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Changes in particulate organic matters and plankton populations in nature-like fishways: role of nature-like fish ways in water treatment

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Abstract – Nature-like fishways, designed to mimic a small natural stream, have been widely used in river restoration projects as well as in rivers with dams and weirs. Because they are built with diverse natural materials similar to those in natural streams, we aimed to estimate the self-purification ability of nature-like fishways. Monthly sampling was conducted at inlet and outlet points of two nature-like fishways in Korea: the Baekjae and Sejong fishways. Two artificial fishways and main river channels were also evaluated to be used as references. Suspended solids (SS), chlorophyll *a* (Chl. *a*), and plankton abundances were measured. A significant reduction in plankton abundances and decrease in SS and Chl. *a* were observed in nature-like fishways, and no significant changes were observed in concrete artificial fishways and main river channels. In Baekjae and Sejong fishways, average 28.2% and 14.9% of the SS concentrations were reduced, respectively. The Chl. *a* concentration also significantly decreased (44.8% and 29.8% in Baekjae and Sejong fishways, respectively). A decreasing pattern was more apparent in the Baekjae fishway, which is longer and has a slower water velocity. The rate of decrease was higher when SS and Chl. *a* concentrations were high at the inlet points. Thus, we confirmed that particulate organic matters could be reduced in nature-like fishways. However, the direct cause and purification process mechanisms in them could not be clearly identified. Further studies should examine the biological and chemical mechanisms in fishways, allowing us to estimate their capacity for self-purification.

Keywords: self-purification / phytoplankton / zooplankton / suspended solid / chlorophyll *a*

Résumé – Changements dans les matières organiques particulaires et les populations de plancton dans les passes de type « rivière artificielle » : rôle des passes de type « rivière artificielle » dans la qualité de l'eau. Des passes de type « rivière artificielle », conçues pour imiter un petit ruisseau naturel, ont été largement utilisées dans les projets de restauration des rivières ainsi que dans les rivières avec barrages et seuils. Parce qu'elles sont construites avec divers matériaux naturels semblables à ceux des cours d'eau naturels, nous avons cherché à estimer l'aptitude à l'auto-épuration des passes de type « rivière artificielle ». Des échantillonnages mensuels ont été effectués aux points d'entrée et de sortie de deux passes de type « rivière artificielle » en Corée : les passes à poissons Baekjae et Sejong. Les deux passes artificielles et les secteurs principaux de rivières ont également été évalués pour servir de référence. On a mesuré les solides en suspension (SS), la chlorophylle *a* (Chl. *a*) et les abondances du plancton. Une réduction significative de l'abondance du plancton et une diminution des SS et de Chl. *a* ont été observées dans les passes de type « rivière artificielle » et aucun changement significatif n'a été observé dans les passes artificielles et les secteurs principaux de la rivière. Dans les passes de type « rivière artificielle » de Baekjae et Sejong, les concentrations moyennes de SS étaient respectivement réduites de 28,2 % et 14,9 %. La concentration en Chl. *a* a également diminué de façon significative (44,8 % et 29,8 % respectivement dans les passes de

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type « rivière artificielle » de Baekjae et Sejong). Un gradient décroissant était plus apparent dans la passe de Baekjae, qui est plus longue et a une vitesse d'eau plus lente. Le taux de diminution était plus élevé lorsque les concentrations SS et Chl. *a* étaient élevées aux points d'entrée. Ainsi, nous avons confirmé que les matières organiques particulaires peuvent être réduites dans les passes de type « rivière artificielle ». Cependant, les causes directes et les mécanismes de purification ne peuvent pas être clairement identifiés. D'autres études devraient examiner les mécanismes biologiques et chimiques dans les passes à poissons, permettant d'estimer leur capacité d'auto-épuration.

Mots clés : auto-épuration / phytoplancton / zooplancton / matière en suspension / chlorophylle *a*

1 Introduction

Dams and weirs have been constructed throughout the world since the 20th century and are used to manage water resources. However, their structure frequently disrupts the river continuum and interrupts the transportation of organic matter, consequently changing water quality in a negative way (Wei *et al.*, 2009). Further, because the connectivity of watersheds is crucial for fishes, the fragmentation of aquatic habitats frequently results in their extirpation (Sheer and Steel, 2006; Yoon *et al.*, 2016).

Therefore, fish ladders, or a fish passes, have been developed to enable fish to pass such barriers (Roscoe and Hinch, 2010). They are generally built using hard engineering materials, such as concrete, metal, and wood, and occasionally using synthetic materials, such as fiberglass (Katopodis *et al.*, 2001). However, in the late 1970s, nature-like bypass channels were developed in Europe and were characterized by a "soft" engineering approach (Katopodis and Rajaratnam, 1983). These nature-like fishways are built with diverse materials, such as large wood debris, boulders, and riparian vegetation, imitating natural stream geomorphologic conditions (Bretón *et al.*, 2013). Due to their heterogeneous structure, compared with conventional fishways, nature-like fishways offer a greater variety of water velocities and depths, making them amenable to a wider range of fish species and sizes (Aarestrup *et al.*, 2003).

Nature-like fishways not only act as a passage but also provide habitats for aquatic organisms by mimicking a natural stream-bed structure. Previous studies have suggested that greater benthic macroinvertebrate diversity is associated with nature-like fishways than with conventional fishways (Gustafsson *et al.*, 2013; Pander *et al.*, 2013). A confirmation of diverse benthic macroinvertebrates combined with a natural channel structure can possibly be related to the existence of other benthic organisms, such as those forming biofilm (Wallace and Webster, 1996; Covich *et al.*, 1999).

Generally, self-purification in a natural stream channel can be achieved by complex physical, chemical, and biological processes. The assimilation of dissolved organic substances and nutrients in the water by bacteria, plants, and animals, as well as dilution and mixing processes are designed to self-purify (Heidenwag *et al.*, 2001). In particular, the uptake of drifting organic matter by macroinvertebrates and fishes also plays an important role in self-purification (Chang *et al.*, 2008; Doi *et al.*, 2008). Therefore, it can be expected that a nature-like fishway with a variety of benthic organisms has the capacity for self-purification. In addition to the basic passage functions of a fishway, any improvements in environmental parameters mean that water purification can be added as another function. However, previous studies have mainly focused on the passage efficiency of fish and the availability of fish habitats in nature-like fishways; as far as we know, this is the first study to estimate the water purification ability of fishways.

In Korea, there are over 33000 weirs but only 15% have fish passage facilities. In 1996, legislation obligated the installation of a fishway and they have since been gradually increasing in number. The most common fishway types in Korea are a channel-weir (28.7%) and a channel type (25.4%). However, the installation of nature-like fishways has recently been increasing due to their availability to a wide range of fish species and high passage efficiency (Kim *et al.*, 2015).

To estimate the water purification ability of nature-like fishways, we traced their environmental parameters change and compared them with hard material (concrete) fishways. Samples were also obtained from the main river channel to determine whether environmental parameters change when river water flows through the weir floodgate, not through the fishway.

2 Materials and methods

2.1 Study area

The study was conducted in two nature-like fishways constructed in the main channel of the Geum River, Korea. The Geum River, located in mid-west South Korea, is 394 km long with an area of 9912 km^2. As part of the Four Major Rivers Restoration Project, the Baekjae and Sejong Weirs were constructed in the main channel of the Geum River in 2012, and the two nature-like fishways were built to improve the up- and down-stream movement of fish on the sides of the weir (Kim *et al.*, 2015).

The artificial Gongju fishway in the Geum River (ice-harbor fishway) and Jamsil fishway in the Han River (pool-and-weir-type fishway) were selected as reference sites. The Han River is the largest river in South Korea at 469.7 km long and with a watershed area of 26200 km^2 (Kim *et al.*, 2003). A total of four fishways were included in this study, the nature-like Baekjae fishway, the nature-like Sejong fishway, and the two artificial sites of the Gongju fishway and Jamsil fishway (Fig. 1). The two artificial fishways were also built on the sides of weirs constructed in the main river channel during the Four Major Rivers Restoration Project in 2012. To compare the water quality, the main channel up- and down-stream of the Sejong and Gongju weirs were also studied. The characteristics of each fishway are summarized in Table 1.

2.2 Sampling methods

Investigations of environmental parameters and plankton populations were carried out at two points in each fishway: where the mainstream water flows into the fishway (inlet) and

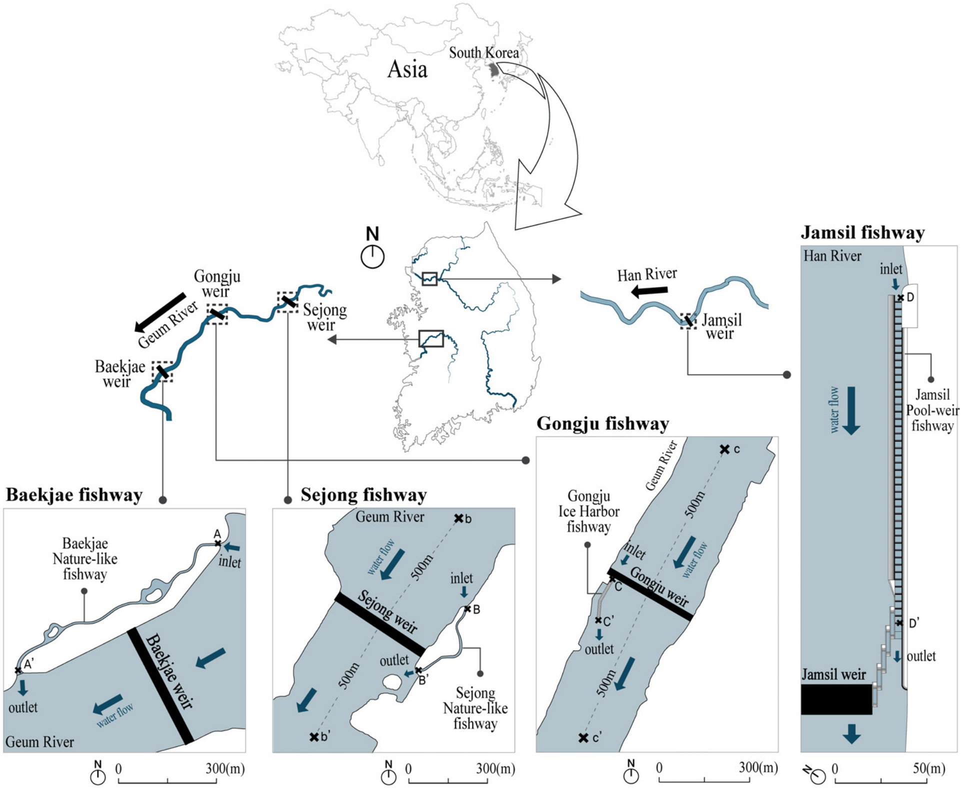

Fig. 1. Study area in Korea. The investigation was conducted at each X point: inlet and outlet points of fishways (Baekjae – A, A′; Sejong – B, B′; Gongju – C, C′; Jamsil – D, D′) and upstream and downstream points of the main stream weir section (Sejong – b, b′; Gongju – c, c′).

Table 1. Characteristics of the Baekjae nature-like, Sejong nature-like, Gongju ice harbor, and Jamsil pool-and-weir-type fishways.

	Baekjae nature-like fishway	Sejong nature-like fishway	Gongju concrete fishway	Jamsil concrete fishway
Structure	Nature-like channel. Two nature-like pools	Nature-like channel. Repetitive runs and riffles	Ice harbor type, made of concrete	Pool and weir type, made of concrete
Length	820 m	355 m	140 m	228 m
Width	6 m	4–6 m	6 m	4 m
Depth	0.3–1.1 m	0.2–1 m	0.7 m	1 m
Slope	0.2°	0.5°	2.9°	2.5°
Velocity	0.12–0.54 m s^{-1}	0.3–1.3 m s^{-1}	0.3–0.9 m s^{-1}	0.8 m s^{-1}
Bed material	Sediment bed and boulders	Sediment bed and boulders	Concrete	Concrete and boulders
Vegetation	Presence	Presence	Absence	Absence

at the downstream confluence of the fishway with the main river (outlet).

Monthly samples of environmental parameters and plankton populations were obtained during May–September 2015 from the Baekjae and Sejong nature-like fishways. To compare the organic matter amount differences between nature-like fishways and the artificial, hard material (concrete) fishways, the Gongju ice-harbor type fishway and the Jamsil pool-and-weir-type fishway were sampled on 28 August and 13 October, respectively. An additional investigation was conducted upstream and downstream of the weir in the main channel (Fig. 1b, b') on 28 August to identify changes in organic matter amounts in the surface water when water flows through the floodgate of the weir instead of the fishway. However, due to sampling difficulties near the weirs in the main channel, samples were collected just once from locations approximately 500 m upstream and downstream from the weir.

A total of basic water quality parameters and changes in phytoplankton and zooplankton populations were measured to estimate the impact of biological interactions in the fishway channel. Water velocity was measured only at the inlet points of each fishway with a global Flow Probe FP 211 (Global-Water, USA) and the average of three repeated measurements was used. Water temperature (°C), dissolved oxygen (DO), chlorophyll *a* (Chl. *a*), pH, and electrical conductivity (EC) were directly measured both at the inlet and outlet fishway points using a DO meter (YSI 55, USA), spectrophotometer (AquaFluor, Turner Designs, USA), and a pH/EC meter (Horiba D-54, Japan), respectively. Suspended solids (SS),

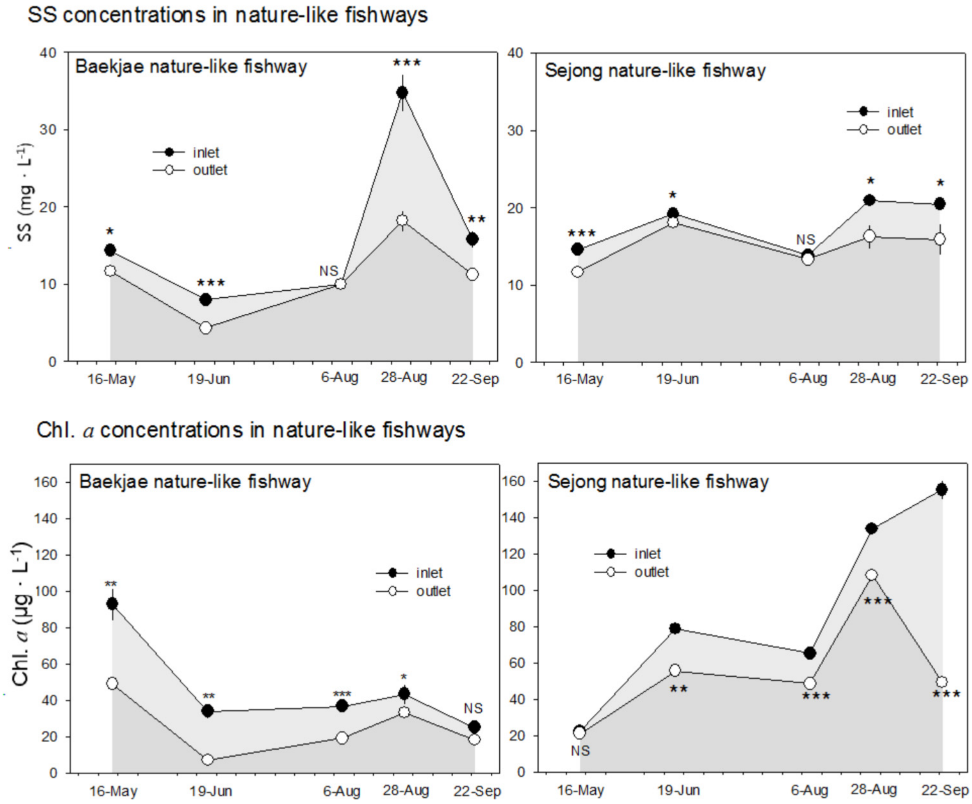

Fig. 2. Concentration of suspended solid (SS) and chlorophyll-*a* (Chl. *a*) at inlet and outlet points of the Baekjae and Sejong nature-like fishways.

total nitrogen (T-N), and total phosphorus (T-P) were determined in the laboratory following standard protocols (APHA, 1995). Suspended solids (SS) were filtered through a pre-baked and pre-weighed 0.7-µm pore size glass fiber membrane (GF/F) by vacuum pump, and determined gravimetrically after being dried at 105 °C. The T-N (chromotropic acid method) and T-P (ascorbic acid method) were analyzed by spectrophotometry. Zooplankton samples were collected by filtering 10 L of river water through a 60-µm mesh zooplankton net. Phytoplankton samples were taken from surface water (250 ml). Zooplankton and phytoplankton were immediately fixed with formalin and Lugol's solution, respectively, and population densities were obtained by counting the species-specific abundance in the laboratory with a binocular stereoscopic microscope. Zooplankton biomass was calculated based on the species-specific values suggested from the length-weight estimations (Dumont *et al.*, 1975; Pauli, 1989).

2.3 Data analysis

Chl. *a* and SS data were analyzed by a *t*-test or Mann–Whitney *U* test according to the normality of the data distribution, and the results were marked based on *P*-values in tables and figures as follows: $P > 0.05$, N.S. (not significant); $^{*}P \leq 0.05$; $^{**}P \leq 0.01$; and $^{***}P \leq 0.001$. A multiple regression analysis was conducted to estimate the effects of water velocity, water temperature and initial concentrations of SS and Chl. *a* on the decrease of SS and Chl. *a* concentrations in the nature-like fishway channel. The relationship between inlet concentration and a reduced concentration of SS and Chl. *a* were estimated by Spearman's rank correlation coefficients as the reduction rates were non-parametric. Statistical analyses were conducted using the statistical software R (version 3.2.4 for windows; R foundation) and software PASW Statistics 18 (v. 18, SPSS Inc. Chicago, IL, USA).

3 Results and discussion

A significant decreases in SS and Chl. *a* were observed at the outlet points of both nature-like fishways (Fig. 2). The mean reduction in SS concentration during the study period was 28.2% in the Baekjae and 14.9% in the Sejong nature-like fishways. The Chl. *a* concentration was also significantly decreased at the outlet points ($P < 0.05$, except in September in Baekjae nature-like fishway and May in Sejong nature-like fishway). The mean reduction of Chl. *a* in the Baekjae and Sejong nature-like fishways was 44.8% and 29.8%, respectively.

On the other hand, between inlet and outlet points of the artificial fishways and main river channels showed that SS and Chl. *a* concentration changes were not statistically significant ($P > 0.05$). The SS and Chl. *a* concentrations in the main channel even increased by 45.8% after the water had flowed down through the Sejong weir ($P < 0.01$, Tab. 2). However, such apparent decreases of SS and Chl. *a* concentrations in fishway channel were not observed in artificial fishways (Fig. 3). In addition, other physico-chemical parameters (DO, pH, EC, T-N, and T-P) did not show any changing patterns

Table 2. Measured environmental parameters at each study site.

Site	Dates (2015)		Velocity ($m\,s^{-1}$)	Water temp. (°C)	Chl. *a* ($\mu g\,L^{-1}$)	SS ($mg\,L^{-1}$)
Baekjae nature-like fishway	5/16	In	0.31	18.9	92.9 ± 8.9	14.3 ± 0.8
		Out	–	20.8	**49.0 ± 3.7	*11.7 ± 0.1
	6/19	In	0.61	28.1	33.9 ± 4.0	8.0 ± 0.3
		Out	–	29.3	**7.2 ± 0.6	***4.3 ± 0.3
	8/6	In	0.30	32.0	36.8 ± 1.9	10.0 ± 0.7
		Out	–	31.8	***19.2 ± 1.7	NS 10.0 ± 0.1
	8/28	In	0.21	27.0	43.4 ± 5.7	34.8 ± 2.4
		Out	–	28.0	*33.3 ± 1.9	***18.2 ± 1.4
	9/22	In	0.43	25.5	25.1 ± 1.3	15.8 ± 1.0
		Out	–	25.7	NS 18.3 ± 2.3	**11.2 ± 0.6
Sejong nature-like fishway	5/16	In	0.84	17.7	22.5 ± 2.2	14.6 ± 0.4
		Out	–	18.4	NS 21.0 ± 1.0	***11.6 ± 0.4
	6/19	In	0.60	23.0	78.6 ± 2.6	19.2 ± 0.6
		Out	–	25.4	**55.6 ± 0.6	*18.1 ± 0.5
	8/6	In	0.67	29.3	65.2 ± 2.3	13.8 ± 0.6
		Out	–	28.5	***48.6 ± 1.1	NS 13.3 ± 0.4
	8/28	In	0.40	25.1	133.7 ± 1.4	20.9 ± 0.2
		Out	–	24.7	***108.0 ± 2.0	*16.3 ± 1.6
	9/22	In	0.37	23.5	155.1 ± 5.3	20.5 ± 0.5
		Out	–	23.6	***49.2 ± 0.8	*15.9 ± 2.0
Sejong main channel	8/28	In	0.00	26.8	133.7 ± 2.8	14.8 ± 0.2
		Out	–	25.9	NS 125.8 ± 5.9	**21.6 ± 0.7
Gongju Ice harbor fishway	8/28	In	0.30	25.2	78.8 ± 2.7	16.8 ± 0.6
		Out	–	19.3	NS 77.5 ± 7.0	NS 17.4 ± 0.2
Gongju main channel	8/28	In	0.10	29.1	78.8 ± 0.5	13.0 ± 0.1
		Out	–	27.3	NS 80.7 ± 1.4	NS 12.9 ± 0.3
Jamsil pool and weir type fishway	10/13	In	0.80	19.5	10.0 ± 4.1	2.8 ± 0.4
		Out	–	19.3	NS 11.0 ± 5.3	NS 2.4 ± 0.0

The results of statistical analyses (paired *t*-test or Wilcoxon signed rank test): N.S (not significant, $P > 0.05$); *$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$.

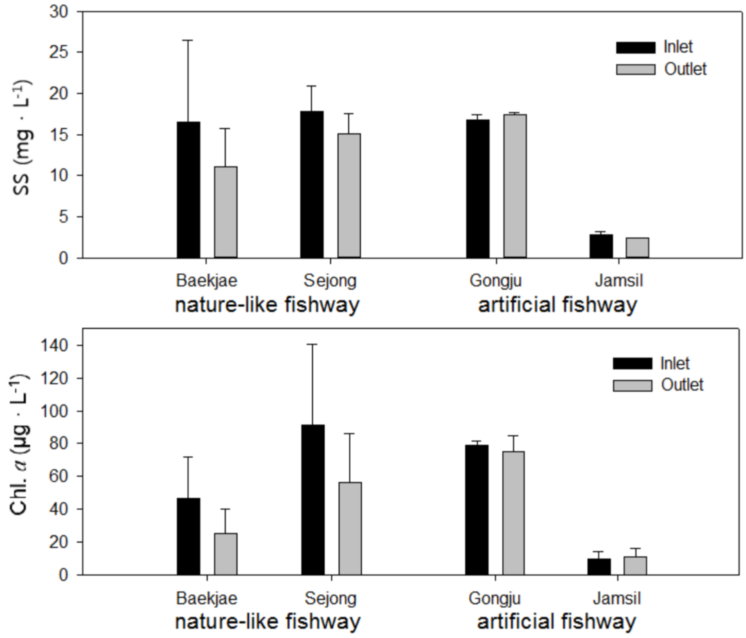

Fig. 3. Comparisons of average SS (upper) and Chl. *a* (lower) concentrations between inlet and outlet in nature-like and artificial fishways.

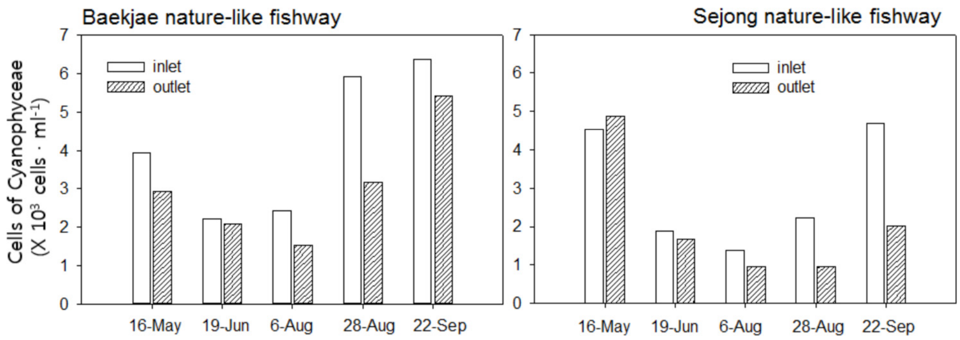

Fig. 4. Change in Cyanophyceae density at inlet and outlet points of the Baekjae and Sejong nature-like fishways.

Table 3. Mean reduction in SS, Chl. *a*, zooplankton, and phytoplankton in nature-like fishways during the study period (mean ± S.D.)

Reduction Rate (%)	Baekjae nature-like fishway	Sejong nature-like fishway
Suspended Solids (SS)	28.2 ± 19.7	14.9 ± 8.2
Chlorophyll *a* (Chl. *a*)	44.8 ± 22.1	29.8 ± 20.7
Zooplankton abundance	57.0 ± 18.1	22.7 ± 15.0
Cyanophyceae abundance	26.1 ± 16.6	29.4 ± 28.3

in both nature-like and artificial fishways during the study period (data not shown).

In eutrophic rivers, autochthonous sources including phytoplankton and zooplankton are the dominant sources of suspended organic matter as well as Chl. *a* in surface river waters (Countway *et al.*, 2007). During the study period, the phytoplankton community of the river was dominated by the Cyanophyceae, particularly *Microcystis* spp., and the cell density of the Cyanophyceae was higher at the inlet points than the outlet points of both nature-like fishways. The mean reduction rate was 26.1% and 29.4% in the Baekjae and Sejong nature-like fishways, respectively (Fig. 4, Tab. 3). Both nature-like fishways showed a clearly decreasing pattern of zooplankton density at the outlet points. On average, 57.0% and 22.7% of the zooplankton, which flowed through nature-like fishways were decreased at the outlet points in the Baekjae and Sejong nature-like fishways, respectively (Tab. 3). Rotifers dominated in both fishways (average of 93%) and they accounted for most of the reduced zooplankton density (Fig. 5). Compared with large-bodied cladocerans such as *Daphnia* of which grazing pressure is an important factor controlling algal biomass, small-bodied rotifers mainly consume the components of microbial loop and their high biomass often co-exist with algal blooms (Ger *et al.*, 2016). Therefore, the decrease of small-bodied zooplankton with Cyanophyceae in nature-like fishway channel can be positive water treatment process removing the sources of suspended organic matter from surface river waters.

It has been reported that filter-feeding macroinvertebrates can be found in nature-like fishways (Gustafsson *et al.*, 2013). They are known to remove fine particulate organic matter (FPOM; <1 mm diameter) from suspension (Wallace and Merritt, 1980). Benthic organisms may also regulate algal biomass (Basu and Pick, 1997). Many studies (Lamberti and Resh, 1983; Feminella *et al.*, 1989) have reported that benthic invertebrate grazers reduce algal biomass. Simultaneously, small zooplanktons are also easily reduced by sedimentation and physical damage. In shallow conditions, increased contact with stream sediments could decrease zooplankton abundance (Chang *et al.*, 2008). Moreover, suspension-feeding, filter-feeding, or net-spinning macrozoobenthic organisms could also reduce zooplankton abundance (Czerniawski *et al.*, 2016). Even within a short section of a productive river that includes zooplankton, phytoplankton, and drift food sources, macroinvertebrates and fishes could play an important role in consuming and removing the drifting particles (Chang *et al.*, 2008; Doi *et al.*, 2008). According to Kim *et al.* (2015) and Park (2015), many fish species were found in Baekjae nature-like fishway and Sejong nature-like fishway during the survey for fish utilization of constructed nature-like fishways. Most frequently found species were *Squalidus japonicus coreanus* and *Squalidus chankaensis tsuchigae* in both fishways, which are known to consume zooplanktons. In the present study, therefore, as the zooplankton density and phytoplankton biomass decreased significantly, the reduction in SS was mostly due to biological uptake by benthic organisms and fish species.

Not only the abundance but also the zooplankton species composition changed with an apparent decrease of Rotifera, Cladocera and Copepoda (Fig. 5). While planktonic rotifer species belonged to genera *Filinia*, *Keratella*, *Polyarthra*, *Brachionus*, *Philodina*, and *Anuraeopsis* decreased, attached epiphytic species increased at the outlet points of nature-like fishways. Epiphytic rotifers found in the Baekjae and Sejong nature-like fishways belonged to genera *Cephalodella*, *Colurella*, *Lepadella*, *Lecane*, and *Monostyla* (Choi *et al.*, 2014, 2015). The total numbers of epiphytic rotifers at the outlet points of the Baekjae and Sejong fishways were 4.8 and 1.8 times higher than at the inlet points, respectively (Fig. 5). Generally, because of the size selection of zooplankton by fish, larger zooplankton, such as the *Daphnia* and Copepoda are the first to be reduced and the rotifers are the last (Chang *et al.*, 2008; Czerniawski *et al.*, 2016). However, when small zooplankton species occur in high densities, then the reduction rate increases due to a higher encounter rate with predators, including benthic invertebrates (Jack and Thorp, 2002). This may explain the high decrease rate of planktonic species. On the other hand, epiphytic rotifers increased at fishway outlet points (Fig. 5). Even though the samples were not directly obtained from the substrates, the result could possibly indicate the presence of substrates to facilitate the

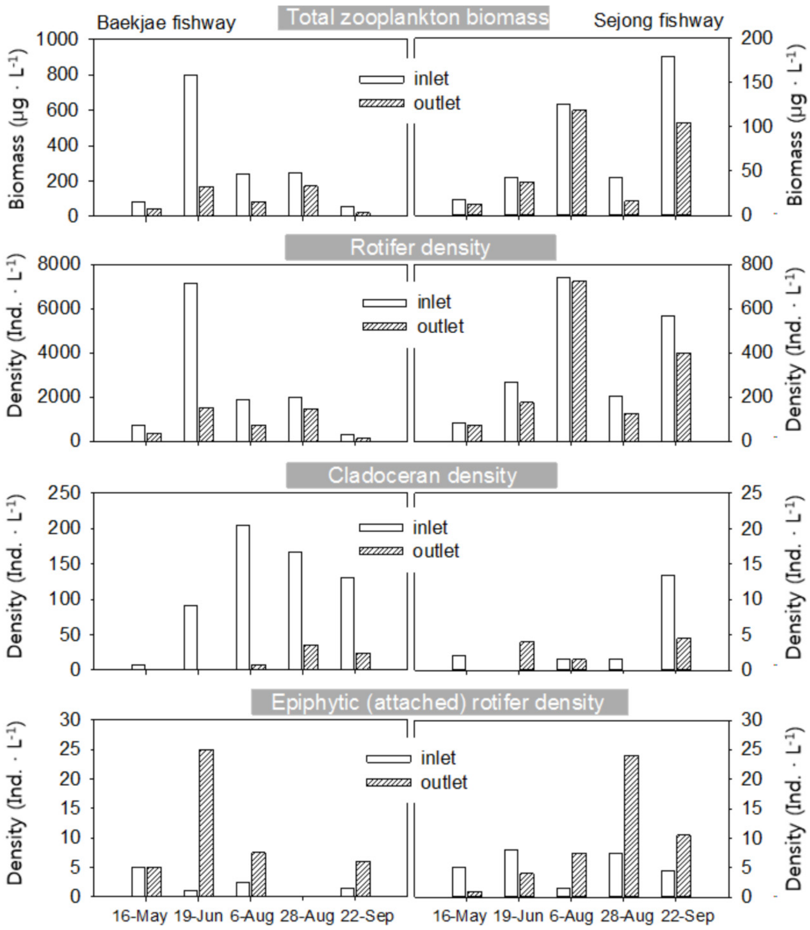

Fig. 5. Change in zooplankton population at inlet and outlet points of the Baekjae and Sejong nature-like fishways.

Table 4. Results of multiple regression analysis among SS, Chl. *a*, water velocity and water temperature. Significance is highlighted in bold.

Variables	R^2	Adjusted R^2	*F*	*P*
Dependent variable: Reduced SS				
	0.739	0.608	**0.035**	
Initial SS				**0.015**
Water velocity				0.632
Water temperature				0.881
Dependent variable: Reduced Chl. *a*				
	0.644	0.466	**0.084**	
Initial Chl. *a*				**0.022**
Water velocity				0.816
Water temperature				0.766

development of a benthic community such as biofilms on the channel beds. The water current within the channel could have transported these organisms away from the bottom or away from macrophytes (Zhou *et al.*, 2008; Czerniawski and Pilecka-Rapacz, 2011).

Among tested parameters (concentrations of SS and Chl. *a* in inlet, water velocity, and water temperature), the results of multiple regressions analysis selected only inlet concentrations are possible factor for the reduced amounts of SS and Chl. *a* (Tab. 4). When the selected relationships were highlighted using simple correlation analysis, there were positive correlations between reduced concentration of SS and Chl. *a* with inlet concentrations of each parameters in the channel of two nature-like fishways ($P = 0.021$ and 0.016, Fig. 6).

There was a greater decrease in SS and Chl. *a* concentrations in the Baekjae fishway, which has a slower current velocity and longer channel length, than in the Sejong fishway does. Consequently, the channel retention time was longer in the Baekjae fishway (37 min) than in the Sejong fishway (10 min). A slower current velocity can increase the efficient use of organic matter by aquatic organisms (Wanner *et al.*, 2002). Although the removal efficiency of particles in nature-like fishways was not significantly correlated to water velocity, there was a negative relationship throughout the study period. On the other hand, a significantly positive relationship between input points and SS and Chl. *a* concentrations suggests that the removal of particles was more apparent when the particle concentration was high. A high particle concentration may increase the potential encounter with predators, including benthic invertebrates.

In the present study, the direct causes and detailed removal mechanisms of particulate organic matter in nature-like fishways could not be clearly identified, although we did confirm significant improvement in terms of particulate matters in nature-like fishways. Recently, the construction of

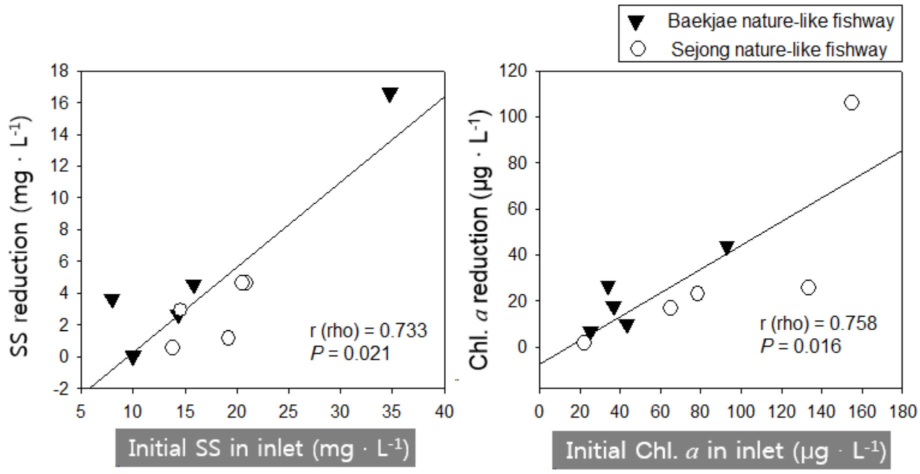

Fig. 6. Relationship between inlet concentration and reduced concentration of SS and Chl. *a* in the Baekjae and Sejong nature-like fishways.

dams and weirs in running waters has become very common for securing and controlling water resources. In the reservoir backwaters, the presence of pre-dam often enhances self-purification processes by cumulating contamination transported by river waters and lowering the amounts of suspended matters in waters flowing into downriver area (Wiatkowski, 2011). However, in the main channel of large river, it has been suggested that dams and weirs can have negative impacts on the self-purification capacity of river (Wei *et al.*, 2009). Our results suggest that nature-like fishways can mitigate such negative impacts by functioning not only as fish passages, but also as an alternative water passage system with self-purification ability. Further research of the detailed interactions among biological components in fishways is necessary to understand their additional functions and apply these to ecological engineering projects. Moreover, a study of the physical characteristics of nature-like fishways, such as materials and morphodynamic components with benthic structures, is also necessary as they essentially determine the habitat types and support species diversity.

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