Change in fish community composition following weir removal, field observations, and physical habitat simulations

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Abstract
The number of untended weirs has increased in Korea in recent years due to land use changes. The removal of abandoned weirs in streams has been attempted following an agreement between local government and residents. The Gongneung Weir-2 was built for irrigation in the 1970s and was removed in 2006. The objective of this study was to investigate the impact of the removal of Gongneung Weir-2 on the composition of the fish community. The study area was a 900-m-long reach in the Gongneung-cheon River in Korea, and Gongneung Weir-2 was located in the middle of the reach. Before weir removal, field monitoring revealed that five fish species were dominant and accounted for more than 80% of the entire fish community. The composition of the fish community changed significantly after weir removal. Lotic fish became dominant after weir removal, whereas lentic fish were dominant prior to weir removal. Physical habitat simulations (PHSs) for individual dominant fish species were carried out. For the PHS, the River2D model and the adaptive neuro-fuzzy inference system method were used for hydraulic and habitat simulations, respectively. The distributions of the highly suitable portion for each fish species were identified before and after weir removal. The PHS successfully predicted changes in the composition of the fish community after weir removal. The PHSs for the entire fish community and for the lotic and lentic guilds were undertaken and the simulated results were compared with each other. The PHSs for the entire fish community could not account for the less dominant fish species in the fish community.

KEYWORDS
ANFIS, fish community, highly suitable portion, lotic and lentic guild, physical habitat simulation, weir removal

1 | INTRODUCTION

Instream structures that cross streams such as dams and weirs degrade the longitudinal continuity of the system. This is serious for both sediment transport and fish migration. Sediment transport in the downstream direction is interrupted, resulting in sedimentation and erosion at upstream and downstream sites of such structures, respectively. These structures also block fish migration in the upstream direction, necessitating countermeasures such as the fishways.

In Korea, there are currently approximately 18,000 weirs including small dams (Kim & Kim, 2012). Approximately 40% of these weirs are over 50 years old, which is the typical expected service life (Korea Rural Community Corporation, 2009). Every year, approximately 100 new weirs are built and 150 weirs are decommissioned for various reasons (Korea Rural Community Corporation, 2009).
Demonstration projects have been implemented to remove untended weirs, focusing on the monitoring of morphological changes and ecological impacts (Korea Institute of Construction Technology, 2007). In the United States, there were more than 90,000 dams in 2016 (U.S. Army Corps of Engineers, 2016). Most were built in the late 1960s, and by 2020, 85% of these dams will outlive their design life (Evans, Mackey, Gottgens, & Gill, 2000). Some outlived dams have already been removed, and others are planned to be removed in the near future. Doyle, Stanley, and Harbor (2003) and Stanley and Doyle (2003) emphasized the importance of monitoring sediment transport and morphological changes following dam removal in the United States.

In order to investigate the change in the composition of the fish community, previous studies relied mainly on observations. Kanehl, Lyons, and Nelson (1997) examined fish community change in an impounded reach following the removal of Woolen Mills Dam in the Milwaukee River, Wisconsin, USA. They found that the abundance and biomass of smallmouth bass and common carp showed significant increase and decrease, respectively. The dam removal induced the conversion of the impounded reach from a lotic to a lentic environment, resulting in a decrease in available habitat for common carp. Catalano, Bozek, and Pellett (2007) studied the impact of the removal of four low head dams on fish assemblage structure in the Baraboo River, Wisconsin, USA. Before dam removal, they observed 11 fish species downstream of the dam, but not upstream of the dam. However, after dam removal, 10 of the 11 fish species were recorded upstream of the dam, indicating that dam removal efficiently restored lotic fish community upstream of the dam site. Magilligan, Nislow, Kynard, and Hackman (2016) analysed the effect of Pelham Dam removal on fish assemblage in the Amethyst Brook in Massachusetts, USA. They observed four fish species, not observed before removal, upstream of the dam and spawning habitats of lamprey due to sedimentation of gravels downstream of the dam after its removal. Physical habitat simulations (PHSs) have also been used to assess the change in fish habitats due to dam or weir removal (Gillenwater, Granata, & Zika, 2006; Im, Kang, Kim, & Choi, 2011; Tomsic, Granata, Murphy, & Livchac, 2007). However, these studies have been limited to PHSs for a single target fish species, not the entire fish community or a dominant group of species.

The objective of this study was to investigate changes in the composition of the fish community following weir removal. A weir removal case in the Gongneung-cheon River in Korea was studied (Korea Institute of Construction Technology, 2007). A 900-m-long reach in the Gongneung-cheon River was selected as the study area. The Gongneung Weir-2 was located in the middle of the study reach (see Figure 1). First, fish monitoring data from field observations before and after the weir removal were analysed. Subsequently, PHSs were carried out. For the PHS, the River2D model and the adaptive neuro-fuzzy inference system (ANFIS) method were used for hydraulic and habitat simulations, respectively. Finally, the results of the PHS for the entire fish community were compared with those from the PHS for lotic and lentic guilds.

2 | METHODS

2.1 | Study area

The study area, a 900-m-long reach of the Gongneung-cheon River, is located in Kyeonggi Province in the north-western part of Korea (Figure 1). The Gongneung-cheon River, a major tributary of the Han River, is 47 km long and has a watershed area of 260.0 km². The mean annual precipitation for the watershed is 1,384 mm (Ministry of Land, Transport and Maritime Affairs, 2012).

The study reach includes Gongneung Weir-2, which was a 1.5 m high, 75 m wide, and 8.8-m-long structure. Specifically, this reach was located 5.1 km downstream of the confluence with the Sukhyn-cheon Stream and 0.58 km upstream of the confluence with the Sunyu-cheon Stream (see Figure 1). The Gongneung Weir-2 was built in the 1970s to provide irrigation water to the surrounding area. However, the weir was left untended for a long time due to land use change in the neighbouring area. In March 2006, the local government and residents agreed to remove the weir, and the removal was completed on April 14, 2006. Im et al. (2011) studied the morphological change after the Gongneung Weir-2 removal and reported that the longitudinal continuity was improved using PHS for a dominant fish, Zacco platypus. Detailed morphological changes and related photographs before and after weir removal can be found in Im et al. (2011).

Within streams, riffle and pool morphology create lentic and lotic zones, respectively. A lotic zone is characterized by dynamic flows and riffles and runs. In contrast, lentic zones are characterized by areas of relatively stagnant water such as pools, backwaters, and marshes. Before the removal of the Gongneung Weir-2, the study reach predominately comprised the lentic zones. One zone was located upstream of the weir, and the other zone close to the downstream end of the reach, created by another weir. Thus, the study area was expected to have both lotic and lentic habitats before weir removal.

To observe the change in stream morphology and fish population, four field monitoring campaigns were carried out. One was performed on April 1, 2006 (before weir removal), and the subsequent three were undertaken on May 30, 2006 (following weir removal), August 4, 2006 (after a flood), and November 1, 2007 (approximately 18 months after weir removal). For geometric surveys, the study reach was divided into 13 transects, with an average distance between transects of about 50 m. The average width of the study reach was 80 m, which was divided equally into 30 sections. The field monitoring on May 30, 2006, indicated that morphological changes occurred rapidly even under a low flow condition (Im et al., 2011).

Before weir removal, river bed materials comprised silt and fine sand upstream of the weir and coarse sand and fine gravel downstream. However, after weir removal, the respective ranges changed to coarse sand and fine gravel upstream and fine gravel and gravel downstream of the weir. In addition, in November 2007, it was observed that a maximum erosion of 2.0 m and a maximum deposition of 1.0 m occurred at an upstream and downstream site of the weir, respectively. Choi, Lee, Yoon, and Woo (2009) showed that the bed
shear stress directly downstream of the weir increased significantly after weir removal, inducing the change in the distribution of bed materials and longitudinal bed elevation. Detailed monitoring data on the morphological change in the study reach can be found in Choi et al. (2009) and Im et al. (2011).

### 2.2 Fish monitoring

For the period of 2007–2010, fish monitoring data were collected in the field as part of government R&D projects (Ministry of Land, Transport and Maritime Affairs, 2011). The sites for fish monitoring remained the same before and after weir removal. Fish monitoring was carried out using 1.5-m-long kick nets (5-mm mesh) and 4.5-m² cast nets (7-mm mesh). The meshes of the kick nets and cast nets were dense enough to prevent underestimation of fish levels. Kick-net samplings were performed for 30 min at each site, and cast nest were thrown 20 times. The total sampling duration was around 1 hr. Sampling was conducted over an estimated 200-m length of stream reach, covering approximately 100 m upstream and 100 m downstream from the central point of the study site. All fish captured were identified, counted, and released.

### 2.3 Hydrology and habitat data

In Korea, approximately two thirds of the annual precipitation occurs during the rainy season (June to September). Outside of the rainy season, low flow conditions are maintained in most streams. In the present study, the low flow required to maintain the stream ecosystem was estimated based on the three methods proposed in Caissie and El-Jabi’s (1995) study. The methods include (a) tenant method, (b) 25% of the mean annual flow, and (c) the flow equalled or exceeded 90% of the time on the monthly flow duration curve. The respective low flow values estimated were 1.53, 1.42, and 1.45 m³/s for the three methods. As a result, a discharge of 1.5 m³/s was selected as the minimum flow for hydraulic simulations.

To train the habitat simulation model, fish monitoring data for the five dominant fish species were collected in neighbouring streams in the Han River basin (Ministry of Land, Transport and Maritime Affairs, 2011). The data include the date, flow depth, velocity, substrate composition, water temperature, concentration of suspended solid, pH, and population of the individual fish species. These data were obtained at points in the study area. The flow depth was measured using a levelling rod and the velocity using the propeller-type current meter (AA-11) at particular points. Specifically, the velocity was measured at three different heights, and they were averaged. The percentage of each dominant fish species in the study reach (in Figure 2) was used to generate the datasets.

The total number of monitoring points were 4,409. In the present study, the Mahalanobis distance method was used to identify outliers in the monitoring data (Im, Choi, & Choi, 2018). The data quality assessment identified 238 outliers, resulting in a total of 4,171 datasets for training of the ANFIS model.
2.4 | Physical habitat simulation

2.4.1 | Hydraulic simulation

In the present study, the River2D model developed by Steffler and Blackburn (2002) was used for the hydraulic simulation. The River2D model solves 2D depth-averaged shallow water equations using the finite element method. This model also offers both wet and dry solutions, by changing the surface flow equations to the groundwater flow equations in dry areas.

2.4.2 | Habitat simulation

Habitat simulation provides the habitat suitability based on physical habitat variables as velocity, flow depth, and substrate. The habitat suitability is given by the values of the composite suitability index (CSI). The CSI ranges from zero to unity, indicating the worst and most optimal habitat conditions, respectively.

In general, both expert-knowledge and data-driven habitat suitability models were used for habitat simulation. The habitat suitability curve is a representative habitat suitability model and has often been criticized because it is easily affected by the subjective opinion of experts. In addition, expert-knowledge models hypothesize that physical habitat variables are not correlated, and the preference of fish species for these variables is valid regardless of the spatial locations. Due to the weaknesses of the expert-knowledge models, data-driven models, such as artificial neural network (ANN) models, fuzzy logic, statistical methods, and genetic algorithms, have been used. In the present study, the ANFIS method, a data-driven model, was used.

The fuzzy inference system (FIS) is a non-linear system that can model the qualitative aspects of human knowledge and reasoning processes without using precise quantitative analysis. FIS considers the uncertainty inherent to data and enables the expression of non-linear relations between variables (Jorde, Schneider, Peter, & Zoellner, 2001; Kampichler, Barthel, & Wieland, 2000; Salski, 1992). However, it requires an expert's knowledge to quantify linguistic descriptions into a mathematical tool, and the inconsistency of expert's knowledge has been debated (Acreman & Dunbar, 2004; Mouton, De Baets, & Goethals, 2009; Strauss & Biedermann, 2007; Wiens & Graham, 2005). For this problem, Jang (1993) combined the FIS and ANN, introducing the ANFIS method. The ANFIS method is based on Takagi and Sugenno's (1985) FIS, and the parameters of FIS are tuned using ANN learning methods. The ANFIS method has been applied to various areas including engineering and environmental science.

The ANFIS method has a five-layer architecture. In Layer 1, the output is the fuzzy membership value to which the given input compiles. Layer 2 involves fuzzy operators to fuzzify the inputs, and the output at each node represents the firing strength of a rule. Layer 3 performs a normalization role to the firing strengths from the previous layer, and the output is called the normalized firing strength. Layer 4 preforms defuzzification, that is, the output is produced by the fuzzy rule with weighting factors obtained in Layer 3. Layer 5 computes the overall output by summing all incoming signals. A detailed organization of the ANFIS method can be found in Jang (1993).

The input values of the physical habitat variables are mapped to the output values of the CSI using the ANFIS method. In the present study, the physical habitat variables included the velocity, flow depth, and substrate. Four membership functions (low, medium, high, and very high) were used for the input values. A triangular membership function, which is most common, was used.

3 | RESULTS AND DISCUSSION

The distributions of the dominant fish species (a) before and (b) after weir removal are shown in Figure 2. These observations were made on April 1 and August 4, 2006, respectively. Abbottina rivularis, Zacco platypus, Rhinogobius brunneus, Abbottina springeri, and Pseudogobio esocinus were the dominant species before weir removal. These five species accounted for more than 80% of the entire fish community.

![Image](a) before weir removal  (b) after weir removal

**FIGURE 2** Distribution of dominant fish species before and after the weir removal

| TABLE 1 | Biological indices before and after weir removal (Ministry of Environment, 2008) |
|---|---|---|---|
| | Upstream reach of the weir | Downstream reach of the weir |
| Index | Before removal | After removal | Before removal | After removal |
| Dominance (D') | 0.82 | 0.53 | 0.71 | 0.73 |
| Diversity (H') | 1.02 | 1.06 | 1.53 | 1.32 |

*aExcellent (D' < 0.25), good (0.25 ≤ D' < 0.5), fair (0.5 ≤ D' < 0.7), poor (0.7 ≤ D' < 0.9), and very poor (D' ≤ 0.9). Here, D' = ln(N) / N. |
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*aExcellent (4.0 ≤ H'), good (3.0 ≤ H' < 4.0), fair (2.0 ≤ H' < 3.0), poor (1.0 ≤ H' < 2.0), and very poor (H' < 1.0). Here, H' = − Σ (n/N) ln (P) with P_i = proportion of the total number of individuals occurring in the i-th species.*
However, after removal, the dominance of the fish species changed dramatically. The most dominant species after the removal was *R. brunneus*, followed by *Z. platypus*, *P. esocinus*, *A. springeri*, and *A. rivularis*. Notably, the most dominant species changed from a lentic species (*A. rivularis*) to a lotic fish (*R. brunneus*) after weir removal. This is due to the change in the flow conditions and bed sediment. Lotic fish (grey coloured) comprised approximately 22% of the total fish community before weir removal (Figure 2). However, the fraction of the lotic fish increased significantly after weir removal to approximately 66% of the total fish community.

Table 1 lists values of the dominance index and the diversity index of entire fish community at the upstream and downstream sites of the weir before and after weir removal. The dominance index provides a measure of how much one or a few species dominates the community, and the diversity index indicates species diversity within a community that consists of two or more species. In the present study, the dominance and diversity indices were calculated by the methods in McNaughton (1967) and Pielou (1966), respectively. After weir removal, the dominance index and the diversity index decreased in the upstream and downstream reaches, respectively. However, the diversity index and dominance index increased slightly in the upstream and downstream reaches, respectively. This can be attributed to the fact that, before weir removal, the lentic and lotic fish were dominant in the upstream and downstream reaches of the weir, respectively. However, after weir removal, the population of the lotic fish increased in both upstream and downstream reaches. The overall continuity

![FIGURE 3](https://wileyonlinelibrary.com) Observed population of dominant fishes against velocity, flow depth, and substrate [Colour figure can be viewed at wileyonlinelibrary.com]
between the upstream and downstream reaches, which was disturbed by the presence of the weir, was slightly improved. This was reflected in the two indices.

The 3D scatter plot of the population of each fish species against the velocity, flow depth, and substrate is presented in Figure 3. The size of the bubble indicates the population of fish, and each habitat variable is normalized by its maximum value. The plots indicate that *R. brunneus* preferred a velocity in the range of 0.2–0.4 m/s, a flow depth of 0.2–0.6 m, and a substrate of 3–4; and for *Z. platypus*, the respective ranges were 0.2–0.4 m/s, 0.3–0.5 m, and 4–5. These two species are lotic. For lentic fish, such as *P. esocinus* and *A. rivularis*, the respective preferred ranges were 0.0–0.3 and 0.0–0.2 m/s for the velocity, 0.4–0.6 and 0.2–0.6 m for the flow depth, and 2–3 and 1–2 for the substrate. Notably, the ranges of the velocity and substrate preferred by the lotic and lentic fish were clearly different, but those of the flow depth were not. Data for *A. springeri* were not included due to the small amount of observed data.

Although fish monitoring campaigns were conducted on April 1 and August 4, 2006, prior to and after weir removal, the time period appears rapid for the major changes in PHSs recorded. However, a

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**FIGURE 4** Distribution of highly suitable portion for each species before weir removal

**FIGURE 5** Distribution of highly suitable portion for each species after weir removal
flood occurred in July with a peak discharge of 412 m³/s. This flood probably induced a significant amount of morphological change, and no further serious change took place in that year within the study area. This helps justify the use of the fish monitoring data in the comparisons with the results from the PHSs.

The distributions of the highly suitable portion (HSP) obtained from the PHS results are shown in Figures 4, 5, 7, and 8. The HSP was defined by the part of the study area where the CSI exceeds a certain value in the entire study reach. Because the weighted usable area (WUA) is the aggregations of the product of the CSI and the area of the study reach, the portion with a low CSI cannot provide fish with truly suitable habitat. In the present study, a CSI value of 0.6 was selected with the hypothesis that a habitat with a CSI equal to or higher than 0.6 would be suitable, and the WUA was computed in the HSP.

In the present study, different life stages of the target fish species were not considered in the PHSs. This is based on the findings by Im et al. (2011), who carried out PHSs for the target fish, Z. platypus, in the same study area, considering three life stages: spawning, juvenile, and adult. PHSs by Im et al. (2011) indicated that the postremoval WUAs increased for all life stages in both upstream and downstream reaches.

The distributions of the HSP for each fish species before weir removal are presented in Figure 4. The HSP for A. rivularis, a lentic fish, was located in the upstream zone of the weir. The HSP for A. rivularis is also formed near the downstream end, which is due to a retention zone created by another weir. However, the HSP for lotic fishes, such as Z. platypus and R. brunneus, did not occur in these zones. The HSP for P. esocinus was rarely recorded in the study reach because the preferred substrate was not available.

The distribution of the HSP for each fish species after weir removal is shown in Figure 5. The habitats of lotic fishes, such as R. brunneus and Z. platypus, were extended over the entire study reach. Specifically, the HSPs for Z. platypus and R. brunneus after weir removal expanded to about 300% and 880% compared with conditions before weir removal. In contrast, the HSP for A. rivularis, a lentic fish, decreased significantly (see Figure 5a). The HSP for A. rivularis after weir removal was reduced to 20% of that before weir removal. This decrease is thought to be affected by the change in the flow and coarsening of the bed sediment after weir removal. The figure clearly demonstrates that the continuity in the lotic ecosystem of the stream is improved by weir removal.

The observed number of fish with the simulated normalized WUA before and after weir removal is presented in Figure 6. The normalized WUA is defined by the WUA divided by the total study area. The PHS successfully predicted the change in the habitat area after weir removal. Specifically, the habitat area of the lotic fish increased dramatically after weir removal. However, the habitat for A. rivularis decreased significantly, confirming results presented in Figures 4 and 5. The habitat area for P. esocinus increased because the substrate changed favourably, that is, the substrate became coarser within the study reach, after weir removal. This can also be seen in Figures 4 and 5.

**FIGURE 6** Comparison between number of fishes observed and normalized WUA simulated [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 7** Distribution of highly suitable portion before weir removal
Subsequently, PHSs for the entire fish community were undertaken, and the results were compared with those from the PHSs for the lotic and lentic guilds. For the PHSs, three datasets were constructed, namely, datasets for the entire fish community and lotic and lentic guilds, and they were used to train the ANFIS model.

Figure 7a shows the distribution of the HSP for the entire fish community before weir removal, and Figure 7b,c shows the same distribution for the lotic and lentic guilds. The lotic guild includes *Z. platypus* and *R. brunneus*, and the lentic guild includes *A. rivularis*, *P. esocinus*, and *A. springeri*. The distribution of the HSP for the entire fish community is very similar to that for the lentic guild. This is because the percentage of lentic fish in the entire fish community is high before weir removal, that is, approximately 60%. This leads to the distribution of HSP in Figure 7a being similar to that of *A. rivularis* in Figure 4a. Interestingly, the HSP distributions in Figure 7 indicate that the PHS for the entire fish community cannot account for the less dominant fish guild. In other words, the PHS for the entire fish community satisfactorily predicts the habitats preferred by the most dominant fish guild, not by the second dominant fish guild.

The HSP distributions after weir removal are shown in Figure 8. In contrast to the previous figure, the distribution of the HSP for the entire fish community is very similar to that for the lotic guild. In addition, the distribution of the HSP in Figure 8a is similar to that of *R. brunneus* and *Z. platypus*. This is because the portion of the lotic fish is higher than 70% after weir removal. Similarly, the trend of the habitat for the lentic fish cannot be recognized in the results of the PHS for the entire fish community.

The observed number of fish and the normalized WUA before and after weir removal are compared in Figure 9. The normalized WUAs were obtained from Figures 7 and 8. The observed number of fish increased after weir removal. However, the normalized WUA obtained from the PHS for the entire fish community changed little after weir removal. This can largely be explained by the finding that the HSP before weir removal in Figure 7a is quite similar to the HSP after weir removal in Figure 8a. If the habitat simulation model is trained separately with the lotic and lentic guilds, the PHS is found to predict habitat quality successfully. That is, after weir removal, the increase in the lotic fish and the decrease in the lentic fish compare favourably to the change in the normalized WUAs obtained from the PHSs.

4 | CONCLUSIONS

The Gongneung Weir-2 was built to supply water to a nearby area for irrigation in the 1970s. Due to land use changes, the weir was removed in April 2006 after an agreement between the local government and residents. This study presented the results of the field observations and PHSs to investigate the impact of weir removal on the composition of the fish community.
A 900-m-long reach was selected for study, with the weir located in the middle of the reach. The study reach included a pool and riffle sequence, thus providing habitats for both lentic and lotic fish. Field monitoring indicated that five fish species were dominant in the study area, namely, *A. rivularis*, *Z. platyous*, *R. brunneus*, *A. springeri*, and *P. esocinus*. Specifically, lentic fish were dominant before weir removal, accounting for approximately 60% of the entire fish species. However, after weir removal, the quantity of lotic fish increased dramatically, comprising approximately 70% of the entire fish species.

The PHSs for individual dominant fish species were undertaken, and the distributions of the HSP for each fish were determined before and after weir removal. The PHS successfully predicted the change in the composition of the fish community after weir removal. The increase and decrease in the habitats for lotic and lentic fish were successfully simulated. Similar PHSs for the entire fish community were performed, and the results were compared with those for the lotic and lentic guilds. The distributions of the HSP from the PHS for the entire fish community are similar to those from the PHS for the lentic guild before weir removal and to those from the PHS for the lotic guild after weir removal. These results indicate that the PHS for the entire fish community was unable to account for the second-dominant guild.

This study reported a case study, in which the change in the composition of fish community was investigated after weir removal. The results of field observations support those from PHSs, and both results were in line with previous field studies. This study demonstrated the potential for quantitative assessment of changes in fish community using PHSs after the removal of instream infrastructures. This highlights that change in fish species and the unintended spread or extinction of fishes by the construction or removal of dams or weirs can be predicted. This may provide river engineers and managers with better tools for stream restoration with a strong emphasis on the aquatic ecosystem.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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