Original Research

Influence of Weir Construction on Chemical Water Quality, Physical Habitat, and Biological Integrity of Fish in the Geum River, South Korea

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Abstract

The objectives of this study were to determine the long-term changes in water chemistry, physical habitat, and fish fauna/composition before and after construction of the Sejong Weir in Geum River, South Korea, during 2007–2014, and to evaluate the integrated ecological health based on chemical water quality, physical habitat, and biotic integrity using a star plot integration approach. As an indicator of water quality, the mean total phosphorus (TP) in the surface water decreased 2.6-fold after weir construction, indicative of P sedimentation from the water column due to structural changes from a lotic to a lentic system. The chlorophyll-a concentration decreased in response to P levels. Considering total nitrogen (TN), more than 91.7% of the total observations after weir construction (n = 96) had a TN:TP ratio >17, indicating potential P limitations on algal growth. The log-transformed TN:TP ratio had a weak positive correlation ($p<0.005$, $R^2 = 0.085$, n = 96) with TN and a strong negative correlation ($p<0.001$, $R^2 = 0.575$, n = 96) with TP. This indicated that the N:P ratio was regulated mainly by variations in P rather than N. After weir construction, the population of the lotic-type fish *Zacco platypus* decreased 13-fold, and the population of the lentic-type fish *Pseudorasbora parva* increased 3-fold. Overall, the integrated ecological health assessments revealed large degradations of >3-fold in biotic health, 2-fold in physical habitat health, and >5-fold in chemical health after weir construction.

Introduction

In recent years, weirs and artificial dams have been built continuously in both small streams and large rivers in order to secure agricultural irrigation and drinking water in watersheds throughout Korea [1]. Due to the monsoon climate, the distribution of rainfall is not consistent among seasons, and securing water resources through multipurpose construction of large dams in Korea is considered to be indispensable [2]. The "Four Major River" project, originally known as the Korean New Deal project, was created in 2008 to resolve water problems such as uneven supply and demand of water

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resources, floods, and droughts [3]. Three weirs, the Sejong, Kongju, and Beakjae, were installed in the Geum River watershed. The goal of the project was to provide fundamental measures to protect against flood damage and drought caused by global warming and to expand investments in social overhead capital. It has since been adopted as a national project for ecosystems with the greatest hydrological and ecological alterations [4].

Despite the original intent, numerous studies have found that weir construction results in the degradation of chemical water quality such as nutrient enrichment [5], habitat disturbance from lotic (river-like) to lentic (lake-like) systems [6], and biological problems such as massive fish kills [7] and toxic algal blooms [8]. For example, phosphorus (P) and nitrogen (N) accumulations in the sediment of weirs in the Geum River have accelerated eutrophication. Moreover, oxygen depletion in the deep zone and phytoplankton algal blooms have occurred continually in lentic-like systems [9]. In addition, chemical water quality pollution has emerged as a major environmental problem for local communities. Under the current conditions, the river bed structure and functions have been affected by habitat simplification and hypoxia at the bottom of the system [10]. At the Sejong Weir, biological health has degraded rapidly due to the dominance of exotic species [11], habitat simplification due to silt accumulation [12], and increased frequency of fish kills.

Such modifications to the physical habitat and hydrological dynamics change the structure of fish species and trophic relationships in river ecosystems, resulting in deterioration of its ecological health. Weir construction has been reported to have various impacts on the chemical conditions [13] and food chains [14] of aquatic ecosystems, and the key impacts are explained well by the serial discontinuity concept of Ward and Stanford [15]. This concept states that artificial weir and dam construction results in discontinuous ecological characteristics upstream, midstream, and downstream in the river ecosystem, thereby influencing ecological structures and functions.

Weir construction causes changes in channel structure and river morphology [16]. Such physical modifications result in an increase in water retention time, and the types of fish may change due to a shift from a lotic to lentic habitat [17]. In turn, these physical environmental changes simplify the fish habitat, which eventually becomes an environment in which only a few fish species can survive by adapting to the changing environment [18]. In addition, weirs interfere with the mobility of living organisms, such as migratory fish [19].

Meanwhile, weir construction can cause the accumulation of sediments and pollutants in the water body, increasing nutrient levels (e.g., P and N) and accelerating eutrophication [20], which can lead to a dramatic increase in the productivity and composition

of primary producers in the modified system [21] and a decrease in dissolved oxygen (DO) in the hypolimnion. In the Baekjae Weir of the Geum River, such changes have triggered massive fish kills [22]. Since increased water levels and frequent water level fluctuations from weir gate control damage riparian vegetation, fish spawning grounds and shelters may be altered.

The objectives of this study were to determine the long-term changes in water chemistry, physical habitat, and fish fauna/composition before and after weir construction and to perform an integrative health assessment based on the chemical water quality, physical habitat, and biotic integrity of the Geum River at the Sejong Weir. The physical habitat health conditions were determined using a qualitative habitat evaluation index, and chemical health was evaluated using water chemistry parameters. In addition, we determined the biological health based on the index of the biological integrity (IBI) model and analyzed the relationships among trophic level, tolerance guild, and fish habitat guild. Based on these parameters, the integrative ecological health was compared before and after weir construction using a star plot integration approach.

Materials and Methods

Study Watershed and Sampling Sites

The Geum River watershed has an area of 9,912 km^2, and the river spans 394 km from the headwater to the estuary (Fig. 1). The river watershed includes several large tributaries of Miho Stream, Gap Stream, Bocheong Stream, and the Cho River. It is influenced substantially by many nonpoint (e.g., rice paddies) and point (e.g., wastewater disposal plants and sewage treatment plants) sources of pollution. Three artificial weirs were constructed in the downstream region of the river under a government project in 2012. The present study was conducted at the Sejong Weir, the most upstream of the three weirs, and this weir is 4 m tall and 348 m wide with a water storage capacity of 1.3 million tons.

Fish Sampling

Fish assemblages were collected twice at each sampling site from 2007 to 2014 during the pre-monsoon and post-monsoon seasons. We selected these two seasons due to the high hydrological stability and lack of flooding. Fish sampling was performed based on the catch per unit effort wading method [23] in all habitat types (e.g., riffles, runs, and pools). The distance and time elapsed for sampling were at least 100 m and 60 min, respectively. A casting net (mesh size: 7×7 mm) and kick net (mesh size: 4 × 4 mm) were used for sampling, as they are the most popular fish sampling
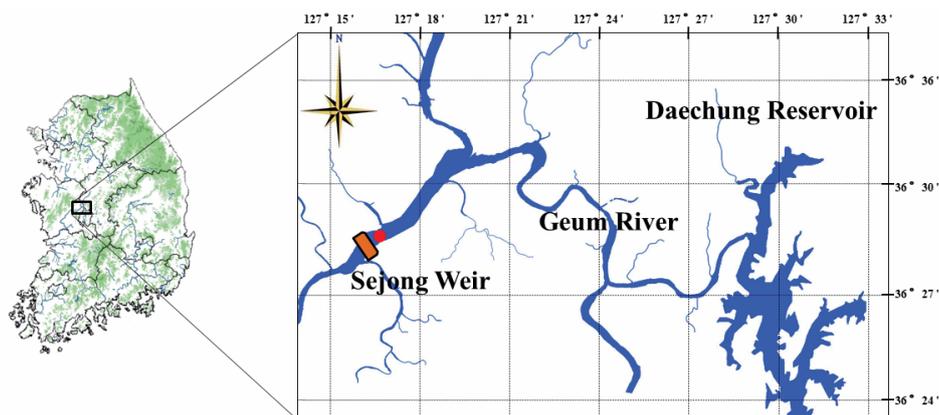
Fig. 1. Map of the study site at Sejong Weir.

gear used in Korea. All fish were identified in the field and released immediately. The external characteristics of individual fish were examined in the laboratory for deformities, erosions (e.g., on skin and barbels), lesions (e.g., open sores and ulcerations), and tumors. Tolerance and trophic guild analyses were based on regional studies [24, 25].

Multimetric Fish IBI Model

The biological health of the lotic ecosystem was evaluated using a multimetric fish IBI model. The metrics consisted of three major ecological characteristics: species richness according to the stream order (M1, M2, and M7), trophic and tolerance guild composition (M3-M6), and fish abundance according to health condition (M8). The metrics were defined as follows: M1, total number of native species; M2, number of riffle benthic species; M3, number of sensitive species; M4, proportion of tolerant species; M5, proportion of omnivorous species; M6, proportion of native insectivorous species; M7, total number of native individuals; and M8, proportion of abnormal individuals. Each metric was assigned a score of 1, 3, or 5, and five classification criteria were used: excellent (A; score = 40-36), good (B; 34-28), fair (C; 26-20), poor (D; 18-14), and very poor (E; ≤13). Detailed descriptions of the specific metric characteristics and scoring criteria for the model are available.

Reference Stream Analysis

For the integrated health assessment, a reference site was selected at the Muju Namdae Stream in the Geum River watershed, which is located in the central region of the Korean Peninsula and experiences a temperate climate. The reference site is a fourth-order stream located near Seomyeon Bridge that is predominantly surrounded by forest (> 70%) and has a moderately well-developed riffle-pool morphology with gravel as the dominant substratum. According to the United States Environmental Protection Agency

[26] and Barbour et al. [27], a reference stream should be located in the same watershed as the surveyed stream, and reference conditions are best established through systematic monitoring of sites that represent the natural range of variation under minimally disturbed water chemistry, habitat, and biological conditions [28]. The reference site was affected by least-point and non-point sources within the Geum River watershed.

Chemical Analysis

Chemical water quality was analyzed using long-term data from the sampling site obtained from the Ministry of the Environment of Korea, and water quality impacts were analyzed based on three categories: before (B_{wc}, 2007-2008), during (U_{wc}, 2009-2011), and after weir construction (A_{wc}, 2012-2014). Surface water sampling at the study site was conducted monthly during 2007-2014, and pH, DO, biological oxygen demand (BOD), suspended solids (SS), electrical conductivity (EC), and chlorophyll-a (Chl-a) were analyzed. Various nutrients, such as total N (TN), dissolved TN, ammonia N, total P (TP), dissolved total P (DTP), and phosphate P, were analyzed following the Korean Standard Chemical Analytical Methods.

Empirical Models

To analyze the relationships between N and P concentrations and sestonic Chl-a, as a measure of algal productivity we developed empirical models of TP–Chl-a, TP–TN:TP, and TN–TN:TP. For temporal analysis, water quality data were categorized into three seasons (pre-monsoon, monsoon, and post-monsoon) and $\log_{10}$-transformed to create a normal distribution curve. Then we performed Pearson's correlation analysis and regression analysis. All statistical analyses were conducted to assess the differences between B_{wc} and A_{wc} using SPSS ver. 12.0 for Windows.

Analysis of the Integrated Health Assessment Model

The integrated health assessment model was developed using a multimetric approach to ecological health. The model was composed of multiple functional metrics and was based on the integration of all parameters derived from biological, chemical, and physical habitat health parameters. The values of the integrated health assessment model were calculated using the star plot approach.

We included six metrics for the biological health assessment: total number of native fish species (BM1), number of riffle benthic species (BM2), proportion of tolerant individuals (BM3), proportion of omnivorous individuals (BM4), total number of native individuals (BM5), and proportion of individuals with deformities, erosions, lesions, or tumors (BM6). In addition, we considered six physical habitat health metrics: epifaunal substrate/available cover (PM1), embeddedness (PM2), velocity/depth combination (PM3), sediment deposition (PM4), channel alteration (PM5), and frequency of riffles or bends (PM6). Finally, we considered six chemical parameter metrics: BOD (CM1), total SS (CM2), TN (CM3), TP (CM4), EC (CM5), and Chl-a (CM6). The integrated model values were expressed as the sum of each area based on a star plot representing the integrated ecological health value. The area score enclosed by each star plot was used to compare the values of the reference site relative to their ecological health response to environmental conditions. The area score of the star plot was calculated using the approach described by Beliaeff and Burgeot [29] and Kim et al. [30]

Statistical Analysis

All data were statistically analyzed by discriminant function analysis, regression analysis, and Pearson's correlation analysis using the SPSS statistical package ver. 12.0 for Windows.

Results and Discussion

Water Chemistry and Relationship with Fish Composition

The N:P ratio, DTP, phosphate P, and SS in ambient water were determined and compared among the dominant fish species (Table 1). *Zacco platypus*, a dominant species in Korean watersheds [31], preferred a low N:P ratio (≤25), and the relative abundance of the fish was 37.5% under such conditions. In contrast, under an N:P ratio >25, the *Z. platypus* population accounted for only 14.3% of all fish. The relative abundance of *Pseudogobio esocinus*, which is an intermediate species in terms of tolerance and insectivore species, was 42.9% under an N:P ratio of 24.5.

Table 1. Relationships between the dominant fish species with trophic and tolerance guilds to the nitrogen-to-phosphorus (N·P) mass ratio, dissolved total phosphorus (DTP), phosphate phosphorus (PO_4-P), and suspended solids (SS).

Species	Tolerance guild	Trophic guild	N:P ratio		TDP			PO_4-P		SS	
			≤ 25	> 25	≤ 40 µg L⁻¹	> 40, ≤ 100 µg L⁻¹	> 100 µg L⁻¹	≤ 70 µg L⁻¹	> 70 µg L⁻¹	≤ 17 µg L⁻¹	> 17 µg L⁻¹
Zacco platypus	TS	O	37.5%	14.3%	0%	12.5%	75.0%	8.3%	100%	50.0%	11.1%
Opsariichthys uncirostris amurensis	TS	C	25.0%	0%	0%	25.0%	0%	16.7%	0%	0%	22.2%
Pseudogobio esocinus	IS	I	0%	42.9%	100%	0%	0%	25.0%	0%	50.0%	0%
Hemibarbus labeo	TS	I	0%	28.6%	0%	25.0%	0%	16.7%	0%	0%	22.2%
Other			37.5%	14.3%	0%	37.5%	25.0%	33.3%	0%	0%	44.4%

IS: Intermediate species, TS: Tolerant species, O: Omnivore, I: Insectivore, C: Carnivore

Compositional Changes in Fish Species

During the study, we collected 9 families and 23 species at the sampling site. *Z. platypus*, a typical lotic-type fish, dominated the community, with a relative abundance of 28.4% B_{wc}, which decreased by 35% A_{wc}. The rapid decline in *Z. platypus* was caused by the combined impacts of the disappearance of riffles, sediment dredging, and channelization for the weir construction, as the system changed rapidly from a lotic to a lentic system [32]. The *Z. platypus* population decreased from 375 individuals B_{wc} to 29 individuals A_{wc}. In contrast, the population of the lentic-type fish *Pseudorasbora parva* increased from 5 (range: 4-5) individuals B_{wc} to 16 (range: 0-30) individuals A_{wc}, and the relative abundance of *Carassius auratus*, a typical lentic-type fish, increased from 1.4 (range: 0-3.6)% B_{wc} to 5.1 (range: 0-10.4)% A_{wc}. Similar changes were

observed for *Cyprinus carpio*, a lentic species (Fig. 2). During the A_{wc} period, marked increases in lentic species and decreases in lotic species were apparent. This indicated that the simplification of trophic singularity due to the dominance of omnivorous and lentic-type fishes disturbed the ecosystem [33], as measured using the ecosystem health index [34] and fish compositional changes.

Compositional Modifications of Exotic and Endemic Species

A previous study conducted in the Geum indicated that no exotic species were present before the 1990s [35]. By contrast, exotic species were collected in this study, including *Carassius cuvieri, Lepomis macrochirus,* and *Micropterus salmoides*. The relative abundance of exotic species at the Sejong Weir was 0% B_{wc}; however,
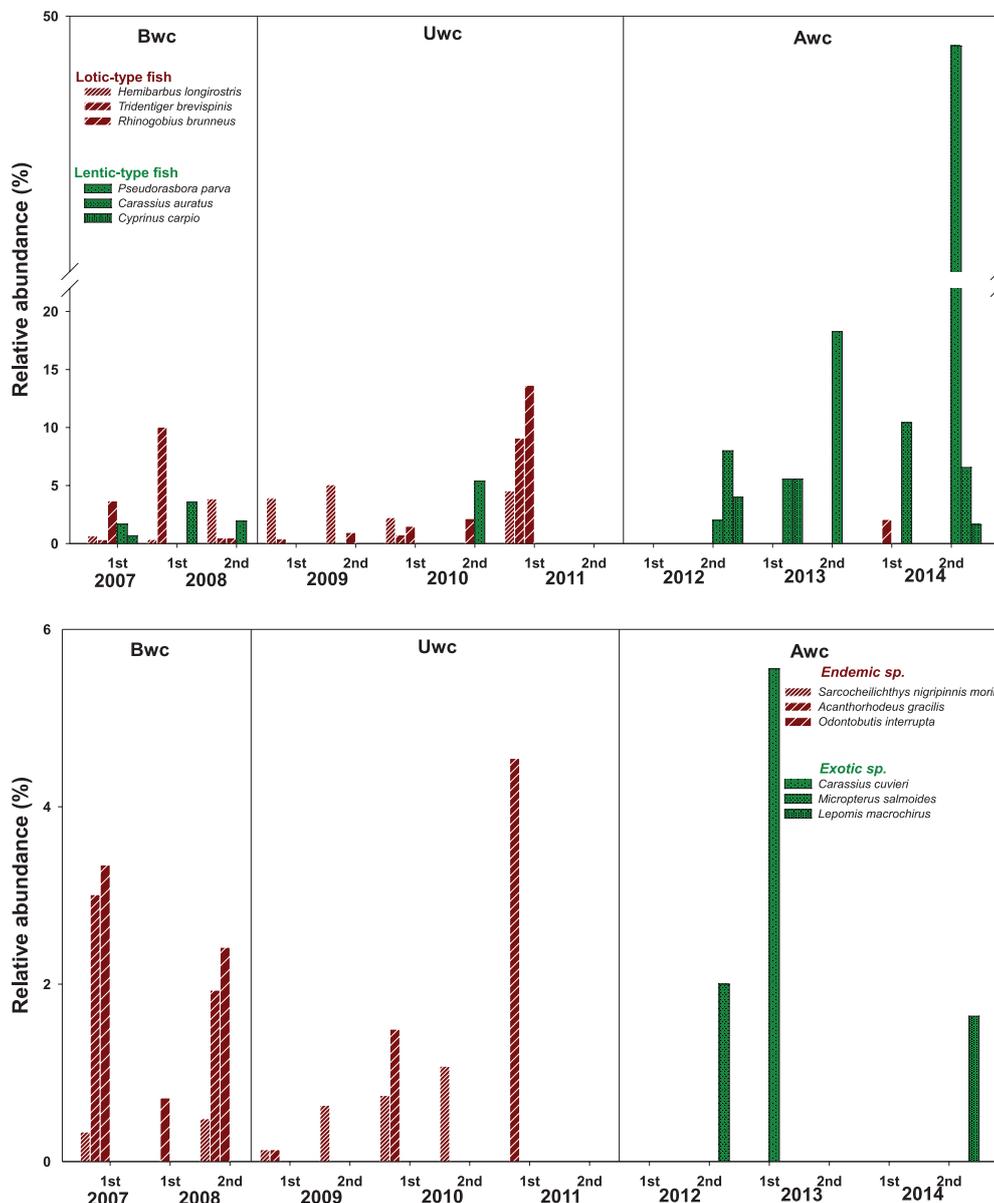

Fig. 2. Interannual fluctuations in the relative abundance of lotic-type versus lentic-type fish, and endemic versus exotic species.

Table 2. Biological health assessment using a multimetric fish model of the index of biological integrity before (B_{wc}), during (U_{wc}), and after (A_{wc}) weir construction.

| Category	Metric	Scoring Criteria			Bwc					Uwc					Awc				
		5	3	1	2007 1st	2008 1st	2008 2nd	2009 1st	2009 2nd	2010 1st	2010 2nd	2011 1st	2011 2nd	2012 1st	2012 2nd	2013 1st	2013 2nd	2014 1st	2014 2nd
Species richness & compositions	M₁ : Total number of native fish species	The expected values of M₁ – M₃ vary by stream size and region.			20	12	18	16	12	18	13	11	4	2	11	7	10	9	8
					(5)	(3)	(3)	(3)	(3)	(3)	(3)	(3)	(1)	(1)	(3)	(1)	(3)	(1)	(1)
	M₂ : Number of riffle benthic species				4	1	2	2	1	3	1	3	0	0	0	1	0	1	0
					(3)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
	M₃ : Number of sensitive species				2	1	1	1	0	1	2	1	0	0	0	1	1	0	0
					(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
	M₄ : Proportion of tolerant individuals	<5	5–20	>20	63.5	72.4	70.0	90.4	88.3	39.6	71.0	40.9	100	0.0	76.0	28.7	76.9	45.8	100
					(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(5)	(1)	(1)	(1)	(1)	(1)
Trophic compositions	M₅ : Proportion of omnivore individuals	<20	20–45	>45	55.2	69.5	63.8	84.9	32.7	23.1	32.3	40.9	6.7	1.5	58.0	33.3	49.0	29.2	65.6
					(1)	(1)	(1)	(1)	(3)	(3)	(3)	(3)	(5)	(5)	(1)	(3)	(1)	(3)	(1)
	M₆ : Proportion of native insectivore individuals	>45	45–20	<20	40.5	28.0	22.2	14.3	44.1	69.4	33.3	59.1	13.3	98.5	36.0	66.7	26.9	50.0	31.1
					(3)	(3)	(3)	(1)	(3)	(5)	(3)	(5)	(1)	(5)	(3)	(5)	(3)	(5)	(3)
Fish abundance & conditions	M₇ : Total number of native individuals	The expected values of M₇ vary by stream size and region.			299	279	207	742	315	134	93	22	15	68	49	17	104	48	60
					(3)	(3)	(3)	(5)	(3)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
	M₈ : Proportion of individuals with deformities, erosions, lesions, and tumors	0	0–1	>1	0	0	0	0	0.95	0	0	0	0	0	2	0	2.88	0	0
					(5)	(5)	(5)	(5)	(3)	(5)	(5)	(5)	(5)	(5)	(1)	(5)	(1)	(5)	(5)
	Total (Criteria)				22	18	18	18	18	20	18	20	16	24	12	18	12	18	14
					(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(D)	(C)	(D)	(C)	(D)
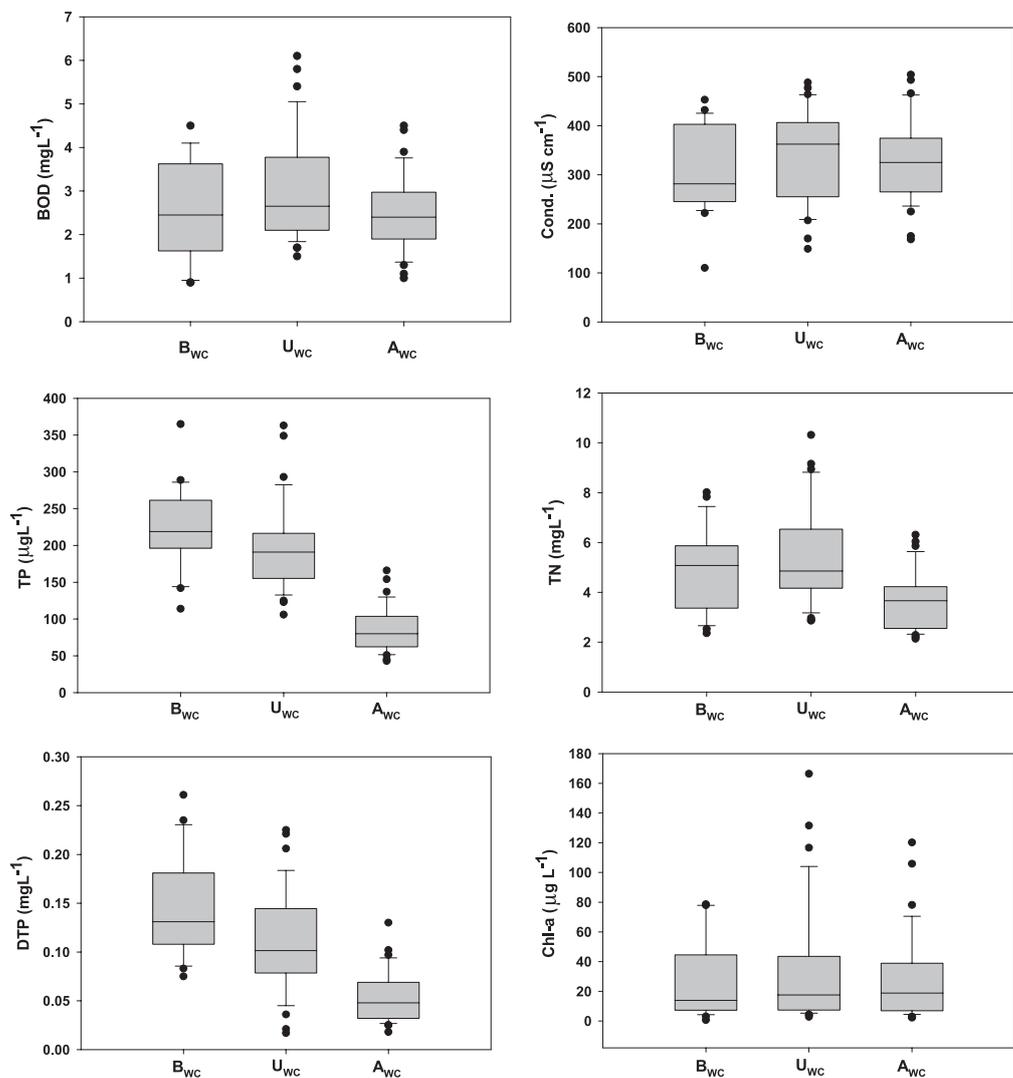
Fig. 3. Biological oxygen demand (BOD), electrical conductivity (Cond.), total phosphorus (TP), total nitrogen (TN), dissolved total phosphorus (DTP), and chlorophyll-a (Chl-a) before (B_{wc}), during (U_{wc}), and after (A_{wc}) weir construction.

the relative abundances of *L. macrochirus, M. salmoides,* and *C. cuvieri* were 1.6%, 2.0%, and 5.6%, respectively, A_{wc}. According to a previous study, the exotic species distribution in the river cannot be directly explained by water chemistry alone, and other environmental factors should be considered [36]. Therefore, we consider the cause of the increase in exotic species at the Sejong Weir to be a combination of water residence time and water quality deterioration [37, 38].

B_{wc}, we collected nine endemic species (e.g., *Acanthorhodeus gracilis, Odontobutis interrupta,* and *Pseudobagrus koreanus*). However, only five species were collected A_{wc}. The relative abundance of *Sarcocheilichthys nigripinnis* decreased from 7.4% B_{wc}

to 2.8% A_{wc}, that of *A. gracilis* decreased from 1.6% B_{wc} to 0% A_{wc}, and that of *O. interrupta* decreased from 2.2% B_{wc} to 0% A_{wc}. According to the Red Data Book of Endangered Fishes published by the International Union for the Conservation of Nature, *S. nigripinnis* and *Squalidus gracilis* were categorized as "near threatened" and "of least concern," respectively; however, they were not found during the A_{wc} period.

Results of the IBI Analysis

The IBI values at the Sejong Weir ranged from 12 to 24 in the watershed, depending on the sampling period, averaging 17.7 (n = 15) during the study (Table 2), and
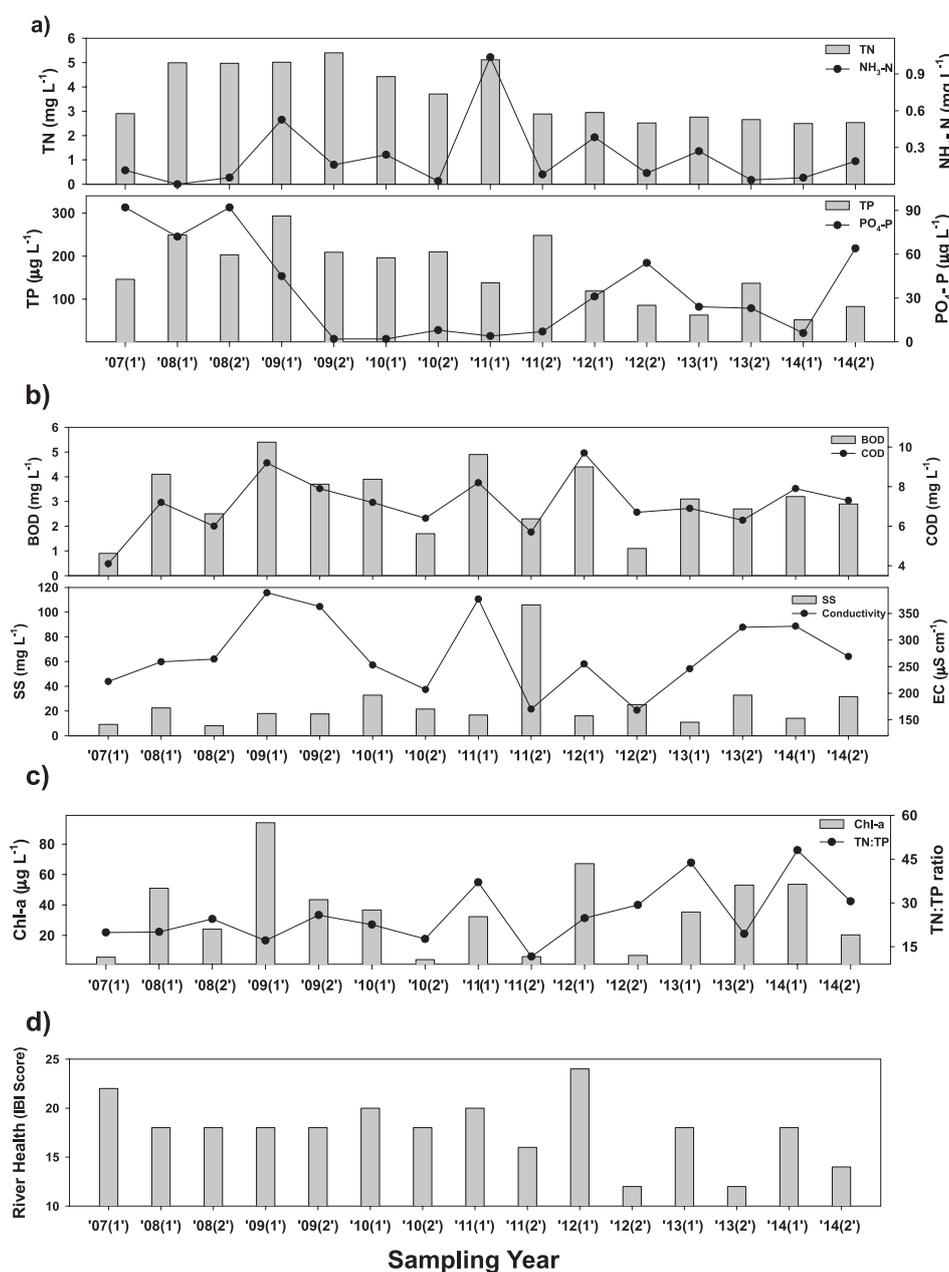

Fig. 4. Annual fluctuations in: a) nutrient regime, b) organic matter and other parameters, c) chlorophyll-a as a measure of primary production and N:P ratio, and d) biological river health based on the multimetric fish model during 2007-2014.

the ecosystem health was graded as condition C to D. Under such fair-to-poor conditions, species composition is generally dominated by low-sensitivity, highly omnivorous, and tolerant species [39, 40]. This trend in species composition and trophic guilds was evident in the present study. In particular, low-IBI values were observed during 2013-2014. Overall, fish habitats were considered to have been disturbed by weir construction. We speculate that ecosystem health degradation is highly associated with habitat conditions and chemical pollution [25, 41], although the flow volume in the stream is another important factor influencing biological

health. In the analysis of the metrics, the values of M2 (number of riffle benthic species) and M3 (number of sensitive species) averaged 1.1 and 1.0, respectively, which were particularly low among the metrics. This result indicates that riffle zones, composed mainly of pebbles and gravel, are absent or rare around the Sejong Weir.

Water Chemistry

As an indicator of organic matter pollution, the mean BOD showed no significant difference ($p>0.05$) from B_{wc} (2.53 mg L^{-1}, range: 0.9-4.5 mg L^{-1}) to A_{wc}
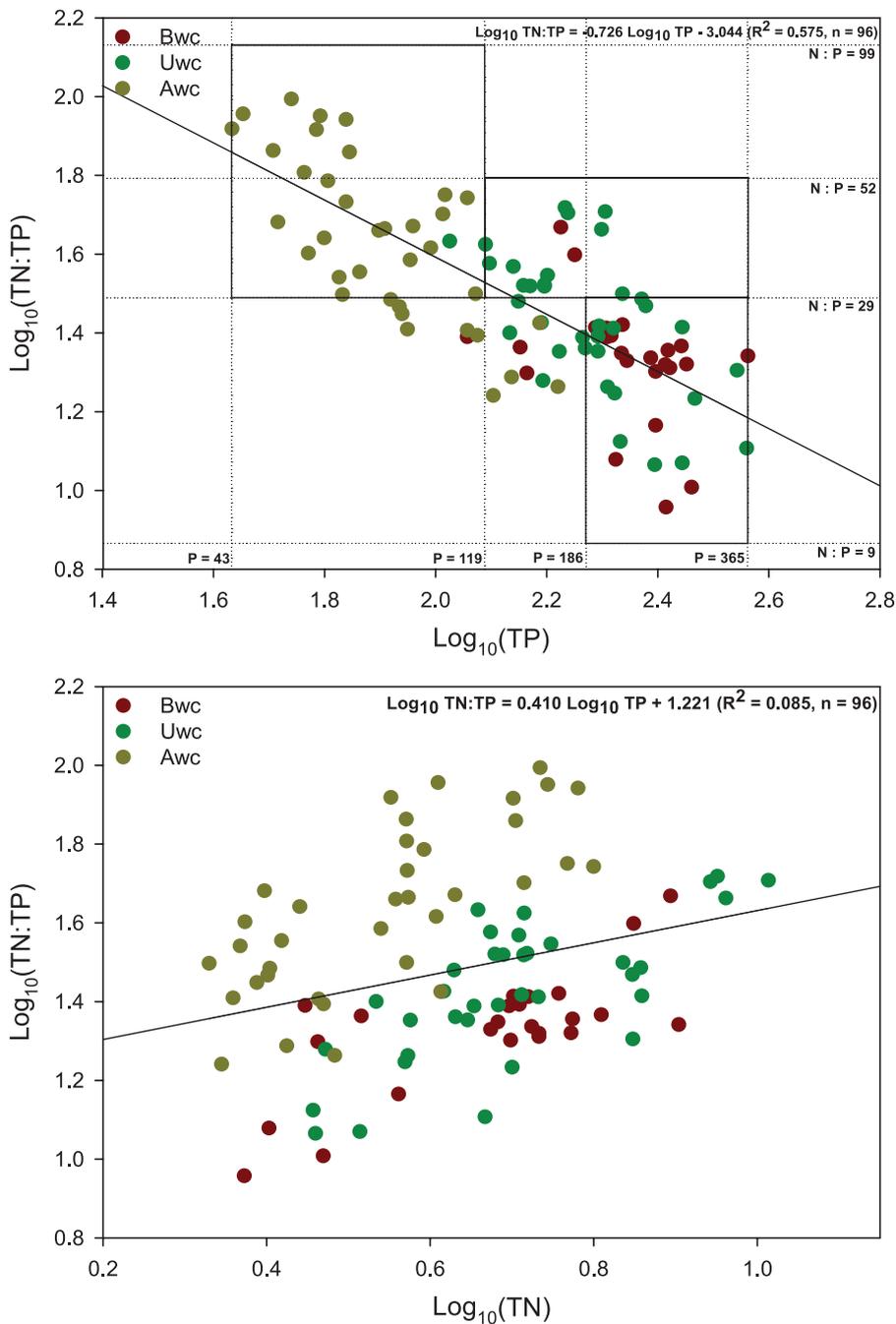

Fig. 5. Relationships between the log-transformed total nitrogen to total phosphorus (TN:TP) ratio and log-transformed TP and TN before (B_{wc}), during (U_{wc}), and after (A_{wc}) weir construction.

(2.50 mg L^{-1}, range: 1.0-4.5 mg L^{-1}; Fig. 3). EC showed a similar trend of 312.0 (range: 110-453 μS) cm^{-1} B$_{wc}$ versus 324 (range: 168–504) μS cm^{-1} A$_{wc}$ (Fig. 3). As an indicator of eutrophication or nutrient enrichment, the mean TP concentration decreased substantially from 226 (range: 114-365) μg L^{-1} B$_{wc}$ to 85.3 (range: 43-116) μg L^{-1} A$_{wc}$ (Fig. 3). The significant reduction in the mean TP was attributed mainly to sedimentation of particulate P due to the shift from a lotic to lentic waterbody [42]. Trophic state was determined based on the criteria of eutrophication established by the OECD [43], and both the B$_{wc}$ and A$_{wc}$ systems were categorized as hypereutrophic to eutrophic. DTP showed a similar trend as that of TP (Fig. 3). P is a key limiting factor that regulates algal growth in lentic ecosystems. The mean Chl-a level showed a similar pattern A$_{wc}$ (mean: 28 μg L^{-1}) in response to TP, and the mean Chl-a A$_{wc}$

was 26.4 (range: 2-120) μg L^{-1}, representing an "alert condition" in algal severity based on the Ministry of the Environment of Korea guidelines (Fig. 3). Meanwhile, long-term fluctuations in nutrient regimes were evident. The TN and TP concentrations decreased substantially (Fig. 4), and the N:P ratio increased, A$_{wc}$. Overall, these parameters indicated a worsening of biological river health after construction of the Sejong Weir (Fig. 4). By contrast, organic matter, measured as BOD and chemical oxygen demand, differed little between the two periods.

Relationship between the N:P Ratio and Nutrients

The annual mass ratio of TN:TP averaged 34.7 (range: 9.1 to 98.6) (Fig. 5), and variations due to

a)

Area score(ref.) = 0.83
Area score(this study) = 0.26

BM1 = Total number of native fish species

BM2 = Number of riffle benthic species

BM3 = Proportion of tolerant individuals

BM4 = Proportion of omnivorous individuals

BM5 = Total number of native individuals

BM6 = Proportion of individuals with deformities, erosions, lesions, or tumors

b)

Area score(ref.) = 0.65
Area score(this study) = 0.32

PM1 = Epifaunal substrate/available cover

PM2 = Embeddedness

PM3 = Velocity/depth combination

PM4 = Sediment deposition

PM5 = Channel alteration

PM6 = Frequency of riffles or bends

c)

Area score(ref.) = 0.37
Area score(this study) = 0.15

CM1 = Biological oxygen demand

CM2 = Suspended solids

CM3 = Total nitrogen

CM4 = Total phosphorous

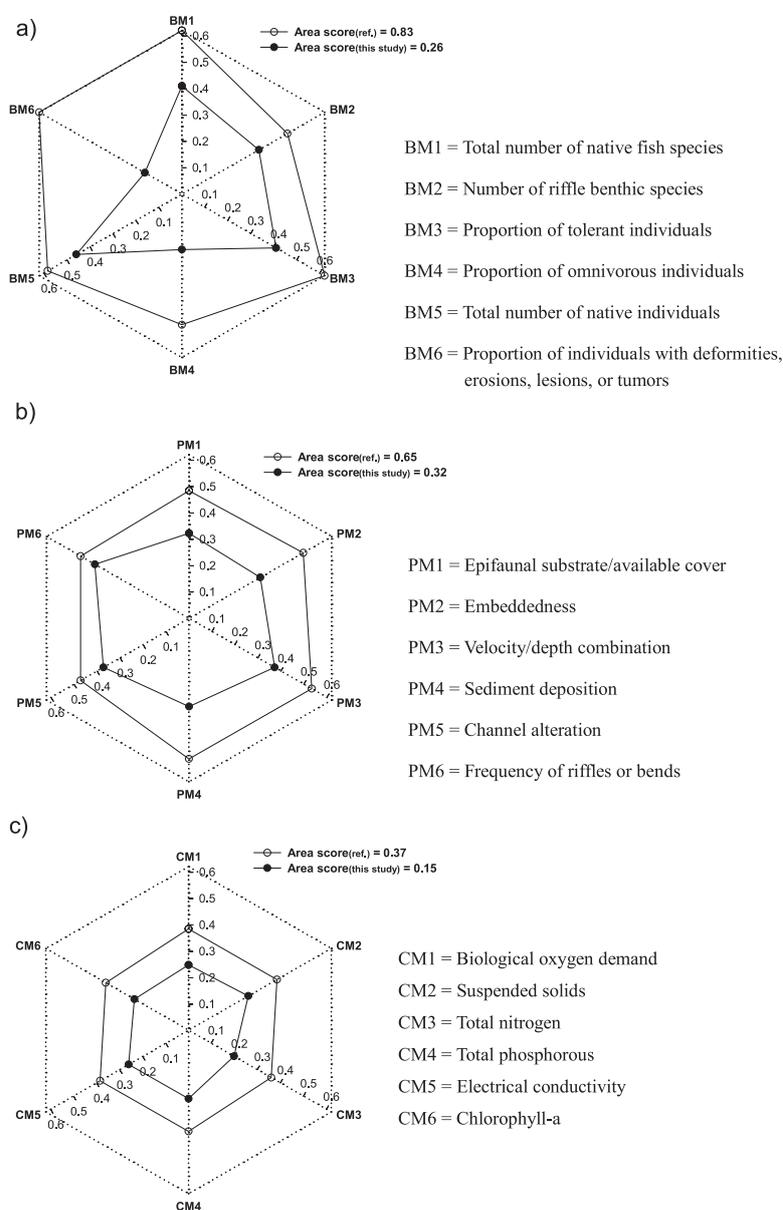CM5 = Electrical conductivity

CM6 = Chlorophyll-a

Fig. 6. Integrated a) ecological health assessments of biological (index of biological integrity), b) physical (qualitative habitat evaluation index), and c) chemical (water quality) health at the sampling site in relation to the reference site.

weir construction were evident. The mean ratios B_{wc}, U_{wc}, and A_{wc} were 22.6, 28.8, and 48.6, respectively. Forsberg [44] suggested that the effects of N limitation on phytoplankton growth occur at TN:TP ratios <10, whereas P limitation is common at TN:TP ratios >17. During the study, 91.7% of the total TN:TP ratio observations (n = 96) were >17 (Fig. 4), and 1% (n = 1) was <10. This suggested that P was a potential limiting factor of algal growth in the reservoir, and the degree of P limitation varied seasonally, which is common in Korean reservoirs. This is because seasonal rainfall fluctuates very much according to the Asian monsoon. The $\log_{10}(TP)$ values B_{wc} were generally >2.1, whereas most A_{wc} values were <2.1, showing distinct differences in TP. In addition, the mean $\log_{10}(TN:TP)$ differed significantly ($p<0.05$) B_{wc} (dark brown, Fig. 4) and A_{wc} (pale yellow, Fig. 4). Thus, the $\log_{10}(TP)$ and $\log_{10}(N:P)$ values showed distinct differences between the two periods, indicating a change in the nutrient regime due to weir construction. Empirical analysis of trophic variables (Fig. 5) showed that $\log_{10}(TN:TP)$ had a weak positive correlation ($p<0.005$, $R^2 = 0.085$, n = 96) with TN and a strong negative correlation ($p<0.001$, $R^2 = 0.575$, n = 96) with TP. This indicated that the N:P ratio was mainly regulated by variations in TP rather than TN (Fig. 5). The weaker correlation between the N:P ratio and N was probably attributed to the richness and lower variability in N relative to P in this system.

Integrated Ecological Health Assessments Based on Physical, Chemical, and Biological Metric Parameters

An integrated ecological health model based on the star plot approach was used to diagnose the overall ecological river health. The mean model values of integrated health were derived by integrating biological health using the IBI, physical habitat health using the qualitative habitat evaluation index, and chemical health using the nutrient pollution index. The area score of biological health in this study was 0.26, which was three times lower than that of the reference site (0.83) (Fig. 6). The difference was predominantly because the proportions of abnormal individuals and omnivorous species at the sample sites were significantly greater ($p<0.05$) than those at the reference site; the values of the axis of abnormal individuals and omnivorous species at the sampling site were 0.16 and 0.21, respectively. Regarding physical habitat health, all six values of the axis were ≥0.31, representing the largest area score compared with the chemical health and biological health scores, but the mean area score (0.32) was still approximately half that of the reference site (0.65). Chemical water quality health had the lowest mean area score (0.15), and the axis values of all parameters were similarly low, indicative of a substantial degradation of chemical water quality health.

Conflict of Interest

All the authors declare no conflict of interest.

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