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Estimation of optimal ecological flowrates for fish habitats in a nature-like fishway of a large river

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Abstract

Fishways are constructed to provide longitudinal connectivity of streams or rivers where their flow has been altered by in-stream structures such as dams or weirs. Nature-like fishways have an additional function of providing fish habitats. In the study, we estimated the role of a nature-like fishway (length: 700 m, slope: 1/100) for fish habitat by using two dominant species in the Sangju Weir, Nakdong River, to calculate the optimal ecological flow rate using Physical HABitat SIMulation (PHABSIM). To identify the dominant species that used the fishway, we conducted trap monitoring from August to November 2012 at the fishway exit. The dominant species were *Zacco platypus* and *Opsariichthys uncirostric amurensis* with a relative abundance of 62.1% and 35.9%, respectively. Optimal habitat suitability indices (HSIs) for *Z. platypus* and *O. u. amurensis* were calculated as 0.6–0.8 m/s (water velocity) and 0.2–0.4 m (water depth), and 0.5–0.7 m/s (water velocity) and 0.1–0.3 m (water depth), respectively. The optimal ecological flow rates (OEFs) for *Z. platypus* and *O. u. amurensis* were 1.6 and 1.7 cubic meter per second (CMS), respectively. The results of the study can be used in a management plan to increase the habitat function of nature-like fishways in the Sangju Weir. This methodology can be utilized as an appropriate tool that can determine the habitat function of all nature-like fishways.

Key words: fishway, habitat suitability index, *Opsariichthys uncirostric amurensis*, PHABSIM, *Zacco platypus*

INTRODUCTION

Structures, such as dams and weirs, constructed for the utilization of water resources in river ecosystems reduce longitudinal connectivity and habitat availability for lotic organisms (Reyes-Gavilán et al. 1996, Rosenberg et al. 1997). Various types of fishways (pool type, vertical slot, Denil pass, eel ladder, fish lock, fish lift, culvert, and nature-like fishway) were developed and built as structures to restore the decreased connectivity (Clay 1994). The nature-like fishway has a slope, substrate type, water movement, and channel morphology similar to natural rivers, and thus, can be used as a pass way for various species (Jungwirth 1996, Eberstaller et al. 1998, Parasiewicz et al. 1998) and functions as a potential habitat for lotic organisms (Pander et al. 2013). In the past, nature-like fishway design emphasized its function as a pass way, and aspects of habitat quality were often overlooked. Recently, however, the habitat use of nature-like fishways by fishes and macroinvertebrates has been monitored, and studies have focused on the function of fishways as a habitat, including measures to increase habitat function by controlling pool area within fishways (Lee et al. 2012, Gustafsson et al. 2013).

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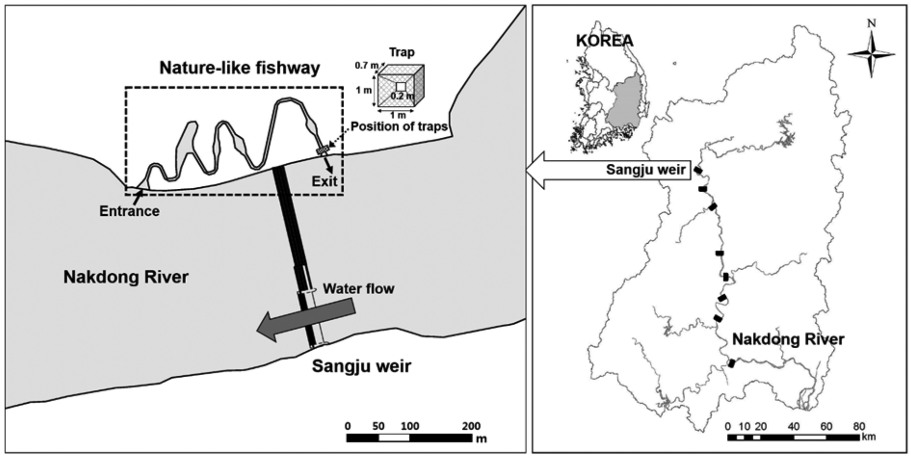

Fig. 1. Location of the Sangju Weir with the nature-like fishway on the Nakdong River in Korea. A total of six traps were installed at the exit part of the fishway to collect ascending fishes.

A method widely used to evaluate the habitat suitability of fish is stream habitat analysis (Moir et al. 2005). The stream habitat analysis calculates the flow rate considering each factor of the ecological environment, and combines results from the physical habitat suitability index and hydraulic analysis of the particular organism to determine a habitat size that can be provided in the target river (Kang et al. 2010). Regarding the stream habitat analysis, a model used in more than 90% of fish habitat modeling is Physical HABitat SIMulation (PHABSIM), which uses instream flow incremental methodology (Bovee 1982). An Ecological flow using the PHABSIM is usually estimated in rivers with regulated flow rates, such as discharge at dam, and this criterion can be used to select the optimal flow rate for ecologically healthy habitat of rivers (Kang et al. 2010).

Fishways are adjusted their flow rate depending on water level of the upper part of structure, and are usually composed of sluices and baffles to regulate flow rate. Therefore, when applied to fishways, the PHABSIM can evaluate habitat function by plotting possible area indicating weighted usable area (WUA), and can provide measures to increase the habitat function by plotting the ecological flow for primary species using fishways. However, this can only be applied to nature-like fishways that have a similar form in rivers. In Korea, there has been an increasing interest in nature-like fishways, as demonstrated through the installation of eight nature-like fishways in 2012. However, most studies conducted using nature-like fishways installed in Korea evaluated their effectiveness as pass ways.

The nature-like fishway in the Sangju Weir, Nakdong River, was constructed to ensure the connectivity of fish that inhabits the upper and lower parts of the weir. By creating decreased lotic environment due to the weir construction, the fishway is predicted to provide a suitable habitat for some lotic fishes. Purposes of this study were to estimate flow rates of the nature-like fishway in the Sangju Weir and to optimize the habitat function. The primary species using the fishway were identified with a trap. We used the PHABSIM to plot the optimal ecological flow rate that would be able to maximize the available habitat within the fishway. The results of the study would be used to provide a management plan considering the function of the nature-like fishway in the Sangju Weir as healthy habitat.

MATERIALS AND METHODS

Study site

As part of the Four Major Rivers Restoration Project in 2012, the Sangju Weir (335 m in length and 11 m in height) was built on the most upper reach as one of 8 weirs constructed in the mainstem of the Nakdong River in Korea. The study was conducted in the nature-like fishway, which was constructed to improve the up- and downstream movement of fish on the right side of the Weir (Fig. 1). Total length of the fishway is 700 m and its slope is 1/100. Moreover, the fishway was designed and constructed to form a zigzag for utilizing the narrow space effectively. The fishway width is generally maintained about 6 m in length, with an average width of 7.4 m. The flow rate within the fishway was related to the water level of the upper part of the weir, so it varies accordingly.

Selection of target species

The primary goal of the study was to confirm the fishway function as a habitat for fishes; therefore, the primary species using the fishway were selected as target species. To determine the primary species, we installed traps (1 × 1 × 0.7 m; mesh, 4 mm) at the exit of the fishway (Fig. 1). Six traps were installed at the exit to block the entire fishway, and all upstream-migrating fishes were collected. The traps were installed and monitored monthly from August to October 2012. We installed traps at 16:00, and collected and identified fishes after 24 hour monitoring.

The collected fishes consisted of 2 families and 9 species, totaling 1,713 individuals (Table 1). The primary species that used the fishway were *Zacco platypus* (relative abundance, RA, 62.1%) and *Opsariichthys uncirostric amurensis* (RA, 35.9%), and the remaining species appeared below RA of 1%. Therefore, we selected *Z. platypus* and *O. u. amurensis* as target species. According to Kim and Park (2002), *Z. platypus* and *O. u. amurensis* are common species that inhabit large domestic rivers and reservoirs. In particular, because *Z. platypus* is predominantly distributed in large domestic rivers and many small rivers, we predict that the results of the study will be widely applicable to other regions.

Calculating optimal ecological flowrate

Calculation of the optimal ecological flow rate (OEF) for *Z. platypus* and *O. u. amurensis* was made as follows. Firstly, we implemented a field study on the physical data of the fishway (water depth, water velocity, and flow rate). Because water depth and water velocity are variated following changes of flow rates, we only considered these two factors for analysis. Then, habitat suitability indices (HSIs) for water depth and water velocity of target species were calculated. Lastly, using Physical HABitat SIMulation (PHABSIM; USGS-MESC, Fort Collins, CO, USA), we plotted the weighted usable area (WUA), which varies with changes in flow rate to calculate OEFs of the target species (Petts and Maddock 1994).

We studied the physical data of the 700 m fishway in 7 sections of about 100-m intervals each. For each section, flux information of the section was calculated by measuring the water depth and water velocity (FP11; Global Water, College Station, TX, USA) 1 m from the waterside. Physical data of this fishway were examined twice in September 2012. HSI of the primary species using the fishway was recorded based on the fish population that appeared at the specific study site or section. The maximum value of physical data in the habitat with the highest number of fish was set to 1.0, and the remaining were set to a relative ratio of the maximum value. HSI of target species is an essential factor in evaluating fish habitats, and through credible data collection, it is important to provide and apply HSIs that reflect actual fish habitat (Bovee et al. 1998). For this reason, HSI is generally based on the habitat environment of fishes in the actual study site. However, because target species were collected at a specific site within the fishway, unlike typical rivers, it cannot be concluded that the fishway is preferred as a habitat. These fishes were collected during migration to the upper stream, and did not necessarily prefer the collected site to use as a pass way, since the fishway is an artificial structure and is the only available pass way for fishes. To overcome this issue, the present study computed the HSI value by using an established habitat information database (Bio-Monitoring Center, Daejeon, Korea) of *Z. platypus* and *O. u. amuren-*

Table 1. List of fishes collected by traps.

Family	Species	Aug	Sep	Oct	Total	RA (%)
Cyprinidae	*Carassius auratus*	3	1		4	0.2
	Pungtungia herzi		2		2	0.1
	Squalidus chankaensis tsuchigae	1			1	0.1
	Hemibarbus labeo	1	2	4	7	0.4
	Hemibarbus longirostris	1			1	0.1
	Zacco platypus	978	66	20	1064	62.1
	Opsariichthys uncirostris amurensis	585	21	9	615	35.9
	Erythroculter erythropterus		3	9	12	0.7
Gobiidae	*Rhinogobius brunneus*	7			7	0.4
	No. of species	7	6	4	9	
	No. of individuals	1576	95	42	1713	

RA, relative abundance.

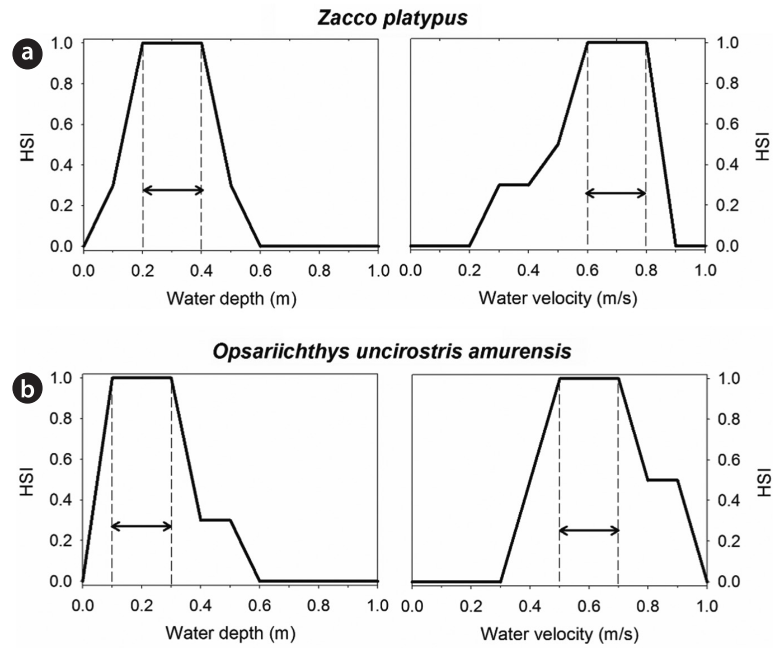

Fig. 2. Habitat suitability indices (HSIs) of water depth (left) and water velocity (right) of (a) *Zacco platypus* and (b) *Opsariichthys uncirostric amurensis*. Arrows indicate optimal HSI range of each species.

sis in natural habitats (26 domestic rivers and streams, 42 sites). We recorded HSIs for two habitat conditions (water depth and water velocity), and followed the method suggested by Hur and Kim (2009). Using physical data of the fishway and HSI values of the target species that appeared through this process, OEF was plotted by species using PHABSIM. Lastly, we applied OEF by species to determine the combined suitability index (CSI) of each cell area within the fishway. CSI values were calculated from the individual suitability values for depth and velocity, which were combined within the HABTAE modeling routine (Waddle 2012). CSI values are ranged between 0 and 1, and if value is close to 1, habitat condition goes to optimal.

To determine the flow rate within the fishway with respect to the water level of the upper Sanju Weir (Nakdong River Flood Control Office), flow rate within the fishway was monitored over 16 times. A regression equation for the water level of the upper part of fishway and flow rate within the fishway was determined using SPSS ver. 18.0 (SPSS Inc., Chicago, IL, USA) software.

RESULTS

HSI values of water depth and water velocity for the primary species, *Z. platypus* and *O. u. amurensis* used the fishway are represented in Fig. 2. The species of *Z. platypus* usually inhabited a water depth of ~0.6 m, and the optimal HSI value was 0.2–0.4 m. For *O. u. amurensis*, the water depth inhabited was ~0.6 m, which was the same as *Z. platypus*, but the optimal HSI value was 0.1–0.3 m, indicating a preference on the shallower water depth compared with *Z. platypus*. Regarding water velocity, *Z. platypus* inhabited a range of 0.2–0.9 m/s, and the optimal HSI value was 0.6–0.8 m/s. However, the water velocity range for *O. u. amurensis* was 0.3–1.0 m/s, and the optimal HSI value was 0.5–0.7 m/s, indicating a preference on the lower water velocity compared with *Z. platypus*.

The water flow-WUA relationship plotted from PHABSIM using the physical environment within the fishway and HSIs of *Z. platypus* and *O. u. amurensis* is shown in Fig. 3. The OEF for the two species were determined as follows: for *Z. platypus*, WUA within the fishway was the widest (514 $m^2 \cdot 1000\ m^{-1}$) when flux was 1.6 cubic meter per second (CMS); for *O. u. amurensis*, WUA within the fishway was the widest (3300 $m^2 \cdot 1000\ m^{-1}$) at 1.7 CMS. Although OEFs of the two species were similar, maximum WUA from OEF was over 6 times wider for *O. u. amurensis* than *Z. platypus*. The CSIs that were determined for each cell area of the fishway by applying the OEF of the two species were both higher in the waterside than the center of the fishway (Fig. 3). *Z. platypus*, showed a very low CSI value (< 0.046) at the center of the fishway even when the OEF was stable; therefore, the fishway could not be considered as a functional habitat for this species. However,

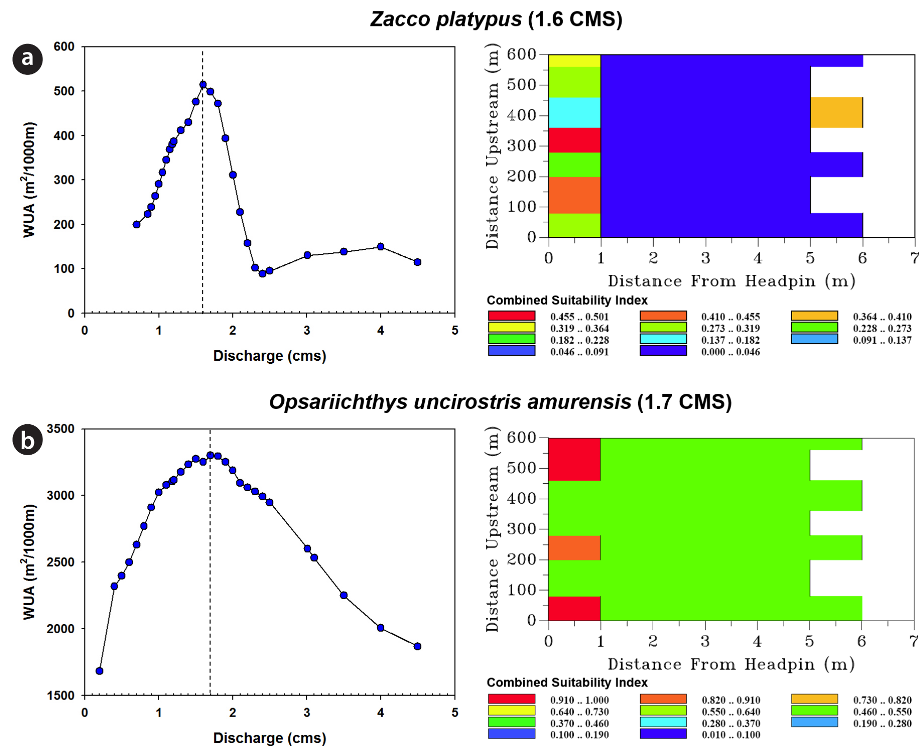

Fig. 3. Plotted by PHABSIM, weighted usable area (WUA) (left) varying with changes in discharge of (a) *Zacco platypus* and (b) *Opsariichthys uncirostric amurensis*. Dotted lines indicate flow rates that showed the widest WUA. Combined suitability index (CSI) of fishway cells applied to the highest WUA of the two species. A headpin is a control point when measuring fishway widths of a certain section, and we measured widths from the left sides of fishway.

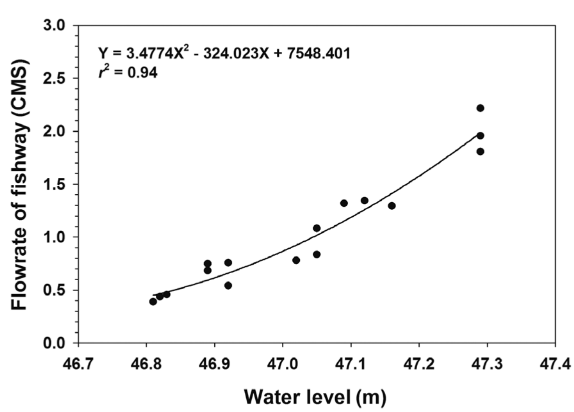

Fig. 4. Variation of the water flow into the nature-like fishway according to changes in the water level of upper part of the Sangju Weir.

O. u. amurensis showed relatively high habitat suitability at the waterside, and the CSI value at the center was above 0.370, indicating that this species could utilize the fishway as a functional habitat.

Changes in flow rate within the fishway, which varied with the water level of the upper part of the Sangju Weir, are depicted in Fig. 4. For an inflow of 1.6–1.7 CMS (the OEF of *Z. platypus* and *O. u. amurensis*) to the fishway, the water level of the upper part must be stabilized at 47.20–47.22 m. The WUA of *O. u. amurensis* and *Z. platypus* in the nature-like fishway was the widest at the present water level. Therefore, the function of the nature-like fishway in the Sangju Weir as a habitat for these two species can be maximized at this water level.

DISCUSSION

The OEFs using PHABSIM for *Z. platypus* and *O. u. amurensis* were 1.6 and 1.7 CMS, respectively. For the nature-like fishway in the Sangju Weir, the flow rate within the fishway changes according to the water level of the upper part of the weir. Therefore, to introduce appropriate OEFs for those predominant species into the fishway, water level of the upper part of the weir must be maintained at 47.20-47.22 m. The current management level of the upper part of the weir is 47 m, and the incoming flow rate is 0.9 CMS. When the present flow rate was stabilized within the fishway, *Z. platypus* acquired 46% WUA and *O. u. amurensis* acquired 88% WUA, compared with the optimal flow. However, the primary goal of fishways is to serve as a pass way (Clay 1994), and this must be considered a priority. Kim's unpublished data showed that the fish passing rate of fishways determined using passive integrated transponder (PIT) telemetry was the highest when the water level of the upper Sangju Weir was 47.19 m. Therefore, the flow rates that satisfy the functions of the nature-like fishway as a pass way and as a habitat are extremely similar. However, the current water level management is 47 m, which is maintained at about 0.2 m lower to satisfy both functions as a pass way and a habitat. Regarding the water level management of the upper Sangju weir, it is difficult to artificially maintain this above the water level of 47 m when the upper part of the weir is full. Therefore, to maximize the function of the fishway as a pass way (and not as a habitat), it is necessary to alter the structure of the fishway entrance to allow a flowrate of 1.6–1.7 CMS for the water level management of upper part of the Sangju Weir. However, by providing an additional section of high CSI within the fishway, the WUA of species using the fishway could be increased without increasing the fishway flow rate. After determining CSIs with respect to cell area within the fishway, both species showed that waterside regions could be utilized as primary habitats. The CSI exhibits horizontal rather than vertical differences because the fishway consists of a single channel in run form without a riffle and pool section. Compared with the center, the waterside had a shallower water depth and a slower water velocity. Therefore, by altering the structure of the run section in the fishway and constructing an additional section with a physical environment similar to the waterside, the WUA of *Z. platypus* and *O. u. amurensis* can be increased, thus, increasing the function of the fishway as a habitat.

There have been various studies on OEF estimations in rivers using PHABSIM for the restoration and preservation of specific fishes (Vilizzi et al. 2004, Moir et al. 2005). The majority of the current studies were conducted for dominant species (Kang et al. 2010, Im et al. 2011, Kang et al. 2011). In addition, there were studies on competitive salmonids (Gibbins et al. 2002, Gard 2009) and endangered species (Boavida et al. 2011). The present study site was a nature-like fishway, and the OEFs of *Z. platypus* and *O. u. amurensis* were computed using them as the target species of fishes that primarily use the fishway. However, when the OEF of the fishway was adjusted for these species, there was a possibility that the function of fishway as their habitat might have decreased for other species. Therefore, when calculating OEFs for all species that use the fishway, it could be helpful for managing fishways centered on specific species. Furthermore, because there were differences in HSIs, even for the same species depending on the life stage, it could provide more detailed data when estimating OEFs classified by life stages (McMahon 1983, Im et al. 2011).

The majority of the current studies have been conducted to understand the function of fishways as pass ways (Bunt et al. 2012), and these have been continuously evaluated using traps, automatic video recording systems, and diverse telemetry methods (PIT, radio, and acoustic tags) (Barry and Kynard 1986, Cada 1998, Oldani and Baigún 2002, Aarestrup et al. 2003, Santos et al. 2005). The results concluded from these have been utilized to design high-efficiency fishways, or provide management plans for fishways (Larinier et al. 2005, Barrett and Mallen-Cooper 2006). In contrast, because the function of fishways as a habitat has not been prioritized historically, there are few related research studies. Similar to the present study, Lee et al. (2012) utilized the River2D model to evaluate the function of fishways as a habitat, but it was limited to a pilot test. However, through PHABSIM, the present study calculated the WUA of primary species that use fishways in an actual operating fishway, and determined its function as a habitat. Moreover, we computed OEFs to propose measures that can increase the fishway habitat functions. Regarding methodology, it could be utilized as an appropriate tool to provide measures to increase and determine the function of fishways as habitats.

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