collected in the main channel of the Nakdong River and the number of individuals, relative abundance (RA) and total length (TL) of fishes that were collected by the traps. TLs are expressed as mean values (±standard deviations), and the ranges are also presented.

Family	Species	River		Fishway													
		N	RA (%)	2012						2013					Total	RA (%)	TL (mm)
				June	July	August	September	October	November	March	April	May	June	July			
Cyprinidae	*Cyprinus carpio*	24	1.5			1	1				3			1	6	<1	343 ± 127 (216–500)
	Carassius auratus	54	3.5	1	3	1	2						2		9	<1	167 ± 92 (46–340)
	Carassius cuvieri [3]	1	<1		5	1	1								7	<1	169 ± 60 (45–230)
	Acheilognathus lanceolatus	4	<1								1				1	<1	115
	Acanthorhodeus macropterus	18	1.1														
	Pseudorasbora parva	4	<1														
	Pungtungia herzi	11	<1		1										1	<1	60
	Sarcocheilichthys variegatus [2]	2	<1														
	Squalidus japonicus coreanus [2]	4	<1									1			1	<1	114
	Squalidus chankaensis tsuchigae [2]	61	3.9	9	21	3						9	8		50	3.4	89 ± 13 (70–123)
	Hemibarbus labeo	41	2.6	1	4	1				4	3	1	5	6	25	1.7	325 ± 151 (50–515)
	Hemibarbus longirostris	7	<1	1			1					3	1	1	7	<1	149 ± 14 (133–168)
	Pseudogobio esocinus	74	4.7	8		1		1			5	3	33	11	62	4.2	169 ± 16 (96–218)
	Microphysogobio yaluensis [2]	2	<1														
	Zacco platypus	631	40.1	21	5	13	27	36			3	8	4	2	119	8.1	121 ± 34 (48–175)

Table 2. *Cont.*

Family	Species	River N	River RA (%)	Fishway 2012 June	2012 July	2012 August	2012 September	2012 October	2012 November	2013 March	2013 April	2013 May	2013 June	2013 July	Total	RA (%)	TL (mm)
	Opsariichthys uncirostris amurensis	504	32.0	84	68	108	26	7		8	36	56	81	113	587	39.9	175 ± 67 (48–330)
	Erythroculter erythropterus	75	4.8	2	15	15	24	4			6	77	96	339	578	39.2	356 ± 53 (136–550)
	Culter brevicauda [1]	9	<1														
	Hemiculter eigenmanni [2]	2	<1		1	1									2	<1	84 ± 53 (46–121)
Cobitidae	*Misgurnus anguillicaudatus*	1	<1		1										1	<1	53
Bagridae	*Pseudobagrus fulvidraco*	11	<1														
Siluridae	*Silurus asotus*	2	<1														
Centropomidae	*Siniperca scherzeri*	4	<1									8	1	1	10	<1	218 ± 61 (158–300)
	Coreoperca herzi [2]	4	<1										1		1	<1	155
Centrarchidae	*Micropterus salmoides* [3]	2	<1			1									1	<1	168
Odontobutidae	*Odontobutis platycephala* [2]	1	<1														
Gobiidae	*Rhinogobius brunneus*	5	<1		2			3							5	<1	46 ± 6 (39–50)
	Tridentiger brevispinis	4	<1														
Channidae	*Channa argus*	1	<1														
	No. of individuals	1564		127	127	146	82	51	0	12	57	166	232	474	1474		
	No. of species	29		8	11	11	7	5	0	2	7	9	10	8	19		

1: Endangered species; 2; Endemic species; 3: Exotic species.

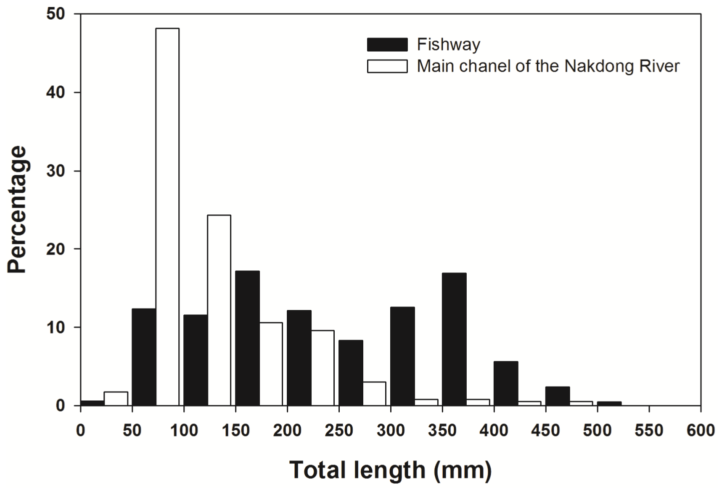

Figure 2. The size distribution of the fish captured by the traps in the nature-like fishway and collected from the main channel of the Nakdong River. Size class intervals were 50 mm.

3.2. Efficiency of the Fishway

Of the 1615 PIT-tagged individuals, 334 individuals were detected in the fishway, showing an attraction rate of 20.7% (Table 1). The species-dependent attraction rate varied widely (0%–50%), with the attraction rates of *Z. platypus*, *O. u. amurensis*, and *P. esocinus*, three species predominantly tagged, being 17.6%, 29.0%, and 15.6%, respectively. Only 49 of the 334 individuals attracted to the fishway succeeded in passing it and moving upstream of Sangju Weir, showing a passing rate of 14.5%. *Z. platypus* showed the highest number of individuals attracted to the fishway, but a below-average passing rate (11.6%, 17/147), whereas *Leiocassis ussuriensis* showed a passing rate of 100% because the only individual of this species that was attracted to the fishway passed it. Some individuals of *H. labeo*, *P. esocinus*, *Z. platypus*, and *O. u. amurensis* attracted to the fishway were detected by the 4th antenna line at the exit, but turned back into the fishway instead of moving upstream into the main channel of the Nakdong River.

The analysis of passing time through the fishway revealed that 36.8% of the individuals passed the fishway within 1 day, while the rest took longer (Table 3), 26.3% of which stayed in the fishway for more than 10 days. The average passing time ranged from 1.2 h to 1559.4 h, showing species-dependent differences. Considerable intraspecific variations in passing time were also verified. For *Z. platypus*, for example, the shortest and longest stays in the fishway were 31.7 h and 2135.0 h. To analyze the effect of body length on passing time, we performed a Spearman's rank correlation analysis between the TL and the passing time of *Z. platypus*, which passed the fishway most frequently, but no statistically significant correlation was confirmed ($r_s = 0.071$, $p > 0.05$). The average attraction time it took each tagged fish to move 300 m from the release site to the fishway entrance was 627.6 h, which amounts to more than 26 days. Additionally, the attraction time varied among individuals, ranging from a minimum of 0.1 h to 7532.2 h. No specific pattern was observed when comparing the data of different species.

The movement time in the Sangju Weir nature-like fishway varied according to the sections (Table 4). The average length of time from the detection at the entrance (1st antenna line) to the detection at the exit (4th antenna line) was 316.7 h, or approximately 13 days. On the other hand, analysis of movement time by section revealed that the longest time (mean = 284.9 h) was spent passing the first section (from the 1st to the 2nd antenna line), which was then increasingly shortened as the individuals approached the exit.

The results of the analysis of upstream water levels at the time of fish attraction and passing revealed that both attraction and passing occurred more frequently when the water level was higher than the intended management water level (47.00 m AMSL), at 47.08 m and 47.19 m AMSL, respectively (Figure 3). By substituting the mean upstream water levels at the attraction and passing times for the changes in water velocity and flow rate in the fishway into the regression analysis formula (Figure 4), it was found that attraction occurred most frequently at a water velocity and flow rate of 0.90 $m \cdot s^{-1}$ and 1.21 $m^3 \cdot s^{-1}$, respectively, and passing at 1.05 $m \cdot s^{-1}$ and 1.57 $m^3 \cdot s^{-1}$, respectively. The results of the analysis of water temperature-dependent attraction and passing rates showed that attraction and passing occurred only at temperatures higher than 4 °C and 9 °C, respectively, and no tagged fish were detected in the months of January and February, when the water temperature dropped below 4 °C (Figure 3).

Table 3. Passing time of the species that passed the fishway. Among the species passing through the fishway, the 1st antenna line detection time of *Carassius cuvieri, Pseudobagrus fulvidraco, Silurus asotus*, and *Coreoperca herzi* were not uploaded to the database (internet server), due to a miscommunication between the data logger and the database of the PIT telemetry system; therefore, we could not present the passing time of these individuals.

Family	Species	Time (h)		Proportion (%)			
		N	Mean (SD)	<1 day	1–5 days	5–10 days	>10 days
Cyprinidae	*Hemibarbus labeo*	1	168.9			100	
	Hemibarbus longirostris	2	8.7 (7.9)	100			
	Pseudogobio esocinus	2	127.4 (172.8)	50		50	
	Zacco platypus	8	470.8 (646.0)		37.5	12.5	50
	Opsariichthys uncirostris amurensis	4	62.4 (107.4)	75		25	
	Erythroculter erythropterus	1	1.2	100			
Bagridae	*Leiocassis ussuriensis*	1	1559.4				100
	Total	19		36.8	15.8	21.1	26.3

Table 4. Attraction time and movement time by fishway section. Attraction time indicates the time spent from the release site to the first antenna. We also presented the movement speed (m/h) in each section.

		Attraction	Movement			Passing
		Release Site→1st	1st→2nd	2nd→3rd	3rd→4th	1st→4th
Distance (m)		300	220	230	200	650
Area (m^2)		-	2695	1562	1235	5492
Time (h)	Mean (SD)	627.6 (1687.9)	284.9 (443.8)	114.2 (185.6)	33.3 (84.0)	316.7 (570.5)
	Range	0.1–7532.2	0.3–2012.4	0.8–740.2	0.7–434.9	1.2–2135.0
Speed (m/h)		0.5	0.8	2.0	6.0	2.1

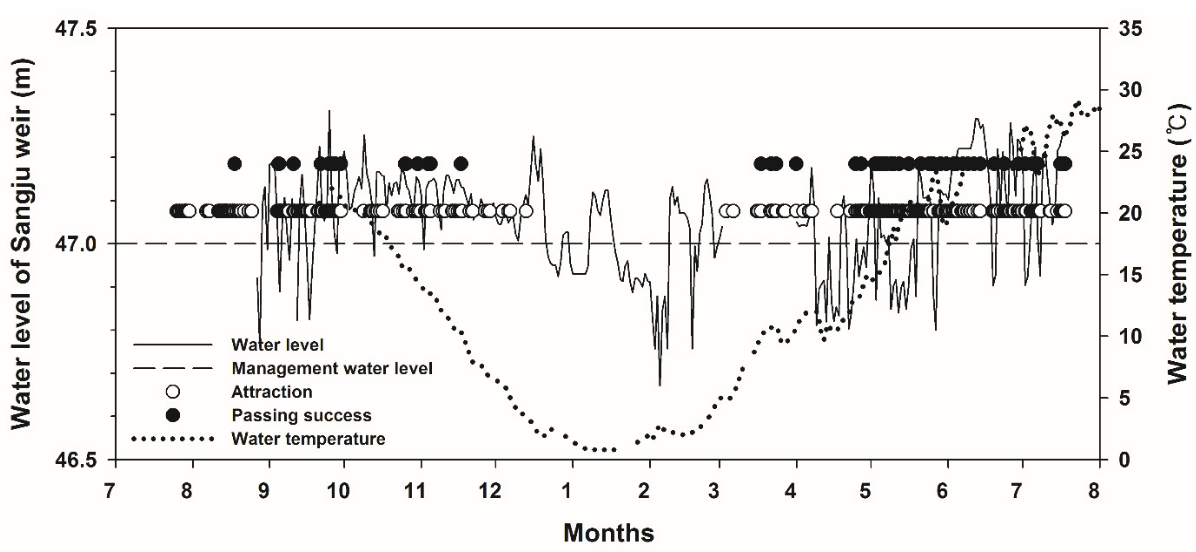

Figure 3. Correlations among upstream water level, water temperature change, and tag detection. Attraction and passing success occurred when the upstream water level was higher than the management water level (47.00 m AMSL), at 47.08 m AMSL and 47.19 m AMSL, respectively. No detection in the fishway was made between mid-December 2012 and March 2013, when water temperature was low.

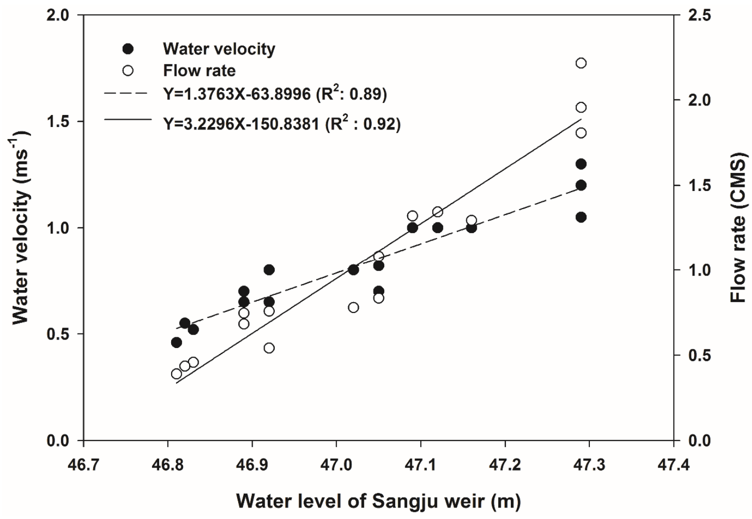

Figure 4. Changes in water velocity and flow rate in the fishway according to the water level upstream of the Sangju Weir.

The detection times of the 4 major species using the fishway were checked against water levels upstream of Sangju Weir. Results showed that all 4 species were using the fishway when the upstream water level ranged from 46.80–47.30 m AMSL (Figure 5), without statistically significant interspecific differences (one-way ANOVA test, $p > 0.05$). The analysis of detection times to compare fishway usage time by species revealed species-specific patterns (Figure 6). *Z. platypus* and *O. u. amurensis* were using the fishway during both daytime (06:00–18:00) and nighttime (18:00–06:00) hours, most frequently during sunset (17:00–19:00) (Figure 6a,b). In contrast, *P. esocinus* and *H. longirostris* used the fishway mostly after sunset, avoiding the daytime hours (Figure 6c,d).

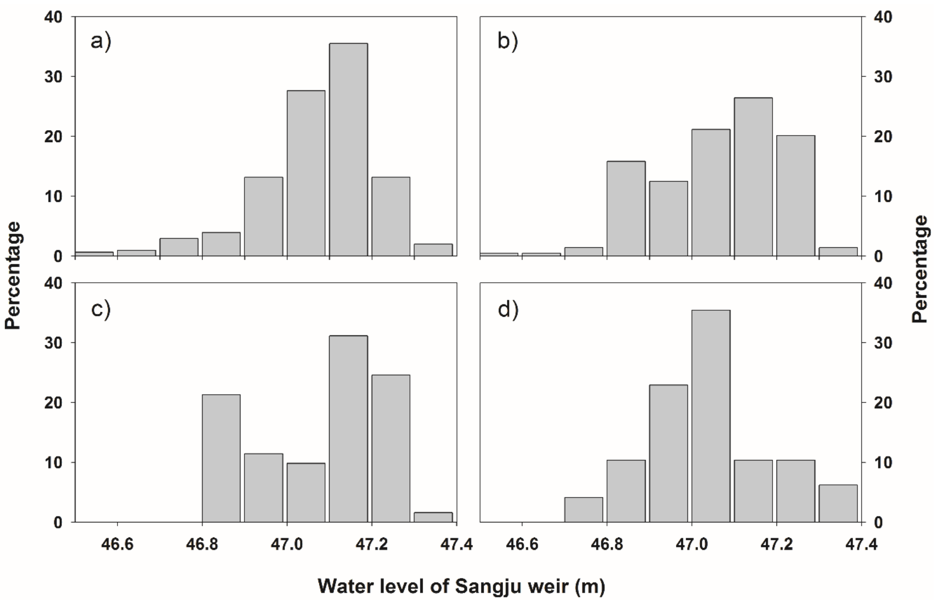

Figure 5. Species-specific patterns of fishway usage depending on upstream water level: (**a**) *Zacco platypus*; (**b**) *Opsariichthys uncirostris amurensis*; (**c**) *Pseudogobio esocinus*; (**d**) *Hemibarbus longirostris*.

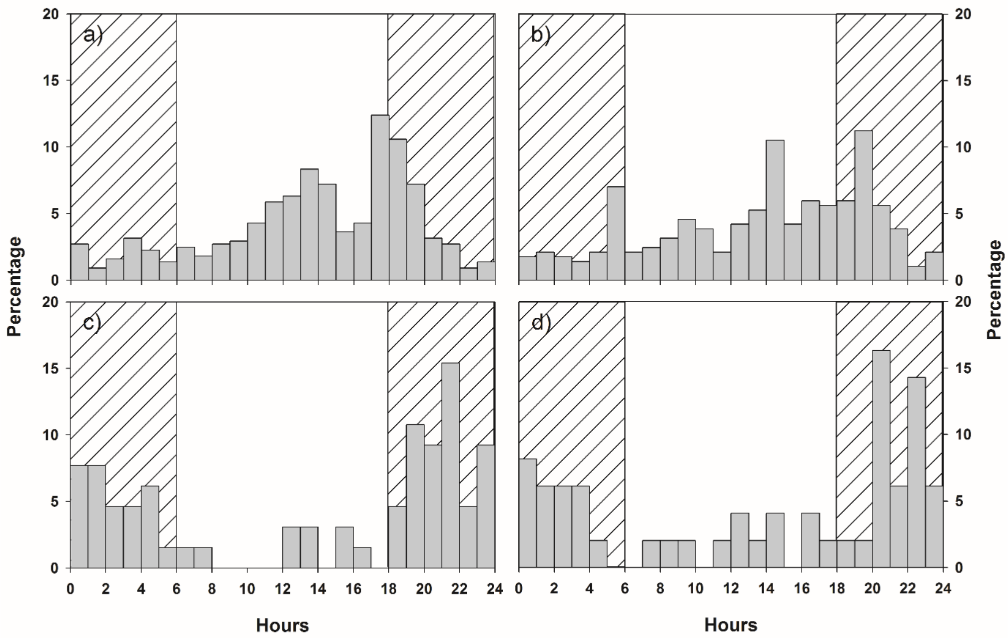

Figure 6. Species-specific patterns of fishway usage depending on the time of the day: (**a**) *Zacco platypus*; (**b**) *Opsariichthys uncirostris amurensis*; (**c**) *Pseudogobio esocinus*; and (**d**) *Hemibarbus longirostris*. For the analysis, the first attraction data of each individual were utilized. Time of day was divided into daytime (06:00–18:00) and nighttime (18:00–16:00, oblique line) hours.

4. Discussion

The recent trend of fishway design reflects the goal of attracting a wide variety of fish species rather than targeted species [18,19]. In Korea too, fishway design features focus on the species diversity of individuals using fishways. A comparison of the fish species using the fishway with those inhabiting the main channel of the Nakdong River showed that a high diversity (66%) of species inhabiting the main channel used the nature-like fishway at Sangju Weir. This included four endemic species and one species protected under the Endangered Species Act. Thirty-four percent of the fish species that inhabit the main channel of the Nakdong Rivier were not observed in the fishway. Unlike the species that utilized the fishway, these species lack the motivation to use the fishway; their usage therefore was not confirmed. The main biological aim of installing a fishway is to enable movement of anadromous and potamodromous fish to their spawning grounds and to help freshwater fish downstream of the weir move upstream (and vice versa), preventing isolation between the two areas [20]. Genetic differences between upstream and downstream species, due to long-term isolation resulting from a structure constructed across the river, have been reported [21]. When such situations persist and genetic diversity decreases, certain species may become endangered or extinct. The Sangju Weir fishway can be used by a variety of fish species of the ichthyofaunal communities in the main channel of the Nakdong River.

The fishway was being used by individuals of all sizes without any size-dependent tendency, with a TL ranging from 39 to 550 mm. The nature-like fishway has a very low slope of 1%, providing lower water velocity and turbulence compared to other fishways [22]. Water velocity is an important parameter for the attraction and passage efficiencies of a fishway because a high water velocity prevents small fish with weak swimming ability from using the fishway [18]. Moreover, Stuart and Mallen-Copper [23] reported that turbulence can also be an adverse factor for the movement of small individuals. In this regard, the Sangju Weir fishway was verified as having an appropriate water velocity and turbulence for a nature-like fishway, facilitating its usage by small individuals. Furthermore, while technical fishways have a constant water velocity and water depth due to their homogenous structure, nature-like fishways have lower slopes and nature-mimicking irregular substrates, producing various water depths and velocities [22]. Such nature-like fishway environments allow fish of different sizes and swimming abilities to use the fishway [9].

Bunt *et al*. [13] performed a meta-analysis using efficiency evaluation results for various types of fishways, and noted that attraction efficiency was lowest for nature-like fishways (mean 48%), while passage efficiency was highest (mean 70%). At 20.7% and 14.5%, respectively, the actual attraction and passage efficiencies of the nature-like fishway at Sangju Weir were lower than the values presented by Bunt *et al*. [13]. From a structural point of view, the extremely low water velocity at the fishway entrance is probably responsible for the low attraction efficiency [24,25]. Moreover, the fishway length is inversely proportional to passage efficiency [5]. Compared to the slopes (1.7%–7.1%) and lengths (12–370 m) of the 7 nature-like fishways analyzed by [13], the Sangju Weir nature-like fishway has a lower slope (1%) and is much longer (650 m), which are both considered structural characteristics unfavorable for attraction and passage efficiencies.

According to the results of the trap survey, despite the high species diversity of the individuals using the Sangju Weir nature-like fishway, all species were freshwater fish, without any anadromous fish species. Since anadromous species have to ascend the stream to return to their spawning grounds, attraction and passage efficiencies for such species are high in most fishways [26]. On the other hand, as freshwater fish species migrate without such a natural drive, their attraction and passage efficiencies may vary among fishways [27]. Consequently, the final results of attraction and passage efficiencies of the nature-like fishway at Sangju Weir can be considered to have been affected by the ecological characteristics of the endemic fish species and the structural characteristics of the fishway.

The benefit of the telemetry method lies in the quantitative evaluation of the efficiency of the attraction and passage of the fishway, which enables the provision of plans to increase the efficiency of the corresponding fishway. In this regard, environmental factors such as water depth, velocity, temperature, and discharge rate were reported to affect the upstream migration of fish [28–31]. In the case of the nature-like fishway at Sangju Weir, the flow rate and water velocity varied as the upstream water level changed, as did its attraction and passage efficiencies. If the optimal conditions for attraction and passage efficiencies are different, a question of priority arises. Attraction efficiency can be increased by changing the position and structure of the entrance without necessarily changing the flow rate [32,33], but this has little influence on the passage efficiency. Thus, when setting standards, passage efficiency should be prioritized and measures to increase attraction efficiency should also be considered. The management water level of Sangju Weir is maintained at 47.00 m AMSL, and it is difficult to maintain a higher upstream water level. Therefore, to increase the passage efficiency of the nature-like fishway at Sangju Weir, the structure of the fishway exit should be altered to induce an optimal flow rate of 1.57 $m^3 \cdot s^{-1}$, which was found to ensure the highest passage efficiency, provided that the management water level upstream of Sangju Weir is maintained. This structural alteration is expected to improve the fishway passage efficiency.

Many studies in which telemetry-based fishway evaluation was performed have measured the attraction and passage efficiencies of fishways, but very few have made actual passing time measurements. Compared to ice-harbor-type fishways constructed at larger rivers, where 83% of passing individuals passed the fishway within 6 h [16], for 63.2% of the individuals that passed the nature-like fishway at Sangju Weir, it took more than one day. Even assuming that this difference may be attributed to the difference in TL and the length of the fishway, some individuals spent up to 28 days (2135.0 h) in the fishway. As the nature-like fishway has a river-like shape, it can function as a habitat as well as a passage [34]. In other words, it may be suspected that those individuals that stayed within the nature-like fishway at Sangju Weir for a prolonged period of time were using the fishway as their temporary habitat. Moreover, although the distance between each section is similar, individuals stayed longest in the 1st→2nd section, which offers the largest area (habitat space), thus supporting the assumption that the nature-like fishway at Sangju Weir also acts as habitat. On the other hand, Agostinho *et al*. [35] reported the problematic usage of the fishway by certain predator fish as their foraging area in Brazil. In this study, we were able to observe the usage of the fishway by predator fish such as *Siniperca scherzeri*, *Coreoperca herzi*, and *Micropterus salmoides* by trapping. If these species use the fishway as their habitat and forage fish within the fishway, this could affect the efficiency of the fishway. Therefore, further studies on the usage of the fishway as a habitat by predator fish should be performed in the near future.

Z. platypus, *O. u. amurensis*, *P. esocinus*, and *H. longirostris* were the major fish species using the nature-like fishway at Sangju Weir, and the frequency of usage increased without any significant interspecific differences when the upstream water level was 47.00–47.20 m AMSL. The water velocity and inflow rate into the fishway suitable for the passage of these fish species ranged from 0.79–1.06 $m \cdot s^{-1}$ and from 0.95–1.60 $m^3 \cdot s^{-1}$, respectively. These values should be considered as design factors for future fishways likely to be used by these species.

Interspecific differences in fishway usage patterns depending on the time of the day were observed among these 4 species. *Z. platypus* and *O. u. amurensis* were observed to use the fishway at both daytime and nighttime hours, more frequently during the daytime until sunset. *P. esocinus* and *H. longirostris* mostly used the fishway during nighttime hours, with a very low daytime usage frequency. Such time-dependent usage patterns are related to different ecological characteristics (diurnal or nocturnal) of the species [36] and the survival strategy of avoiding visual predators [37]. However, given the similar sizes of the species and the absence of strong predators among cohabiting species in the fishway, it is difficult to understand the nocturnal pattern in terms of visual predator avoidance. Thus, this difference is assumed to be ascribable to the differences in ecological characteristics. Given the lack of studies on these species, however, further research is required to determine the exact reason for the time-dependent interspecific differences.

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