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Preliminary Ecological Assessments of Water Chemistry, Trophic Compositions, and the Ecosystem Health on Massive Constructions of Three Weirs in Geum-River Watershed

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Abstract

Major objectives of the study were to analyze chemical and biological influences of the river ecosystem on the artificial weir construction at three regions of Sejong-Weir (S_j-W), Gongju-Weir (G_j-W), and Baekje-Weir (B_j-W) during 2008-2012. After the weir construction, the discharge volume increased up to 2.9 times, and biological oxygen demand (BOD) and electrical conductivity (EC) significantly decreased ($p < 0.05$). Also, the decrease of total phosphorus (TP) was also evident after the weir construction, but still hyper-eutrophic conditions, based on criteria by OECD (1982), were maintained. Multi-metric model of Index of Biological Integrity (IBI) showed that IBI values averaged 21.0 (range: 20-22; fair condition) in the B_{wc}, and 14.3 (range: 12-18; poor condition) in the A_{wc}. The model values of IBI in S_j-W and G_j-W were significantly decreased after the weir construction. The model of Self-Organizing Map (SOM) showed that two groups (cluster I and cluster II) of B_{wc} and A_{wc} were divided in the analysis based on the clustering map trained by the SOM. Principal Component Analysis (PCA) was similar to the results of the SOM analysis. Taken together, this research suggests that the weir construction on the river modified the discharge volume and the physical habitat structures along with distinct changes of some chemical water quality. These physical and chemical factors influenced the ecosystem health, measured as a model value of IBI.

Keywords: ecological impact assessment, ecosystem health, physical habitat, water quality, weir construction

INTRODUCTION

Large rivers have longitudinal gradients of chemical water quality and physical habitats from the headwaters to the downrivers near the estuary, resulting in structural and functional variations in riverine fish community (Schlosser 1982, Gelwick 1990). These gradients, however, may be interrupted by natural processes (Balon and Stewart 1983, Maret et al. 1997) or artificial constructions of dams or weirs on the rivers (Baxter 1977, Dynesius and Nilsson 1994, Richter et al. 1997). Thus, serial discontinuity concept (SDC) was hypothesized by Ward and Stanford (1983) who emphasized numerous impacts of physical, chemical and biological re-setting (Ward and Stanford 1979) by weir or dam constructions on the rivers.

The weir-construction or serial impoundment-induced changes in current velocity or inflow regime caused physical habitat alteration, with decreased flow velocities and high siltation rates near the upstream of weirs (Kondolf 1997) and increased flow velocities leading to substrate

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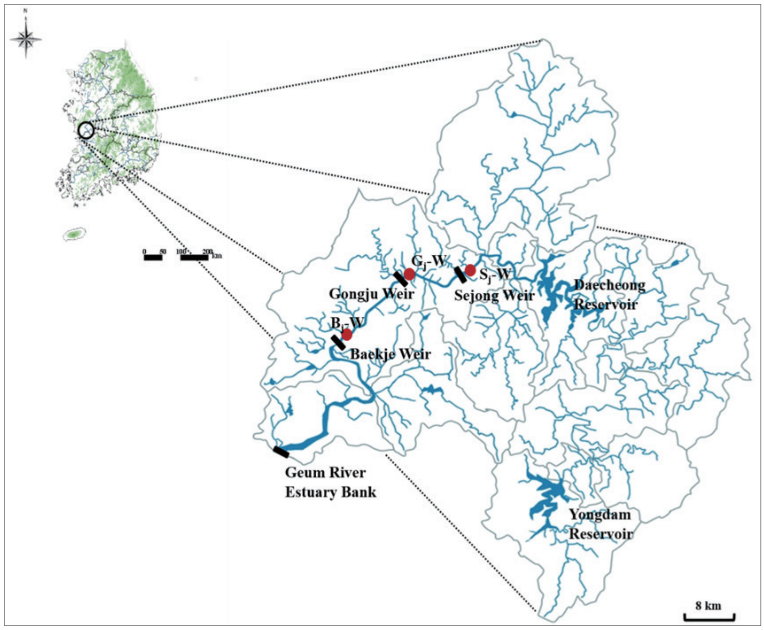

Fig. 1. The study locations and sampling sites at three weirs of Sejong Weir (S_j-W), Gongju Weir (G_j-W) and Baekje Weir (B_j-W) within Geum-River watershed.

scouring downstream (Camargo and Voelz 1998). These habitat modifications create conditions favorable for exotic or non-native species (Marchetti and Moyle 2001), which can then further alter fish assemblage compositions via a predation and competition (Godinho and Ferreira 1998, Eby et al. 2006). Water chemistry in the river ecosystem is directly or indirectly influenced by the weir or dam constructions (Hannan and Young 1974). These influences on the water chemistry can either be spatially inflow of high nutrients, such as nitrogen (N) and phosphorus (P), from extensive crop lands, urban pipes or a wastewater disposal plant. Predicting inputs from the point sources is relatively simple, but attributing chemical factors of river water to non-point sources (NPS) is much more difficult (Baker 2003).

The weir constructions of Geum-River watershed, which belong to our study location, were initiated from the Korean government's five-year national plan of "The Four Major Rivers Restoration Project" in July 2009. Recent studies of the weirs constructed in the region pointed out hydrological modifications of water retention time, current velocity (Kim 2013), chemical pollutions by rapid eutrophication, and biological impacts. Within the regions of weirs, the hypoxia near the bottom, frequent algal blooms, and surface scums were frequently observed along with massive fishkills, indicating an impacts of aquatic environments.

However, little is known about influences of the weir constructions on fish compositions and the community structure in this Asian region. Poff et al. (1997) pointed out that more intensive researches are required to understand functional and trophic modifications of fish community in impounded rivers. In this study, some influences of chemical water quality and fish community on the weir constructions were analyzed between the two periods of before- (2008 – 2009) and after the weir construction (2011 – 2012) within the Geum-River watershed. Also, tolerance guilds and trophic compositions of fish, as an ecological indicators, were compared along with river ecosystem health assessments, based on multi-metric fish model of index of biological integrity (IBI).

MATERIALS AND METHODS

Sampling sites and methods

This study was conducted in the Geum River watersheds including mainstream regions, which is located in the midwest temperate region of South Korea (Fig. 1). Total three sites were selected for fish sampling where each site represents the characteristics of the weir-constructed area within 1 km upper region from the artificial weir constructed on the Geum River watersheds. It was consisted of every 3 sites of each weir region; Sejong-Weir (S_j-W), Gongju-Weir (G_j-W) and Baekje-Weir (B_j-W) and also conducted in premonsoon (May - June) and postmonsoon (September - October) in periods of before the weir construction (B_{wc}; 2008 - 2009) and after the weir construction (A_{wc}; 2011 - 2012) respectively. All sampling was operated by the modified wading method (An et al. 2004) to adapt the Korean aquatic ecosystem based on the Ohio EPA method (1989).

For the fish sampling, we considered all habitat types such as riffle, run, and pool in the same site and directed in an upstream to downstream reach for at least 200 m distance during 50 minutes for the catch per unit efforts (CPUE). Casting-net (7 × 7 mm, CN) and kick-net (4 × 4 mm, KN), the most popular fish sampling gears in Korea, were applied to collect samples. All fishes were identified at the sampling place and released immediately. All specimens were identified according to classification keys of Kim and Park (2002).

Water quality analysis and stream ecosystem health assessment

Water quality data were obtained from the Water Information System (WIS) of the Ministry of Environment, Korea (MEK) during 2008 – 2012, except 2010 for physicochemical water quality analysis. Nine parameters such as water discharge (Flow), pH, dissolved oxygen (DO), biological oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), electric conductivity (EC) and chlorophyll-a (CHL-a) were examined for the analysis. For the study, eight metric model of the Index of Biological Integrity (IBI) was applied, instead of original 12 metric model originally suggested by Karr (1981). The model was modified by the regional application of the Geum River Watershed (An et al. 2002, 2004). The metrics consisted of three major groups as ecological characteristic and species composition, trophic composition, and fish abundance and health condition. Each metric was scored in 1, 3, or 5 point after the approach of US EPA (Barbour et al. 1999). Each metric and criteria characteristics were previously described in An et al. (2004). These scores were then summed to obtain a site-specific model value that ranged from 8 to 40, and categorized with excellent (A, 36–40), good (B, 26–35), fair (C, 16–25), poor (D, ≤15) conditions.

Statistical analysis

We used various statistical analysis methods for correlation analysis and t-test by SPSS (Version 12.0K for windows). To confirm the change pattern and clusters on all sites along the weir construction, Self-Organizing Map (SOM; Kohonen 1982) was utilized. We adopted the initialization and training methods based on the SOM Toolbox that allow the algorithm optimized. Also, to identify the major environmental factors influencing on the annual changes clustered by SOM, we used PC-Ord in (Version 4.25 for Windows; McCune and Mefford 1999).

RESULTS AND DISCUSSION

Physico-chemical water quality

River discharge (flow regime) was significantly increased (t = -5.99, p < 0.001) which showed 61.4 m^3s^{-1} (Range: 23.9 – 148.0 m^3s^{-1}) as its average value in the B_{wc} whereas it was 179.7 m^3s^{-1} (Range: 47.7 – 586.3 m^3s^{-1}) in the A_{wc} (Fig. 2). In contrast, the value of BOD, a well-known indicator of organic pollution, was significantly decreased (t = 6.09, p < 0.05), which showed 3.4 mgL^{-1} (Range: 1.0 – 7.1 mgL^{-1}) as its average value in the B_{wc} whereas it was 2.7 mgL^{-1} (Range: 1.1 – 6.6 mgL^{-1}) in the A_{wc}. Value of EC which indicates degree of organic pollution like BOD, was 351.0 μScm^{-1} (Range: 198 – 477 μScm^{-1}) in the B_{wc}, however, after the construction of weirs completed, it was significantly decreased (t = 7.07, p < 0.001). Those results that both BOD and EC were decreased might be due to dilution effects of the river water by greater water volume (Flow) along with the weir construction. Additionally, concentrations of TP, well-known indicator of phosphorus nutrient contamination, were decreased significantly (t = 6.74, p < 0.001). It averaged 199.7 μgL^{-1} (Range: 135 – 349 μgL^{-1}) in the whole weir-constructed regions at the B_{wc} whereas it was 125.8 μgL^{-1} (Range: 45 – 278 μgL^{-1}) at the A_{wc} (Fig. 3). The significant reduction in TP concentrations might be caused by the sedimentation of nutrients, but trophic conditions based on the criteria of eutrophication established by OECD (1982) were hyper-eutrophy in both B_{wc} and A_{wc}. Chl-a also showed the similar patterns to TP analysis. Average value of Chl-a was decreased in A_{wc} with 26.4 μgL^{-1} (Range: 1.7 – 120.2 μgL^{-1}) compared to B_{wc}, but this value was mean level of the phytoplankton warnings (> 25 μgL^{-1}) based on the phytoplankton alert system by the Ministry of Environment, Korea (MEK). In addition, according to the trophic categories proposed by OECD (1982), trophic states were eutrophy in both B_{wc} and A_{wc}.

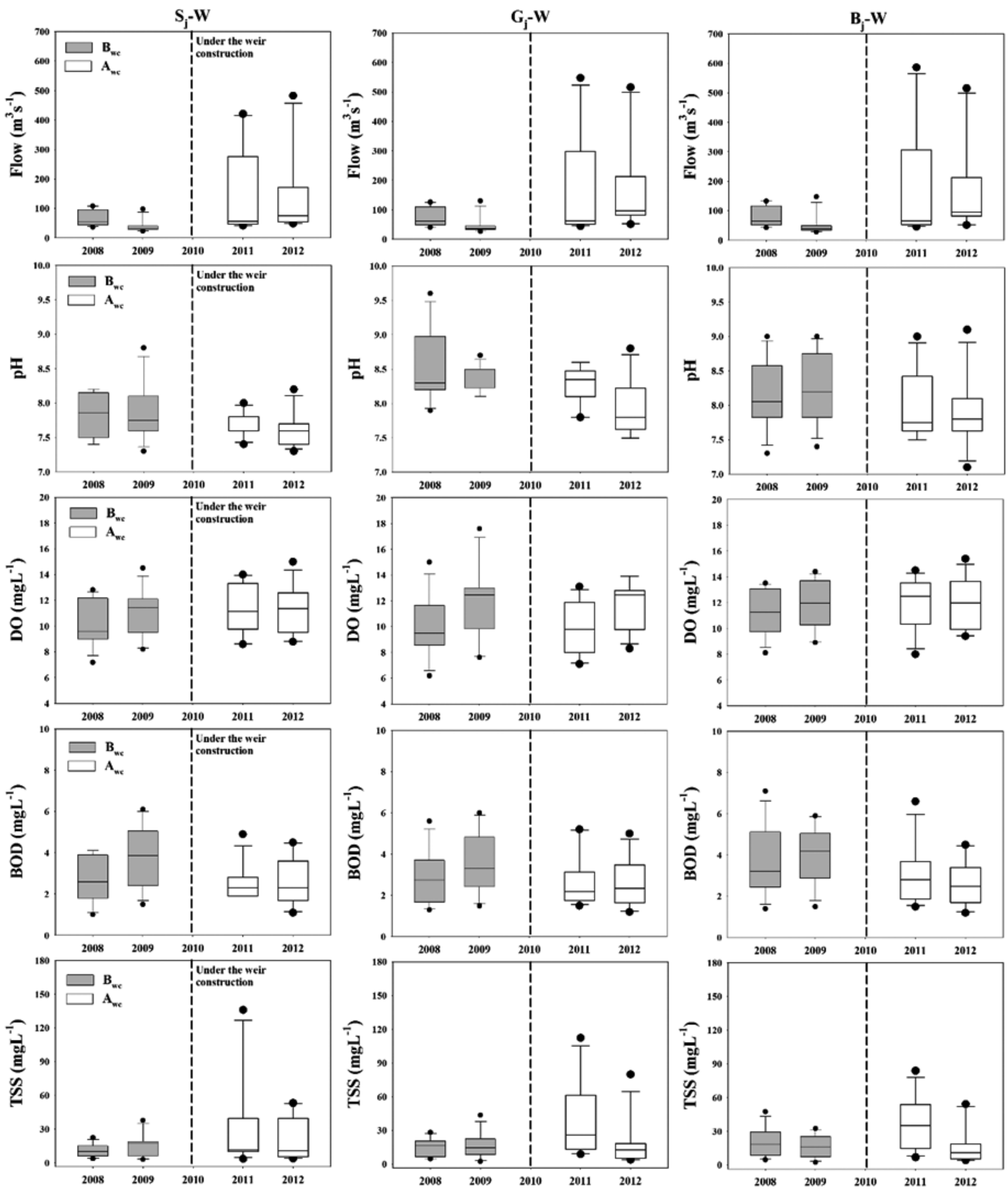

Fig. 2. Physico-chemical water quality (Flow, pH, DO, BOD, TSS) in the three weirs of Sejong Weir (S_j-W), Gongju Weir (G_j-W) and Baekje Weir (B_j-W) in the periods of before (B_{wc}; 2008 - 2009) and after the weir construction (A_{wc}; 2011 – 2012).

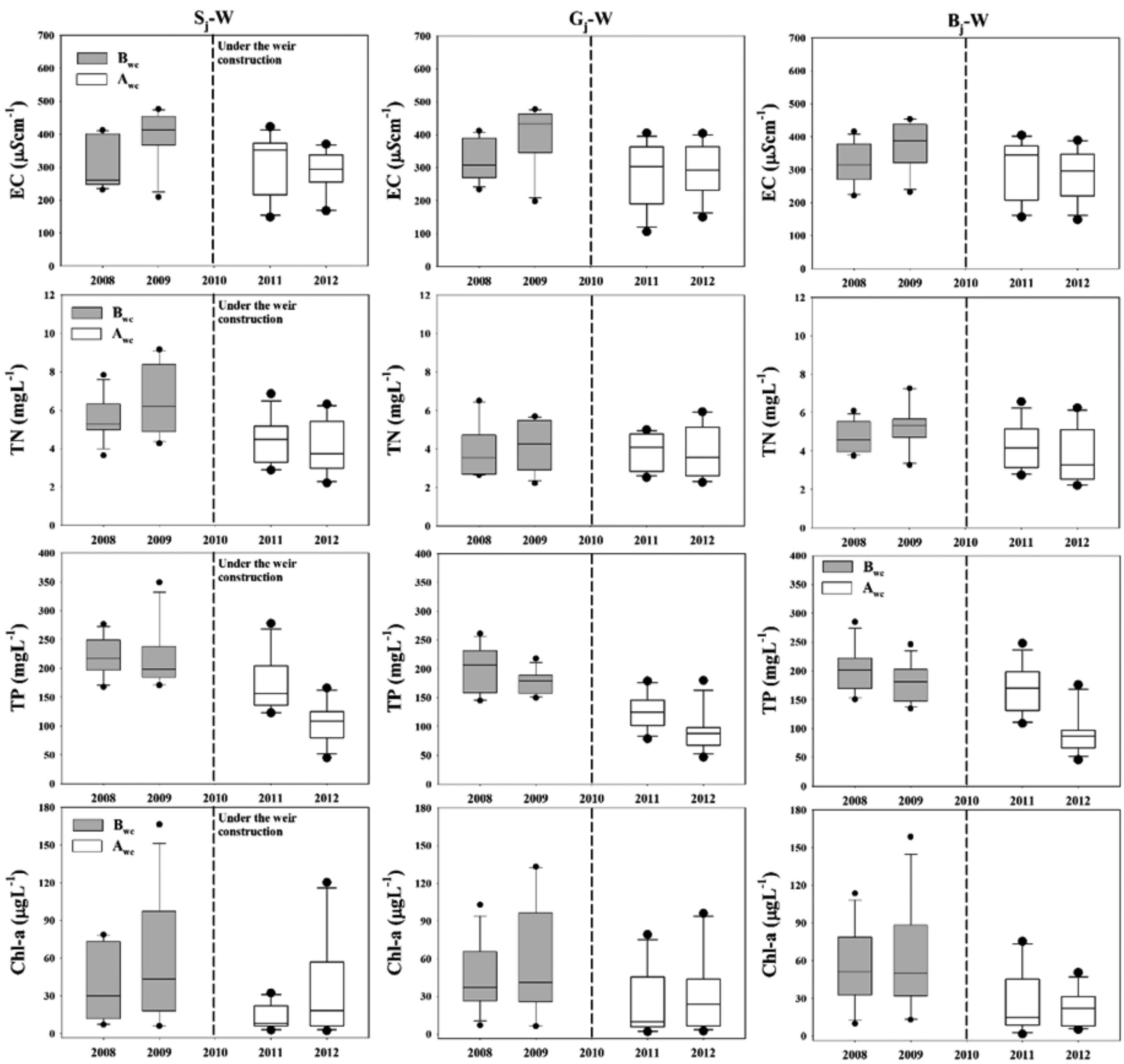

Fig. 3. Chemical parameters (EC, TN, TP, Chl-a) in the three weirs of Sejong Weir (S_j-W), Gongju Weir (G_j-W) and Baekje Weir (B_j-W) in the periods of before (B_{wc}; 2008 - 2009) and after the weir construction (A_{wc}; 2011 – 2012).

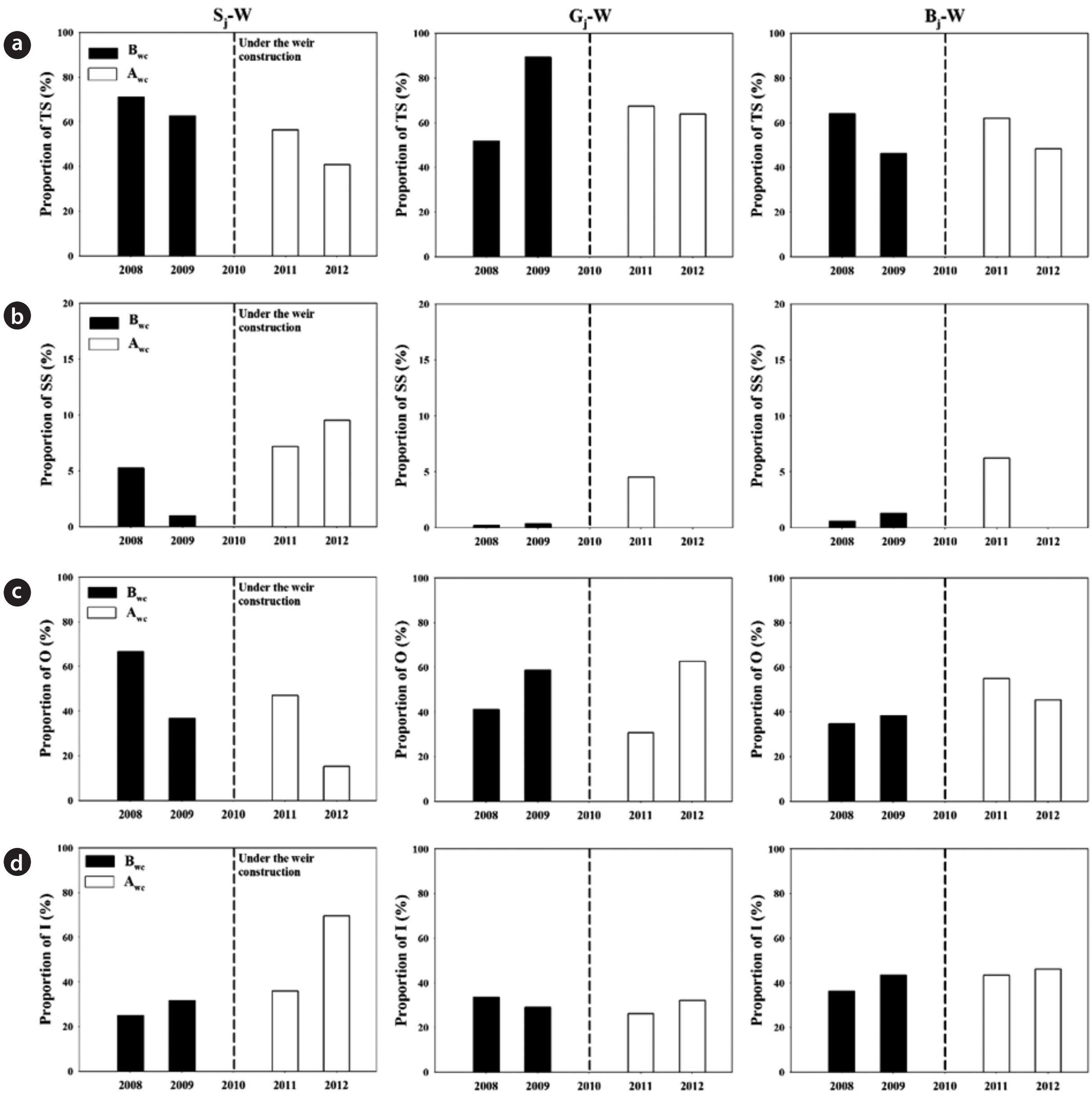

Fig. 4. Tolerance and trophic guilds analysis in each weir (S_j-W: Sejong-Weir, G_j-W: Gongju-Weir, B_j-W: Baekje-Weir) constructed in Geum River watershed. The abbreviations are as follows; TS = tolerant species, SS = sensitive species, O = omnivore species, I = Insectivore species.

Ecological indicator characteristics

According to the results of tolerance guilds analysis, tolerant species (TS) dominated with over 60% of its relative abundance (RA) in both before- and after the weir construction (Fig. 4a). However, sensitive species (SS) presented only 1-6% of the RA in both B_{wc} and A_{wc} (Fig. 4b). These results support the previous research results (Karr 1981, US EPA 1991) that sensitive species tend to rapidly disappear along with degradation of the physical and chemical condition caused by organic pollution, disturbance or destruction of habitats, but tolerant species showed dominant distribution. Thus, the whole weir regions, where tolerant species distributed dominantly, were affected by inflow of organic pollutants from urban streams (Lee et al. 2013, Kim et al. 2014, Lee and An 2014). Also, it might consider that these phenomenon could be increased by habitat destruction and water quality degradation according to the weir construction.

Meanwhile, trophic guild analysis also showed the similar patterns as tolerance guilds. Omnivore species was increased after weir construction showing over 50% as

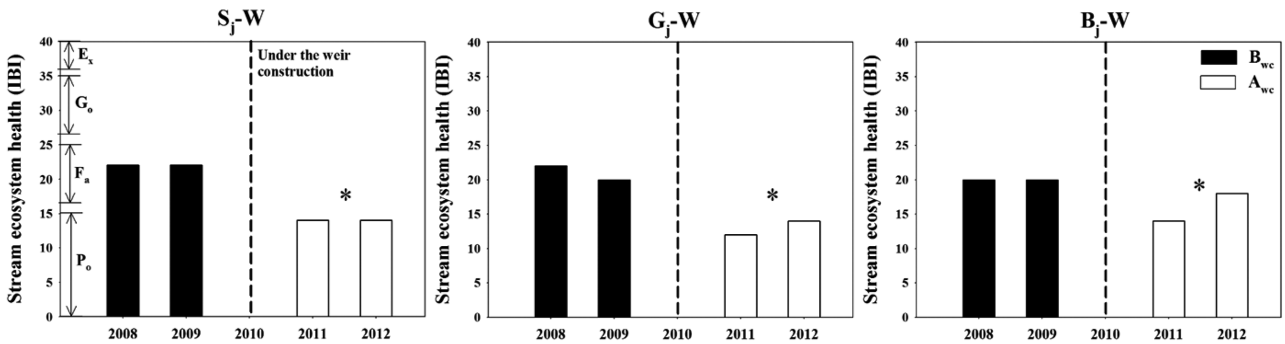

Fig. 5. Changes of stream ecosystem health in each weir (S_j-W: Sejong-weir, G_j-W: Gongju-weir, B_j-W: Baekje-weir) constructed in Geum River watershed, *: Significant difference ($p < 0.05$) between B_{wc} and A_{wc}. The abbreviations are as follows; E_x = excellent condition, G_o = good condition, F_a = fair condition, P_o = poor condition.

RA (Fig. 4c). Insectivore species was also increased in A_{wc} (Fig. 4d), but it was because *P. esocinus*, and *M. jeoni*, were dominant species. Barbour et al. (1999) reported that organic pollution and toxicant inflows were increased along the stream order increase and then, these phenomenon could cause the trophic simplification of fish community related to omnivore abundance so that these results could affect to degradation of overall ecosystem health.

Ecosystem health assessments

Stream ecosystem health assessment based on the Index of Biological Integrity (IBI) resulted in an average 21 (range: 20 – 22; C) classified as fair condition and 14 (range: 12 – 18; D) classified as poor condition in B_{wc} and A_{wc}, respectively ($p < 0.05$) (Table 1, Fig. 5). These results that decrease of IBI values and deterioration of ecosystem health were caused by significant decrease of individuals and sensitive species, but increase of tolerant species, omnivores and anomalies after the weir construction. Therefore, it might consider that deterioration of ecosystem health could be increased by habitat destruction and water quality degradation according to the weir construction.

Ecological pattern analysis using an approach of self-organizing map (SOM)

In order to confirm the ecological change pattern by artificial weir construction obstructing stream flow and severing between the upper and lower regions at each weir, we used SOM (Kohonen 1982) for patterning and visualizing the fish community in study regions. Chemical water quality data and fish community data were used for train-

Table 1. Stream ecosystem health assessments, based on the multi-metric index of biological integrity (IBI) model in three weirs of Sejong Weir (S_j-W), Gongju Weir (G_j-W) and Baekje Weir (B_j-W)

Metric Attributes	Metric Components	B_{wc} (2008-2009)			A_{wc} (2011-2012)		
		S_j-W	G_j-W	B_j-W	S_j-W	G_j-W	B_j-W
Species richness and compositions	M_1: Total number of native species	5	3	3	3	3	3
	M_2: Number of riffle-benthic species	1	1	1	1	1	1
	M_3: Number of sensitive species	1	1	1	1	1	1
	M_4: Tolerant species as percent individuals	1	1	1	1	1	1
Trophic compositions	M_5: Omnivores as percent individuals	1	3	3	1	1*	3
	M_6: Insectivores as percent individuals	3	3	3	3	3	4
Fish abundance and Individual Health	M_7: Total number of individuals	5	4	3	2*	1*	1*
	M_8: Anomalies as percent individuals	5	5	5	2*	2*	2*
Total Score of IBI Model		22	21	20	14*	13*	16*
Ecological Health Criteria		F	F	F	P	P	F

*: significant difference ($p < 0.05$) between B_{wc} and A_{wc}
B_{wc}: before the weir construction, A_{wc}: after the weir construction, F: fair condition, P: poor condition

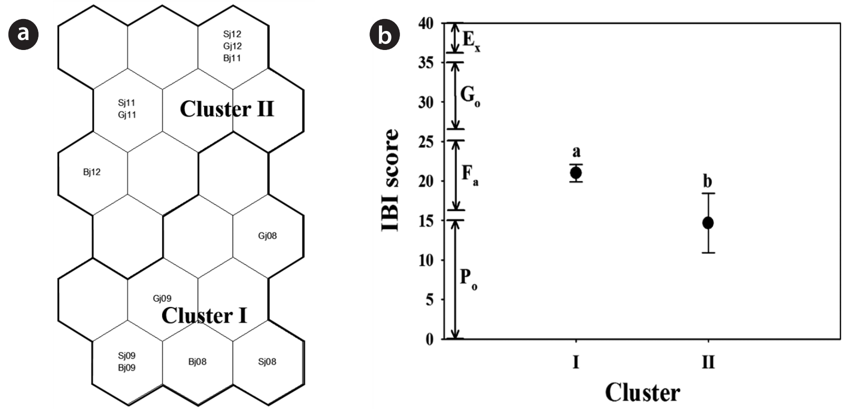

Fig. 6. The map trained by Self-Organizing Map (SOM) for clustering study sites along the weir construction in Geum River watershed from 2008 to 2012.

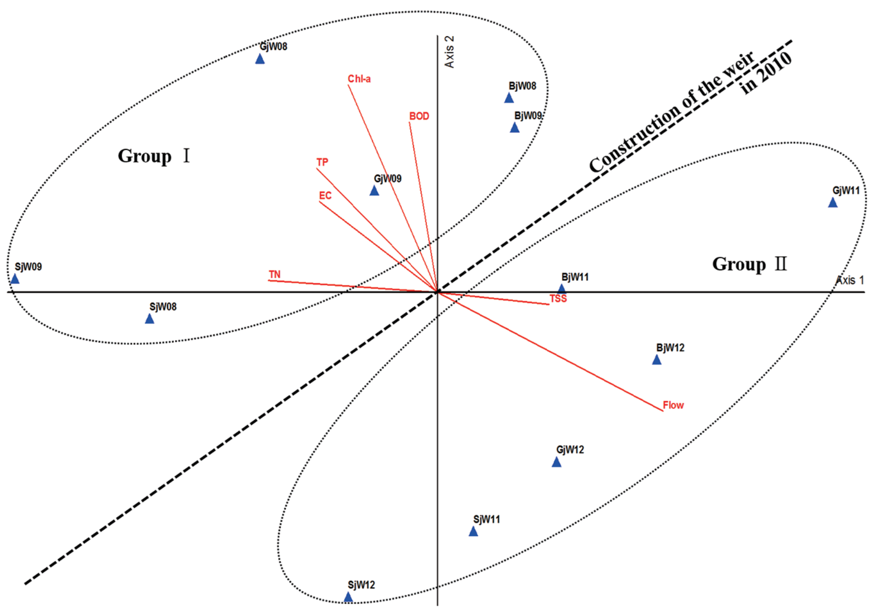

Fig. 7. Principal Component Analysis (PCA) of the three weir (S_j-W: Sejong-weir, G_j-W: Gongju-weir and B_j-W: Baekje-weir) constructed in Geum River watershed during 2008 - 2012, based on biological components (tolerance guilds, trophic guilds, fish composition, IBI model values) and physico-chemical factors.

ing (Fig. 6). The study sites were firstly grouped along the impact of organic pollution and secondly to the periods of weir construction (Fig. 6a). The clusters were vertically arranged according to degree of pollution: the study sites with severe organic pollution appeared in the lower area of the map (e.g., cluster I), while relatively clean sites were grouped in the upper right area (e.g., cluster II). Several specific water quality factors related to the impact of weir construction and nutrient pollution such as Flow, TN, TP, EC and Chl-a were measured based on clustering by SOM. Fig. 6b showed the differences in physico-chemical water quality indices related to IBI scores. Chemical indices were clearly differentiated with statistical significance among different clusters. In the meantime, we monitored change patterns in each study site as time progressed. The study sites surveyed twice a year in Geum River watershed from May 2008 to October 2012 were recognized in a sequence on the trained SOM. As time progressed, study sites moved from the fair condition of ecosystem health in cluster I to the poor condition in cluster II indicating degradation of the ecosystem health in A_{wc} (2011 – 2012) showing the decrease IBI scores in cluster II (Fig. 6b). These results supposed that biological health might be deteriorated as weir construction. Additionally, the further study should be continued to monitor the change patterns regarding overall factors such as physico-chemicals and biological health.

Table 2. Principal component analysis (PCA), based on tolerance guilds (TS, SS), trophic guilds (O, I), fish composition (TNS, TNI), multi-metric IBI mode values, and the physico-chemical parameters. The abbreviations are as follows; SS = Sensitive Species, TS = Tolerance Species, O = Omnivore Species, I = Insectivore Species, TNS = Total number of species, and TNI = Total number of individuals

Principal component analysis / Eigenvalue > 1.0			
Structure metrics	**Factor 1**	**Factor 2**	**Factor 3**
Weir	0.2901	0.3754**	0.4601
Construction period	0.3031	- 0.4929**	0.0319
% TS	- 0.4099*	- 0.1472	0.1014
% SS	0.2518	0.0111	- 0.6659***
% O	- 0.3238	- 0.4534**	- 0.0170
% I	0.3843*	0.0409	- 0.3918
TNS	- 0.3450*	- 0.1629	- 0.3032
TNI	- 0.3976*	0.2684	- 0.0900
IBI score	- 0.2507	0.5372**	- 0.2823
Eigenvalue	4.249	1.997	1.417
Proportion of variance	47.213	22.188	15.744

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Environmental factor analysis using a principal component analysis (PCA)

In this study, we used Principal component analysis (PCA; McCune and Mefford 1999) among factor analysis to diagnose variables effect to the site with analyses of biological parameters (IBI, tolerance and trophic guilds, and species composition) and physico-chemical water quality parameter (Flow, BOD, TSS, TN, TP, EC and TP). For diagnosis of interrelationship among dependent factors, we decided two of the three factors (Eigenvalue > 1.0). As a result, Factor 1 (proportion of tolerant species, total number of individuals, proportion of insectivores, and total number of species) could describe with 47.2% and Factor 2 (IBI score, periods of weir construction, proportion of omnivores, and weir regions) was with 22.2% (Table 2).

In addition, we also tried hierarchical cluster analysis per study site using parameters in PCA and it could divide with 2 groups from total 12 sites of each three weir region in Geum-River watershed (Fig. 7). Group I was classified to sites studied before the weir construction (B_{wc}, 2008 - 2009) with high IBI values. While, Group II was studied after the weir construction (A_{wc}, 2011 - 2012) with decreased IBI values. These results were similar to pattern analysis using SOM. It was divided by the periods of weir construction remarkably, and showed decrease of the IBI score.

Overall, our results suggest that partial chemical changes were evident after the weir construction. Especially, total phosphorus (TP) in the epilimnion (surface water) decreased significantly ($p < 0.05$) but TP in the whole water column (including hypolimnion) may increase in the systems. And, stream health, based on the IBI model, was more impaired after the weir construction. Further researches are required to manage and predict the health conditions of artificial weir ecosystem.

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LITERATURE CITED

An KG, Kim DS, Kong DS, Kim SD. 2004. Integrative assessments of a temperate stream based on a multimetric determination of biological integrity, physical habitat evaluations, and toxicity tests. Bull Environ Contam Toxicol 73: 471-478.

An KG, Park SS, Shin JY. 2002. An evaluation of a river health using the index of biological integrity along with relations to chemical and habitat conditions. Environ Int 28: 411-420.

Baker AC. 2003. Flexibility and specificity in coral-algal symbiosis: diversity, ecology, and biogeography of Symbiodinium. Annu Rev Ecol Evol Syst 34: 661-689.

Balon EK, Stewart DJ. 1983. Fish assemblages in a river with unusual gradient (Luongo, Africa-Zaire system), reflections on river zonation, and description of another new species. Environ Biol Fish 9: 225-252.

Barbour MT, Gerritsen J, Snyder BD, Stribling JB. 1999. Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates and fish. 2nd Ed. US Environmental Protection Agency, Washington, DC.

Baxter RM. 1977. Environmental effects of dams and impoundments. Annu Rev Ecol Syst 8: 255-283.

Camargo JA, Voelz NJ. 1998. Biotic and abiotic changes along the recovery gradient of two impounded rivers with different impoundment use. Environ Monit Assess 50: 143-158.

Dynesius M, Nilsson C. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266: 753-762.

Eby LA, Roach WJ, Crowder LB, Stanford JA. 2006. Effects of stocking-up freshwater food webs. Trends Ecol Evol 21: 576-584.

Gelwick FP. 1990. Longitudinal and temporal comparisons of riffle and pool fish assemblages in a northeastern Oklahoma Ozark stream. Copeia 1990: 1072-1082.

Godinho FN, Ferreira MT. 1998. The relative influences of exotic species and environmental factors. Environ Biol Fish 51: 41-51.

Hannan HH, Young WJ. 1974. The influence of a deep-storage reservoir on the physicochemical limnology of a central Texas river. Hydrobiologia 44: 177-207.

Karr JR. 1981. Assessment of biotic integrity using fish communities. Fisheries 6: 21-27.

Kim IS, Park JY. 2002. Freshwater Fishes of Korea. KyoHak Publishing Co., Seoul.

Kim JH, Yeom DH, An KG. 2014. A new approach of Integrated Health Responses (IHRs) modeling for ecological risk/health assessments of an urban stream. Chemosphere 108: 376-382.

Kim Z. 2013. Assessment of riverbed change due to the operation of a series of gates in a natural river. PhD dissertation, Texas A&M University, College Station, TX, USA.

Kohonen T. 1982. Self-organized formation of topologically correct feature maps. Biol Cybern 43: 59-63.

Kondolf GM. 1997. Profile: Hungry water: Effects of dams and gravel mining on river channels. Environ Manag 21: 533-551.

Lee JH, An KG. 2014. Integrative restoration assessment of an urban stream using multiple modeling approaches with physical, chemical, and biological integrity indicators. Ecol Eng 62: 153-167.

Lee JH, Kim JH, Oh HM, An KG. 2013. Multi-level stressor analysis from the DNA/biochemical level to community levels in an urban stream and integrative health response (IHR) assessments. J Environ Sci Health, Part A 48: 211-222.

Marchetti MP, Moyle PB. 2001. Effects of flow regime on fish assemblages in a regulated California stream. Ecol Appl 11: 530-539.

Maret TR, Robinson CT, Minshall GW. 1997. Fish assemblages and environmental correlates in least-disturbed streams of the upper Snake River basin. Trans Am Fish Soc 126: 200-216.

McCune B, Mefford MJ. 1999. PC-ORD. Multivariate analysis of ecological data. Version 4.0. MjM Software, Gleneden Beach, OR.

Ohio EPA. 1989. Biological criteria for the protection of aquatic life: Vol III. Standardized biological field sampling and laboratory method for assessing fish and macroinvertebrate communities. Ohio Environmental Protection Agency, Columbus, OH.

OECD. 1982. Eutrophication of waters: monitoring assessment and control. OECD, Paris.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaar KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: A paradigm for river conservation and restoration. BioScience 47: 769-784.

Richter BD, Braun DP, Mendelson MA, Master LL. 1997. Threats to imperiled freshwater fauna. Conserv Biol 11: 1081-1093.

Schlosser IJ. 1982. Fish community structure and function along two habitat gradients in a headwater stream. Ecol Monogr 52: 395-414.

US EPA. 1991. Technical support document for water quality-based toxics control. EPA 505-2-90-001. US Environmental Protection Agency, Office of Water, Washington, DC.

Ward JV, Stanford JA. 1979. Ecological factors controlling stream zoobenthos with emphasis on thermal modification of regulated streams. In: The Ecology of Regulated Streams (Ward JV, Stanford JA, eds). Springer, New York, NY, pp 35-55.

Ward JV, Stanford JA. 1983. The serial discontinuity concept of lotic ecosystems. In: Dynamics of Lotic Ecosystems (Fontaine TD, Bartell SM, eds). Ann Arbor Science Publishers, Ann Arbor, MI, pp 29-42.