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Article

Analysis of Key Environmental Variables Affecting Fish Communities and Species Distribution in Asian Lotic Ecosystems

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Abstract: In 2011, Korea installed artificial structures on four rivers to secure water resources and reduce flood damage; however, these structures have altered ecosystems and aquatic communities. This study analyzed fish communities and environmental variables at 72 sites in the Geumgang River. Fish communities and environmental variables before weir installation were examined using site data from 2008–2009. The results showed that Cyprinidae dominated the 70 observed species. A self-organizing map categorized the 72 sites into 4 groups based on fish communities. Sensitive and insectivorous species decreased, whereas tolerant and omnivorous species increased from Groups I to IV. Twenty-one indicator species were identified, with fewer and less distinct distribution patterns in Groups II and III than in Groups I and IV. The fish assessment index (FAI) showed a decline in grades A and B and an increase in grades C and D from Groups I to IV. Correlation analysis between FAI and environmental variables indicated that fish communities in the Geumgang River were mainly influenced by water quality, reflecting altitude gradients and pollution levels. This study's findings are anticipated to significantly inform water management strategies for the Geumgang, Yeongsangang, Nakdonggang, and Hangang Rivers.

Keywords: Geumgang; fish communities; fish assessment index; indicator species; freshwater ecosystems

1. Introduction

Freshwater ecosystems, which cover smaller areas than terrestrial or marine ecosystems, possess high biodiversity relative to their size [1]. Among freshwater ecosystems, including rivers, lakes, and wetlands, diverse aquatic organisms inhabiting rivers display variations in community structure up-, mid-, and downstream. These variations are influenced by naturally changing environmental variables and energy flows, as described by the river continuum concept (RCC) by Vannote et al. [2], even in the absence of anthropogenic disturbances [3]. Thus, rivers are considered ecosystems that contribute most to enhancing biodiversity within freshwater systems. In river ecosystems, fish species are critical because of 1) their sensitivity to anthropogenic disturbances affecting physical, chemical, or hydrological variables within the water body and 2) their role as higher trophic level consumers in the food web. The species composition of top predators in river ecosystems can reflect the diversity of their prey and represent the characteristics of the river to the local community, making fish an important bioindicator [4–6]. Ecological studies on freshwater fish in rivers have continuously focused on 1) the community structure within specific watersheds or tributaries [7–9] and 2) the development and improvement of biological integrity or health assessment methods [10–13]. Changes in the aquatic environments within river ecosystems affect fish habitats and spawning grounds. Recently, owing to increased social interest in environmental issues and the impacts of water withdrawal activities on humans, research on habitat suitability indices and the calculation of environmental flows has surged [14–16]. Additional studies have investigated the distribution and characteristics of protected species [17–19], species composition, community structure based on

environmental DNA [20,21], and the toxicological effects on fish exposed to pollutants such as microplastics [22,23].

In the Republic of Korea, water management is organized around four major watersheds: the Hangang, Nakdonggang, Geumgang, and Yeongsangang Rivers. Among these, the Geumgang River originates in Subun-ri, Jangsu-eup, Jangsu-gun, and flows into the Yellow Sea through the estuary between Seocheon-gun and Gunsan-si, making it the third-largest watershed after the Hangang and Nakdonggang Rivers. Pollutants from residential, agricultural, and industrial activities have degraded the water quality of the Geumgang River. Additionally, variations in water flow due to water resource management and the emerging impacts of climate change are affecting the aquatic communities inhabiting these areas [24–26]. The construction of three weirs—Gongju, Sejong, and Baekje—on the Geumgang River as part of the Four Major Rivers Project in 2011 aimed to secure water resources and mitigate flood damage. However, the transformation of fast-flowing habitats with distinct riffle or flow characteristics into slower, deeper water habitats, except for the central areas where flow is maintained, has shifted these areas to more lentic environments [26,27]. Such habitat changes have led to alterations in biological communities, with decreases in lotic species and increases in lentic or pollution-tolerant species, resulting in reduced species diversity [28–30].

Research on fish community structure within the Geumgang River watershed has been conducted in various areas, including the Chogangcheon [31], Gapcheon [32], and Mihocheon streams [33], Mangyeonggang River [34], and specific sections of the Geumgang River mainstream [28]. While this study on fish communities within the Geumgang River may be similar to previous studies, it is distinguished by its focus on the mainstream and major tributaries, as well as its analysis based on pre-weir construction data. Therefore, the results of this study are expected to serve as foundational data for future comparisons of the environmental and fish community changes resulting from weirs installed in the Geumgang River.

2. Materials and Methods

2.1. Study Area

The Republic of Korea is situated between 37°00' N latitude and 127°30' E longitude and experiences four distinct seasons owing to the combined influence of continental and maritime climates [35]. This geographic location results in summer monsoon precipitation accounting for approximately 60–70% of the annual rainfall. Floods occur frequently because of the intensity and frequency of precipitation during the monsoon season. Conversely, during winter and spring, except immediately after rainfall in autumn, river flow is mainly maintained by base flow, leading to significant changes in water width and a high coefficient of the river regime [36]. The Republic of Korea's land area is approximately 100,339 km², with low-altitude mountainous regions covering approximately 60% of the total land area [37]. The eastern part of the country is characterized by high-altitude mountains, resulting in steep slopes toward the east, while the western part gradually lowers into lowland plains, forming a topography of higher elevations in the east and lower elevations in the west [38]. Due to these topographical features, rivers in the Republic of Korea are predominantly formed in high- or low-altitude mountainous areas rather than on plains.

The Geumgang River, the subject of this study, has a length of 401 km and watershed area of 9,866 km² [27], making it the third-largest river system in the Republic of Korea. As it flows toward the west coast, the lower reaches exhibit characteristics of a brackish river. While the upper watershed is primarily forested, the mid- and downstream areas pass through urban regions dense with agricultural, livestock, and industrial activities (such as Daejeon, Sejong, Gongju, Nonsan, and Iksan), leading to increased pollutants and nutrients entering the water body. Consequently, organic pollution, nutrient levels, and conductivity rise [39,40].

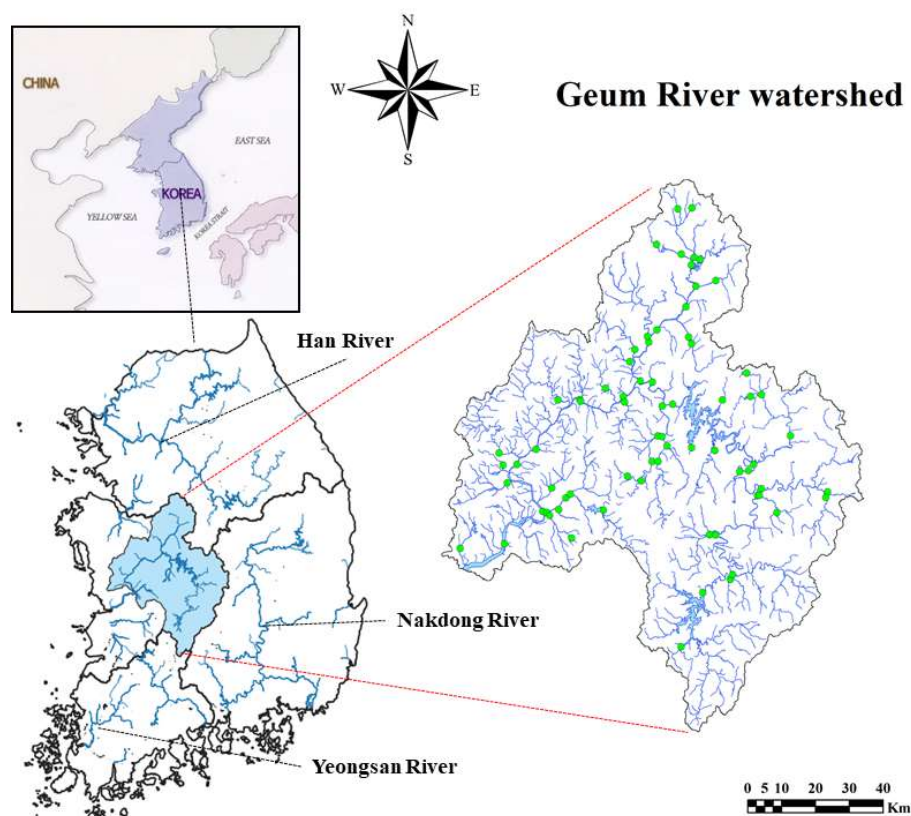


Figure 1. Location of the 72 sampling sites (green circles) in the mainstream and tributaries of the Geumgang River watershed. Thick black lines indicate the major river watersheds (Hangang, Nakdonggang, Geumgang, and Yeongsanggang). Thin blue lines indicate the main and tributary streams of each watershed.

2.2. Data Collection

The data used in this study were derived from the results of the “Nationwide Aquatic Ecological Monitoring Program” conducted by the Ministry of Environment and the National Institute of Environmental Research (NIER) during 2008–2009. Fish surveys and environmental variable measurements were performed following the methods described by MOE/NIER [41]. Among the surveyed sites in the 4 major river watersheds, 72 sites were within the Geumgang River watershed: 14 in the mainstream and 58 in its tributaries (Figure 1). Data from four sampling units per site yielded 288 samples. Before fish collection, nine environmental variables were measured at each site. The stream order was determined based on Strahler’s method [42] using a 1:120,000 scale map. Stream width was measured as the distance between banks using a laser distance meter (Bushnell Inc., Overland Park, KS, USA). The elevation was recorded at each site using a GPS unit (Triton 500; Magellan Inc., San Dimas, CA, USA). Biological oxygen demand (BOD₅), suspended solids (SS), total nitrogen (TN), and total phosphorus (TP) were analyzed in water samples collected at each site according to the water pollution process test standards [43]. Conductivity was measured using a multi-probe portable meter (YSI 6920; YSI Inc., Yellow Springs, OH, USA) or U-22XD water quality analysis system (Horiba, Kyoto, Japan). The environmental variables obtained were averaged for each site and used for analysis.

Fish were collected using cast (7 × 7 mm mesh; 10 throws at each site) and kick (5 × 5 mm mesh; 30 min at each site) nets within a 100-m section up- and downstream of each site, targeting multiple microhabitats. All collected fish were identified and immediately released back into the river sites. The total number of individuals captured by cast and kick nets was combined for the analysis. Fish were identified to the species level and further classified into three tolerance guilds according to the US EPA 1993 [44] and An et al. [45], as well as four trophic guilds based on the US EPA 1991 [46] and An et al. [45].

2.3. Data Analysis

To examine the biological similarities between the 72 sampling sites based on fish collected from the mainstream and tributaries of the Geumgang River, a self-organizing map (SOM) analysis was conducted. A SOM with a 9×5 output node grid was used to compare the frequency of the occurrence of fish species at each site. Following SOM analysis, cluster analysis based on the similarity of fish communities was performed to group the sampling sites. Fish community data from four surveys conducted at each site in 2008–2009 were combined for SOM analysis. One-way analysis of variance (ANOVA) was used to identify the key environmental variables that distinguished each cluster group based on the 72 biologically defined sites. The environmental variables used for the analysis were the average values for each site.

Indicator species analysis was used to identify potential indicator species for each cluster group based on their distribution weights. Species-specific indicator values for each group were calculated as the product of relative frequency and relative abundance, as proposed by Dufrêne and Legendre [47], and expressed on a scale of 0 to 100. However, as the number of surveyed sites and species increases, achieving an indicator value of 100 becomes challenging. Therefore, species with higher indicator values than those of other groups or rare species that did not appear in other groups were selected as representative indicator species for each cluster group. A Monte Carlo test was used to determine the statistical significance of the indicator values, and species that did not meet the statistical significance despite high indicator values were excluded from the candidate indicator species.

The health assessment of the rivers for each cluster group classified based on fish community similarity was performed using the fish assessment index (FAI) currently employed by the Nationwide Aquatic Ecological Monitoring Program [41] in the Republic of Korea. The FAI is a multi-metric index that evaluates river health based on eight metrics such as species richness, abundance, species composition, sensitivity, habitat, and feeding characteristics: M_1 , number of native species; M_2 , number of riffle-benthic species; M_3 , number of sensitive species; M_4 , Proportion of tolerant species; M_5 , proportion of omnivores; M_6 , proportion of native insectivores; M_7 , number of native individuals, M_8 , proportion of anomalies. It assigns differential index values according to the scale and stream order of the rivers, with the final assessment grade being the sum of scores for each metric. Pearson correlation analysis was conducted to estimate the key environmental variables influencing the fish community in the Geumgang River by examining the relationship between FAI and environmental variables at the 72 sites. The FAI calculated for each sampling unit was averaged for each site and was used in the analysis.

When conducting statistical analyses such as Pearson correlation and one-way ANOVA, which assume a normal distribution of the data, the raw data for biological or abiotic variables were transformed to follow a normal distribution.

The SOM analysis was performed using the SOM Toolbox package for MATLAB ver. 6.1. (MathWorks, Natick, MA, USA), indicator species analysis using PC-ORD (MjM Software, Gleneden Beach, OR, USA), and one-way ANOVA and Pearson correlation analysis using SPSS Inc. (Chicago, IL, USA). Statistical significance was determined at $p < 0.05$.

3. Results and Discussion

3.1. Overview of Environmental Variables at Sampling Sites

Before analyzing the fish community, we examined the distribution of environmental variables measured from the mainstream and tributary sites of the Geumgang River (Figure 2). Considering that this study targeted both the mainstream and tributary rivers of the Geumgang River, the sampling sites varied widely in terms of stream size, elevation, and pollution levels, ranging from small to large streams, high to low-altitude streams, and low to high pollution streams.

When the distribution characteristics of each variable were expressed using probability distribution models, stream order and width, which represent the stream size, showed different patterns. The stream order displayed a near-normal distribution, with most sites falling within the 3rd to 5th orders. In contrast, the stream width followed a positively skewed log-normal distribution, with many sites having widths less than 75 m. According to Kim et al. [37], most sites fell within the

transitional zone between small streams and large rivers based on stream order, whereas most sites were classified as small-scale streams (less than 75 m) based on stream width.

Altitude data, based on Min et al. [48], indicated that most sites were in the lowland category (below 150 m). BOD₅, SS, TN, TP, and conductivity also showed positively skewed log-normal distributions. Owing to the positive skewness, the modes of these environmental variables were lower than the mean and median, which were closer to the minimum values than to the maximum. This implies that while the surveyed sites generally had high stream orders, they were relatively small in size and low in elevation.

Based on the average values of each water quality variable, the organic pollution levels indicated by BOD₅ were assessed as β -mesosaprobic, according to Sládeček [49]. The trophic status based on TN and TP was determined to be eutrophic following the criteria of Dodds et al. [50]. According to the water quality standards outlined in the Enforcement Decree of the Framework Act on Environmental Policy in the Republic of Korea, the BOD₅ level was rated as slightly good (Grade II), whereas the TP level was rated as moderate (Grade III). This suggests that the nutrient status was higher than the organic pollution levels. The high background concentration of nitrogen due to intensive land use in the relatively small territory of the Republic of Korea [51], along with phosphorus inflow from agricultural lands, is considered to maintain high nutrient levels in rivers [52].

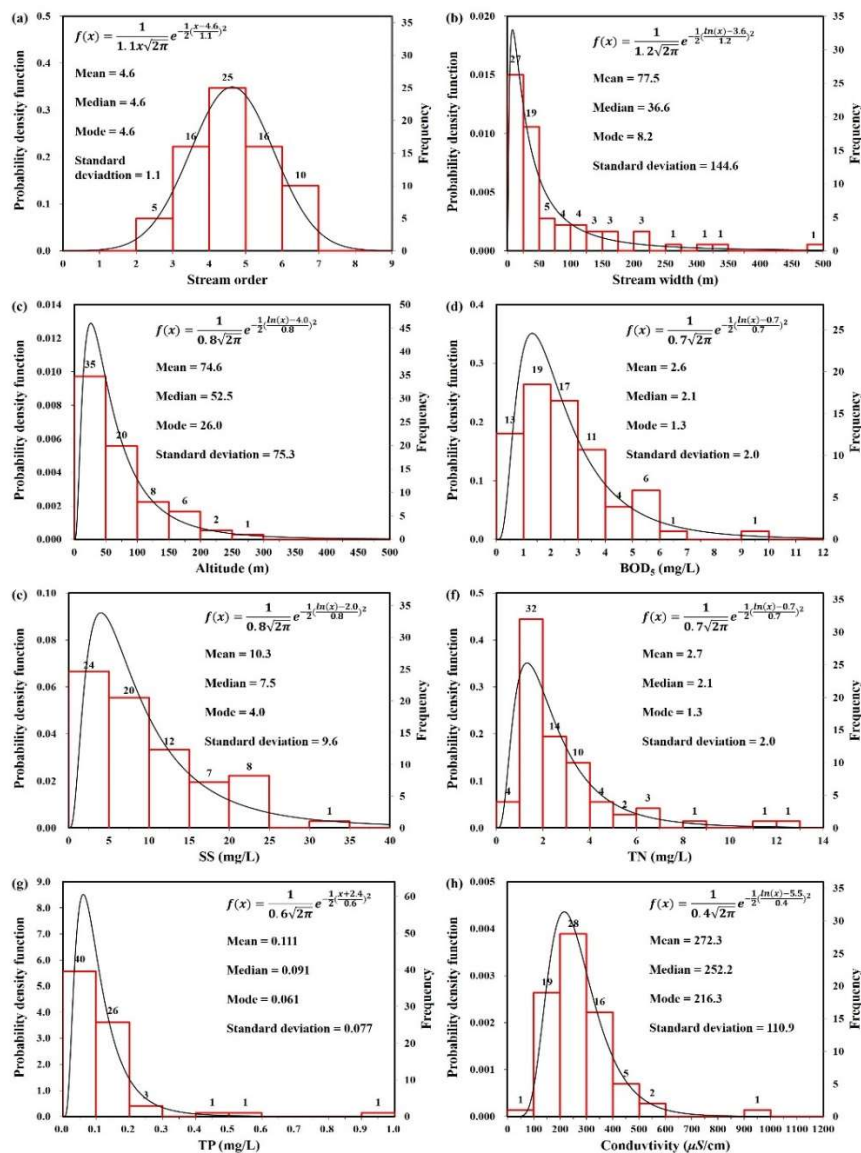


Figure 2. Distribution of each environmental variable at the 72 sampling sites based on log-normal or normal distributions of (a) stream order, (b) stream width, (c) altitude, (d) biological oxygen demand

5-day test (BOD₅), (e) suspended solids (SS), (f) total nitrogen (TN), (g) total phosphorus (TP), and (h) conductivity. Red quadrilaterals indicate the probability mass function, and black curves indicate the probability density function of each environmental variable. Numbers above the red bars indicate the number of sites in that range.

3.2. Fish Species Composition and Distribution Characteristics in the Geumgang River

During 2008–2009, 51,079 individual fish representing 70 species from 16 families were collected from 72 sites in the mainstream and tributaries of the Geumgang River. Among these, the family Cyprinidae (carp family) was the most diverse, comprising 39 species with the highest relative abundance (RA; 86.0%), indicating dominance in terms of individual numbers compared with other families (Figure 3). The high occurrence frequency and abundance of Cyprinidae can be attributed to several variables: 1) According to the 2023 National Species List of Korea (<https://species.nibr.go.kr/index.do>, accessed on June 25th), Cyprinidae includes 78 species, making it the second most species-rich family after Gobiidae (86 species); 2) Gobiidae species primarily inhabit brackish or marine environments, showing lower species diversity in freshwater; and 3) the surveyed sites often contained suitable microhabitats for diverse Cyprinidae species, such as riffles or runs with shallow depths and fast flow, and pools with riparian vegetation [53,54].

At the species level, the most frequently occurring species at the 72 sites were *Zacco platypus* and *Pseudogobio esocinus*, both found at 70 sites, followed by *Carassius auratus* (64 sites) and *Rhinogobius brunneus* (61 sites). These species are common throughout the Geumgang River watershed, indicating that they do not prefer specific habitats. In terms of individual numbers, *Z. platypus* was the predominant species with a RA of 34.9%, followed by *P. esocinus* (6.7%), showing a large difference in abundance between the pre- and subdominant species. The results regarding species frequency and RA were consistent with those from previous studies on fish communities and water quality in the Geumgang River watershed [29,40,55–57].

In the Republic of Korea, approximately half the country comprises mountainous areas; therefore, naturally formed lakes are few, but the stream ecosystems are well-developed, supporting diverse aquatic organisms and a high proportion of endemic species [24,26,58,59]. Thus, the presence and abundance of endemic species are indicators of habitat conditions, with their proportions sharply decreasing in degraded habitats [60,61]. In the present study, 27 endemic species (38.6%) were obtained, mostly from Cyprinidae, including *Squalidus japonicus coreanus*, *Zacco koreanus*, and *Hemiculter eigenmanni*, with a RA of 24.1%, indicating high endemic species occupancy.

Six legally protected species (8.6%) were identified: *Cobitis choii* (Natural Monument No. 454 and Endangered Species Class I; 3 tributary sites), *Pseudopungtungia nigra* (Endangered Species Class I; 13 sites in both the mainstream and tributaries), *Liobagrus obesus* (Endangered Species Class I; 1 mainstream site), *Gobiobotia nakdongensis* (Endangered Species Class I; 1 tributary site), *Gobiobotia macrocephala*, and *Gobiobotia brevibarba* (Endangered Species Class II; 4 sites in both the mainstream and tributaries). Among these, *P. nigra* and *C. choii* are representative endemic species of the Geumgang River, preferring riffle habitats with minimal water quality disturbances [18,62]. The RA of protected species was 0.7%, which was very low compared with the number of species.

Three alien species (4.3%) were identified: *Carassius cuvieri*, *Micropterus salmoides*, and *Lepomis macrochirus*. Among these, *M. salmoides* appeared at 50 sites, *C. cuvieri* at 17 sites, and *L. macrochirus* at 11 sites, indicating widespread distribution across the Geumgang River watershed. However, their RA was low (1.3%), considering that predation pressure and disturbance from alien species were not high at the sites (or habitats).

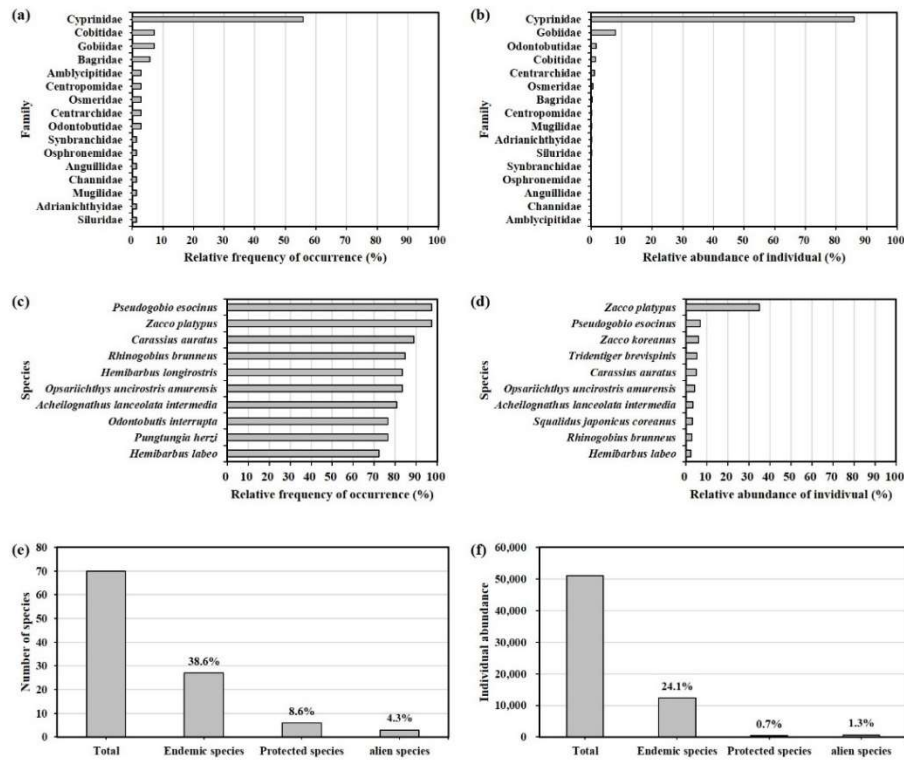


Figure 3. Composition at the family and species levels of fish at the 72 sampling sites and the occurrence of endemic, protected, and alien species. (a and b) Relative frequency and abundance at the family level; (c and d) Relative frequency and abundance at the species level for the top 10 species; (e and f) Occurrence according to species features. The percentages above the bars in (e) and (f) indicate the relative values.

3.3. Typology of Fish Communities in the Geumgang River Watershed Based on Species Composition

Based on SOM analysis, the 72 sampling sites in the Geumgang River watershed were classified into 4 Groups (I to IV) at a Euclidean distance level of 0.9, reflecting their biological similarities (Figure 4).

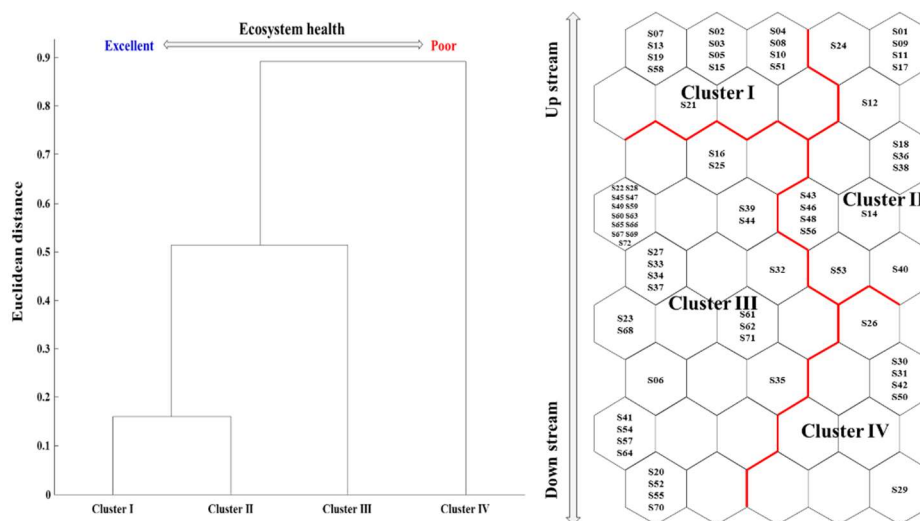


Figure 4. Self-organizing map (SOM) of the 72 sampling sites based on the Euclidean distance of the fish communities. Thick red lines represent the boundaries of each cluster group.

3.3.1. Characteristics of Environmental Variables in Cluster Groups

When examining the distribution of environmental variables by cluster group, the average values indicated that stream size increased in the order of Groups II, I, III, and IV, whereas altitude decreased in the order of Groups I to IV (Figure 5). Water quality variables generally tended to increase in the order of Groups I to IV. TN and TP showed the lowest mean in Group II, indicating a distribution trend opposite to that of stream size rather than altitude.

Sites classified under cluster Group I were mainly in the upstream reaches of the mainstream Geumgang River and major tributaries, including the Mujunamdaecheon, Yeongdongcheon, Chogangcheon, and Jicheon streams. These sites are characterized by high altitudes, with watershed land mostly consisting of forests, thus experiencing minimal anthropogenic physical and chemical disturbances. Although the mean stream order was not significantly different from that of the other groups, the range between the 25th and 75th percentiles was the widest, indicating a relatively diverse range of stream sizes. Cluster Group II comprised mostly of the mid-upper reaches of the tributaries. Compared with Group I, these sites were at lower altitudes but had the smallest stream size and minimal water quality disturbances from land use. Sites in Group II were closely related to Group I in terms of the fish community based on the Euclidean distance clustering analysis and exhibited minor differences in the fish community despite variations in stream size, elevation, and water quality.

Cluster Group III included the mid-lower reaches of the mainstream Geumgang River and tributaries, such as the Bonghwangcheon, Gilsancheon, and Nonsancheon streams. These sites showed neither large nor small stream sizes, low elevations, and increasing trends of organic and inorganic pollution and nutrient status due to higher agricultural land occupancy. Cluster Group IV encompassed the lower reaches of typical urban rivers, such as Gapcheon, Yudeungcheon, and Mihocheon streams. These sites are characterized by large stream sizes, low elevations, and high levels of anthropogenic disturbances.

One-way ANOVA showed significant differences in altitude, BOD₅, SS, and conductivity. However, the remaining four variables did not show significant results, with only variations in the values among the groups. These results suggest that fish communities inhabiting the mainstream and tributaries of the Geumgang River are primarily influenced by altitude and organic and inorganic pollution levels. Although nutrient status may be an important variable, its influence appears to be lower. Regarding conductivity, which typically shows significant changes when freshwater transitions to brackish water due to salinity [63], the significant increase in cluster Group IV sites likely reflects organic pollution and nutrient enrichment from agricultural and urban areas rather than salinity, as these sites are inland tributaries of the Geumgang River. These findings align with previous studies indicating increased pollution and nutrient levels in areas with intensive agricultural activities and higher conductivity in rivers passing through urban regions owing to pollutant inflows [39,52].

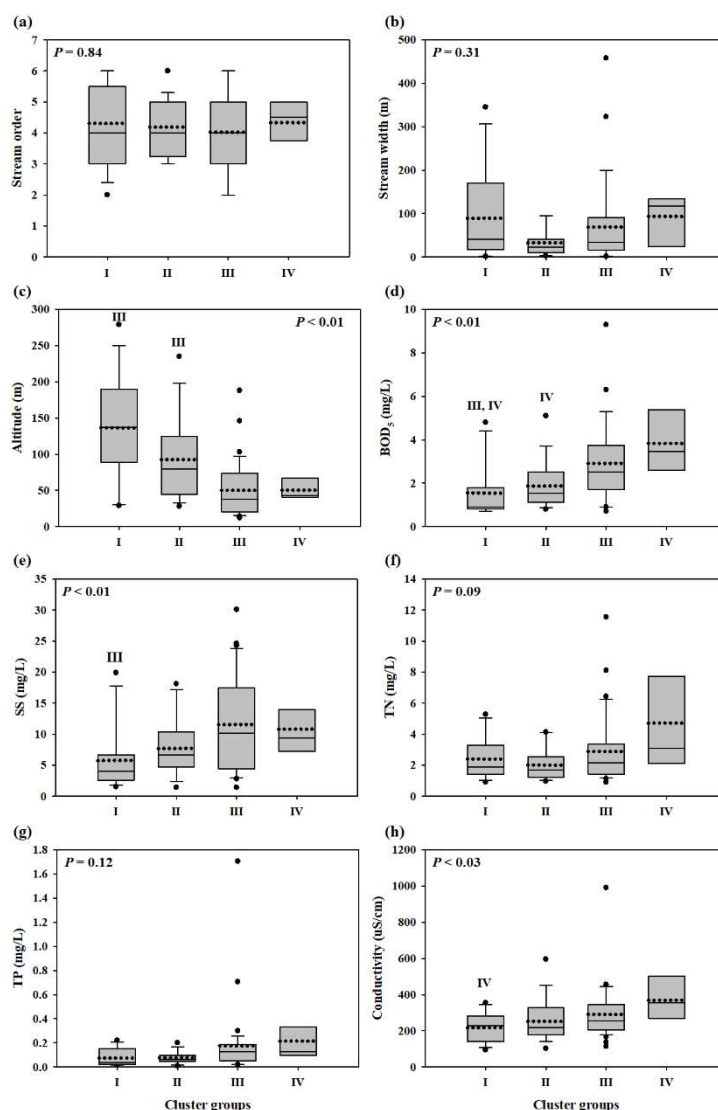


Figure 5. Distribution of each environmental variable in the self-organizing map (SOM) groups. (a) Stream order, (b) stream width, (c) altitude, (d) biological oxygen demand 5-day test (BOD_5), (e) suspended solids (SS), (f) total nitrogen (TN), (g) total phosphorus (TP), (h) conductivity. The boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles with standard deviations. The horizontal dotted and solid lines in each box represent the mean and median, respectively. The p -value for each environmental variable was derived by one-way analysis of variance (ANOVA), and Roman numerals above the outliers in each box indicate group differences by Bonferroni's post hoc test.

3.3.2. Distribution of Fish Community Metrics by Cluster Group

When selecting the top five species based on RA for each cluster group, *Z. platypus* was the predominant species across all groups, whereas the subdominant species varied by group (Table 1). Excluding *Z. platypus*, the species with high RA in each group were *Z. koreanus*, *Tridentiger brevispinis*, *Pungtungia herzi*, and *Acheilognathus koreensis* in Group I. *Z. koreanus* prefers riffles with fast flow and coarse particle substrates upstream with low water pollution. Given that the sites in cluster Group I are mostly small streams, this indicates suitable habitat conditions for *Z. koreanus* [60,64,65]. *P. herzi* also showed a high occurrence, as it prefers spawning habitats with coarse particle substrates, similar to *Z. koreanus*.

Species with a high occurrence in Group II included *P. esocinus*, *Z. koreanus*, *Acheilognathus lanceolata intermedia*, and *C. auratus*. Although *Z. koreanus* still had high dominance, its RA decreased. *P. esocinus*, *A. lanceolata intermedia*, and *C. auratus* prefer slower velocities and fine particle substrates

such as runs or riparian vegetation zones [32,55]. The proportion of tolerant species began to increase with higher organic pollution compared with that in Group I.

In Group III, species with high RAs were *T. brevispinis*, *Opsariichthys uncirostris amurensis*, *P. esocinus*, and *S. japonicus coreanus*. In Group IV, *C. auratus*, *P. esocinus*, *Hemibarbus labeo*, and *O. uncirostris amurensis* were highly abundant. Among these, *H. labeo* and *O. uncirostris amurensis* are tolerant species frequently found in the mid-lower reaches of rivers with high flow and deep water [28,29].

Based on the prevalent species, sensitive species (SS) were mainly *Z. koreanus*, found only in Groups I and II, which comprised several mid-to-upper stream sites. In contrast, Groups III and IV, which included more lower reaches of the main and tributary streams, had intermediate (IS) and tolerant (TS) species due to severe water quality disturbances caused by land-use activities. Regarding trophic guilds, insectivorous species (I) decreased from Group I to IV, whereas carnivorous (C) and omnivorous (O) species increased, indicating changes in major food sources corresponding to variations in stream size and function.

Table 1. The top five dominant species in each group in terms of relative abundance, tolerance, and trophic guild.

Cluster	Dominant species	Tolerance guild	Trophic guild	RA(%)
I	<i>Zacco platypus</i>	TS	O	36.7
	<i>Zacco koreanus</i>	SS	I	16.0
	<i>Tridentiger brevispinis</i>	IS	I	4.8
	<i>Pungtungia herzi</i>	IS	I	4.0
	<i>Acheilognathus koreensis</i>	IS	O	3.8
II	<i>Zacco platypus</i>	TS	O	33.7
	<i>Pseudogobio esocinus</i>	IS	I	10.3
	<i>Zacco koreanus</i>	SS	I	7.5
	<i>Acheilognathus lanceolatus</i>	IS	O	5.6
	<i>Carassius auratus</i>	TS	O	5.2
III	<i>Zacco platypus</i>	TS	O	35.5
	<i>Tridentiger brevispinis</i>	IS	I	8.2
	<i>Opsariichthys uncirostris amurensis</i>	TS	C	6.1
	<i>Pseudogobio esocinus</i>	IS	I	6.1
	<i>Squalidus japonicus coreanus</i>	TS	O	4.4
IV	<i>Zacco platypus</i>	TS	O	28.0
	<i>Carassius auratus</i>	TS	O	19.1
	<i>Pseudogobio esocinus</i>	IS	I	8.4
	<i>Hemibarbus labeo</i>	TS	I	6.7
	<i>Opsariichthys uncirostris amurensis</i>	TS	C	5.0

RA, relative abundance; SS, sensitive species; IS, intermediate species; TS, tolerant species; O, omnivores; C, carnivores; I, insectivores.

When analyzing the changes in fish communities in each cluster group, the number of species varied among sites, but the mean was similar across groups, ranging from 22 to 26 species (Figure 6). However, the number of individuals gradually decreased from Group I to IV, with a difference of approximately 200 individuals between the maximum (Group I) and minimum (Group III). This likely reflects the habitat conditions and fish sizes at the sampling sites. Upstream areas with low

flow, narrow water widths, and shallow depths tended to support small fish. In contrast, downstream areas with high flow, wide water widths, and deep depths tend to support larger species [2,54,58]. Therefore, despite the same sampling effort, the diversity of accessible microhabitats decreased in deeper, non-wadable streams. Additionally, the presence of large fish, which prefer solitary behavior, may result in high total biomass but a limited number of individuals collected [66].

In the tolerance guild classified by species sensitivity to organic pollution, the proportion of sensitive species decreased from Group I to IV, whereas that of intermediate and tolerant species increased, with larger changes in individual abundance than in the number of species. In the trophic guilds, based on the main food sources of species, the proportion of insectivorous species decreased from Group I to IV, whereas that of omnivorous species increased, again showing greater changes in individual abundance than in the number of species. According to Karr [11] and USEPA [44], the number and proportion of tolerant and omnivorous species increase because of the degradation of the physical and chemical components of the habitat, such as organic pollution, velocity reduction, and streambed disturbance. The fish community distribution patterns in Group IV, characterized by large river systems and significant water quality disturbances due to watershed land use, were similar to those found in previous studies on the Geumgang River [29,40,53].

Although tolerance and trophic guilds represent functionally different groups of fish, both guilds showed that sensitive species and insectivores decreased with lower altitude and higher water quality disturbances, whereas tolerant and omnivorous species increased. Among the fish observed at the 72 sites, 16 were sensitive, 28 were intermediate, and 26 were tolerant species. Sensitive species included 13 insectivores, intermediate species included 13 insectivores and 12 omnivores, and tolerant species included 13 omnivores. These findings suggest that sensitive-insectivores and tolerant-omnivores are more interdependent than the independent indicators of habitat change.

The changes in fish communities from up- to downstream follow the river continuum concept proposed by Vannote et al. [2], which explains the natural variations in fish size, biomass, habitat preferences, food availability, and temperature tolerance along a river's water course. This concept focuses on the functional changes in the river itself, such as increased size, decreased elevation, slower velocity, deeper water, and finer substrates from up- to downstream, and how these changes affect energy flow between producers and consumers. These environmental changes also affect freshwater invertebrate communities, which are higher-level taxonomic groups, including aquatic insects that serve as prey for insectivorous fish.

Upstream of Republic of Korean rivers, the EPT taxa (Ephemeroptera, Plecoptera, Trichoptera [67]), which are the main food sources for small fish, are abundant, whereas downstream, an increase in Mollusca, Annelida, and Crustacea, and a decrease in EPT taxa are observed [48]. The decrease in aquatic insects is also related to substrate composition, as freshwater invertebrates are highly influenced by substrate structure [51]. As substrates become finer, from sand or smaller particles, the abundance of burrowing species (e.g., Tubificidae, Ephemerae, Chironomidae) and collector-gatherers increases, whereas scrapers and collector-filterers, which prefer coarse substrates, decrease [37,48,68]. Therefore, unlike upstream fish that primarily depend on aquatic insects, downstream fish adapt by utilizing benthic organisms and organic matter in finer substrates or by feeding on other fish [54]. This suggests that the decrease in the proportion of insectivorous fish and the increase in omnivorous fish along the river's continuum is a natural phenomenon, even in the absence of anthropogenic disturbances. However, the results of this study indicate that the fish communities in the Geumgang River are significantly affected by water quality and physical disturbances from land use, in addition to natural functional changes in the river [40].

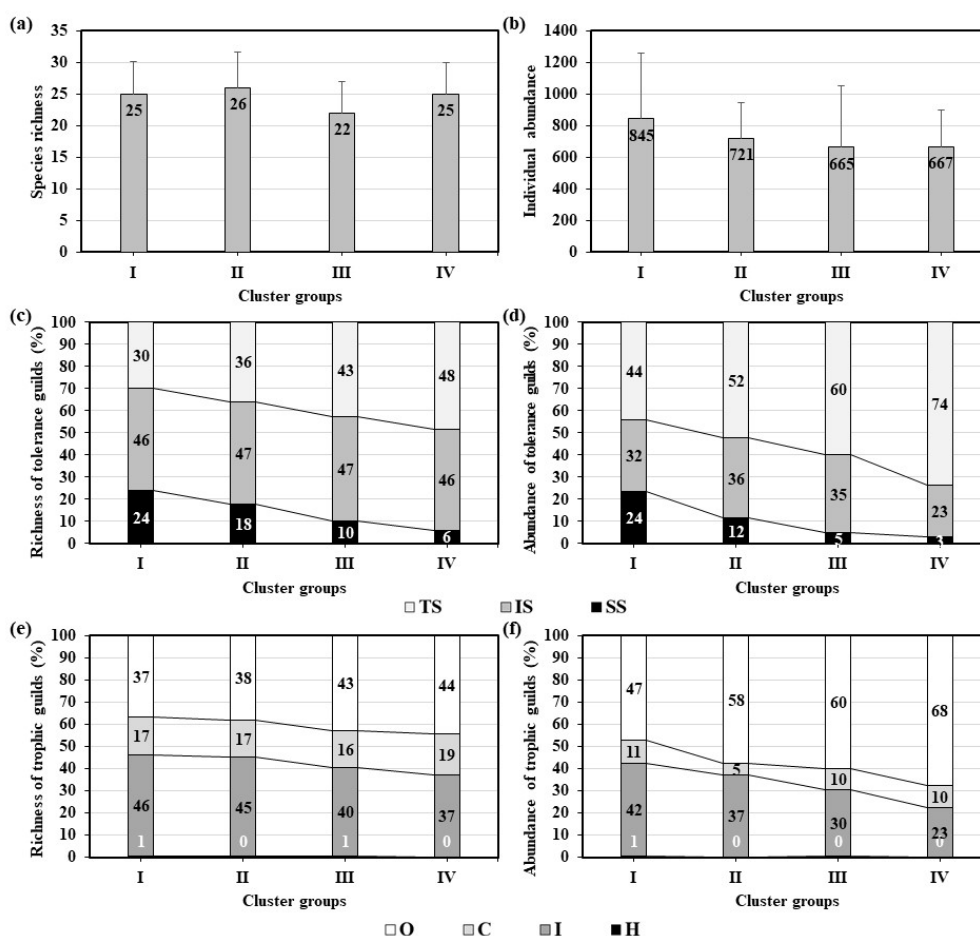


Figure 6. Changes in fish community in terms of (a) species richness (number of species), (b) individual abundance, percentage of tolerance guilds based on (c) species richness and (d) individual abundance, and percentage of trophic guilds based on (e) species richness and (f) individual abundance of each group. The numbers (black or white) in each bar graph are the values for each metric (mean or proportion), and TS, IS, SS, O, C, I, and H indicate tolerant species, intermediate species, sensitive species, omnivores, carnivores, insectivores, and herbivores, respectively.

3.3.3. Indicator Species Representing Cluster Groups

Indicator species analysis was conducted for all fish species observed in this study for each cluster group (Table 2). The analysis revealed the following: 1) Species showing a significant difference ($p < 0.05$) in frequency and occurrence within a specific group were considered representative species for that group, even if their indicator values were low; 2) A species appearing in a specific group was designated as a protected species and was selected as an indicator species if it had value as an indicator species, even if the indicator value was low and groups did not significantly differ. Based on these criteria, 21 out of 70 species (Cyprinidae: 13 species, Centrarchidae: 1 species, Odontobutidae: 1 species, Cobitidae: 2 species, Centropomidae, Siluridae, Channidae, Amblycipitidae: 1 species) were selected as indicator species representing the environmental characteristics of each group.

The selected indicator species were distributed as follows: 10 species in Group I, 2 species in Groups II and III, and 7 species in Group IV. Group I's representative indicator species included *Z. koreanus*, *A. koreensis*, *Coreoleuciscus splendidus*, *Acheilognathus majusculus*, *Odontobutis platycephala*, *P. nigra*, *Iksookimia koreensis*, and *Coreoperca herzi*. These species prefer small streams at high altitudes with coarse substrates, such as runs and riffles. Although *C. choii* and *L. obesus* had low indicator values and did not show significant differences from the other groups, they were selected as indicator species because of their status as protected species. Group I had the most indicator species among the four groups, including sensitive species, such as *Z. koreanus*, *C. splendidus*, *P. nigra*, *O. platycephala*, *C.*

herzi, *I. koreensis*, *C. choii*, and *L. obesus*, which were rarely found in Groups III and IV, indicating a clear preference for specific habitats.

The indicator values of most of the 11 species with the highest indicator values in Group II did not significantly differ from those of species in Groups I and III, depending on their frequency or abundance. Despite the high individual abundance of the protected species *G. macrocephala* and *G. brevibarba* at certain sites, their low frequency of occurrence resulted in low indicator values. Group II sites were mainly located in the middle and upper reaches of the tributaries of Groups I and III. The similarity of fish communities based on the water environment of Group II was not significantly different from that of Group I based on the cluster results. However, considering the concept of indicator species that considers both frequency and abundance, Group II is judged to correspond to the transitional zone between Groups I and III.

In Group III, the indicator species selected based on statistical differences in indicator values was *M. salmoides*, whereas the protected species *G. naktongensis* was selected because of its ecological importance. This means that some of the sites belonging to Group III were microhabitats based on a streambed structure centered on gravel (2–16 mm) or sand (0.063–2 mm), according to the standard of Cummins [69], and had slower velocities than that of riffles. This microhabitat composition was suitable for the habitat of *G. naktongensis*, but because the main indicator species was *M. salmoides*, most sites were judged to be severely affected by disturbance-causing species [70–72].

The indicator species in Group IV included *C. auratus*, *H. labeo*, *Gnathopogon strigatus*, *Cyprinus carpio*, *Erythroculter erythropterus*, *Silurus asotus*, and *Channa argus*. These species are typically found in urban streams and large rivers (non-wadable streams) and are highly tolerant to organic and inorganic pollution and high nutrient status. Among the seven indicator species, only *G. strigatus* is an intermediate species, whereas the remaining six species were tolerant species, with no sensitive species present. In terms of trophic guilds, the number of insectivorous species decreased, whereas that of omnivorous and carnivorous species increased.

Table 2. Species selected by indicator species analysis in each cluster group.

Species	Indicator values for each cluster group				p-value
	I	II	III	IV	
<i>Zacco koreanus</i>	49	12	4	0	0.001
<i>Acheilognathus koreensis</i>	44	10	1	0	0.006
<i>Odontobutis platycephala</i>	43	14	4	1	0.006
<i>Iksookimia koreensis</i>	38	19	6	0	0.015
<i>Pseudopungtungia nigra</i>	35	5	1	0	0.006
<i>Coreoleuciscus splendidus</i>	32	14	1	0	0.037
<i>Pungtungia herzi</i>	30	30	12	11	0.178
<i>Microphysogobio yaluensis</i>	30	22	8	11	0.129
<i>Acheilognathus yamatsutae</i>	29	12	1	0	0.021
<i>Hemibarbus longirostris</i>	28	26	17	16	0.331
<i>Coreoperca herzi</i>	27	8	1	0	0.049
<i>Sarcocheilichthys variegatus wakiyae</i>	23	7	3	0	0.128
<i>Rhodeus uyekii</i>	16	5	8	4	0.471
<i>Cobitis choii</i>	14	0	0	0	0.096
<i>Leiocassis ussuriensis</i>	11	1	1	0	0.261
<i>Rhodeus ocellatus</i>	9	1	0	0	0.407
<i>Plecoglossus altivelis</i>	8	3	1	0	0.555

<i>Liobagrus obesus</i>	8	0	0	0	0.291
<i>Rhynchocypris oxycephalus</i>	7	5	4	3	0.877
<i>Pseudobagrus koreanus</i>	23	30	4	9	0.096
<i>Rhinogobius brunneus</i>	19	28	18	24	0.366
<i>Pseudogobio esocinus</i>	23	27	21	27	0.419
<i>Zacco platypus</i>	26	26	22	24	0.598
<i>Siniperca scherzeri</i>	17	25	1	2	0.079
<i>Misgurnus anguillicaudatus</i>	21	25	9	18	0.448
<i>Squalidus gracilis majimae</i>	14	20	6	17	0.606
<i>Sarcocheilichthys nigripinnis morii</i>	7	15	9	12	0.747
<i>Cobitis nalbanti</i>	11	12	8	1	0.791
<i>Gobiobotia macrocephala</i>	1	9	0	0	0.356
<i>Gobiobotia brevibarba</i>	2	7	1	0	0.508
<i>Micropterus salmoides</i>	4	13	36	13	0.031
<i>Microphysogobio jeoni</i>	0	2	23	1	0.106
<i>Tridentiger brevispinis</i>	10	12	21	12	0.570
<i>Hemiculter eigenmanni</i>	4	4	20	8	0.290
<i>Squaliobarbus curriculus</i>	4	2	18	10	0.383
<i>Squalidus chankaensis tsuchigae</i>	4	2	18	13	0.459
<i>Lepomis macrochirus</i>	1	9	9	0	0.640
<i>Abbottina springeri</i>	1	4	6	0	0.783
<i>Hypomesus nipponensis</i>	0	0	5	0	0.723
<i>Oryzias sinensis</i>	0	0	5	0	0.719
<i>Mugil cephalus</i>	0	0	5	0	0.770
<i>Liobagrus mediadiposalis</i>	0	0	5	0	0.731
<i>Gobiobotia naktongensis</i>	0	0	3	0	1.000
<i>Rhinogobius giurinus</i>	0	0	3	0	1.000
<i>Gymnogobius urotaenia</i>	0	0	3	0	1.000
<i>Anguilla japonica</i>	0	0	3	0	1.000
<i>Leiocassis nitidus</i>	0	0	3	0	1.000
<i>Tridentiger obscurus</i>	0	0	3	0	1.000
<i>Monopterus albus</i>	0	0	3	0	1.000
<i>Silurus asotus</i>	5	7	1	51	0.004
<i>Erythroculter erythropterus</i>	3	2	5	42	0.008
<i>Carassius auratus</i>	10	20	21	41	0.001
<i>Cyprinus carpio</i>	1	9	12	41	0.010
<i>Hemibarbus labeo</i>	13	17	14	39	0.013
<i>Gnathopogon strigatus</i>	1	22	7	37	0.020
<i>Odontobutis interrupta</i>	21	24	10	32	0.106
<i>Pseudorasbora parva</i>	2	10	15	28	0.130
<i>Channa argus</i>	0	0	1	28	0.011

<i>Acheilognathus lanceolata intermedia</i>	15	23	19	27	0.391
<i>Pseudobagrus fulvidraco</i>	0	14	10	26	0.118
<i>Opsariichthys uncirostris amurensis</i>	14	21	22	26	0.633
<i>Misgurnus mizolepis</i>	4	22	4	25	0.148
<i>Carassius cuvieri</i>	0	8	6	25	0.081
<i>Squalidus japonicus coreanus</i>	12	16	17	23	0.520
<i>Acheilognathus macropterus</i>	2	4	9	17	0.365
<i>Acanthorhodeus chankaensis</i>	1	16	13	16	0.636
<i>Acheilognathus rhombeus</i>	2	12	8	15	0.520
<i>Macropodus ocellatus</i>	2	0	0	13	0.172
<i>Abbottina rivularis</i>	0	10	3	11	0.511
<i>Rhodeus notatus</i>	1	0	7	9	0.465

The bold text represents the species that were selected as indicator species based on the highest indicator value in each group and were statistically significant. Species marked in bold represent the indicator species selected for each group.

3.3.4. Biological Water Environment Assessment

Based on the mean FAI derived from the fish communities in each group, Groups I and II were assessed as grade B (good), whereas Groups III and IV were grade C (moderate). Despite having the same grade, FAI tended to decrease from Groups I to IV (Table 3). When examining the FAI results for each site within the same group, the proportion of sites rated as grades A and B decreased from Group I to IV, while the proportion of sites rated as grades C and D increased. The highest proportion of sites rated as E was found in Group III.

Among the FAI components, the metrics with significant variation between the groups were M₁ (6.5–8.4), M₃ (0.0–5.0), M₄ (7.0–11.4), and M₆ (4.4–7.2). However, the overall low values across all groups indicated that the major metrics contributing to the decline in FAI were M₂ (3.6–6.3), M₃ (0.0–5.0), M₅ (3.9–6.4), and M₆ (4.4–7.2). This suggests that as the environment changes from Groups I to IV, species that prefer riffles, are sensitive to disturbances, and primarily feed on aquatic insects decrease, whereas those with high tolerance and are omnivorous increase. Particularly, in Group IV, the M₃ component, which pertains to sensitive species, scored 0, the lowest score.

Table 3. Biological river health assessment based on the fish assessment index (FAI) for each group, scores for each FAI metric, and the proportion of each group by FAI grade.

Metrics	Mean ± SD (Scores)			
	Cluster I	Cluster II	Cluster III	Cluster IV
M ₁	9.4 ± 3.8	9.2 ± 4.2	6.5 ± 4.9	8.6 ± 4.0
M ₂	6.3 ± 4.5	6.3 ± 4.2	3.6 ± 3.9	4.2 ± 4.0
M ₃	5.0 ± 4.3	2.3 ± 3.9	1.0 ± 2.5	0.0 ± 0.0
M ₄	11.4 ± 3.4	10.3 ± 3.9	8.4 ± 4.9	7.0 ± 4.6
M ₅	6.4 ± 4.7	5.1 ± 4.1	4.4 ± 4.2	3.9 ± 3.6
M ₆	7.2 ± 5.0	6.4 ± 4.9	4.6 ± 4.9	4.4 ± 5.0
M ₇	9.5 ± 4.4	10.2 ± 4.1	7.6 ± 5.2	9.1 ± 4.1
M ₈	12.0 ± 2.4	11.9 ± 2.7	11.2 ± 3.8	12.5 ± 0.0
FAI	67.2 ± 21.3	61.6 ± 20.7	47.5 ± 22.4	49.8 ± 15.8
Grade	B	B	C	C

Cluster groups	Proportion of grades for FAI				
	A	B	C	D	E
I	36.6%	34.6%	21.2%	3.8%	3.8%
II	18.8%	39.0%	32.8%	4.7%	4.7%
III	4.1%	28.4%	37.7%	14.9%	14.9%
IV	-	20.8%	50.0%	25.0%	4.2%

SD: standard deviation.

To determine the environmental variables most closely associated with the FAI derived from the 72 sites, Pearson correlation analysis was conducted. The results indicated that altitude, BOD₅, SS, conductivity, TP, TN, stream width, and stream order were correlated with FAI in descending order of correlation strength (Figure 7). However, stream order and width showed a low correlation and were not significant. These results suggest that the fish communities in the Geumgang River are primarily influenced by differences in altitude and the intensity of water quality disturbances [39,52], with altitude and organic pollution having relatively large impacts. Conductivity typically varies significantly due to salinity, but because all sites were located inland, the high correlation with FAI likely reflects water quality disturbances from pollutants entering urban rivers [40].

Fish communities are influenced by various environmental variables, including stream size, altitude, substrate structure, and water quality [73–77]. Water quality is closely related to land use within the watershed [78–80]. Studies on the relationship between land use and water quality in the Geumgang River watershed have indicated that key chemical variables that determine the biotic community, such as BOD₅, TP, TN, and SS, are higher in areas with high proportions of agricultural or urban land use and lower in areas with high forest cover, which have fewer (non)point source pollutants [39,40]. Agricultural areas significantly impact nutrient status due to the use of fertilizers, whereas urban areas experience sharp increases in organic pollution and conductivity [52,80,81].

Historically, changes in fish communities along the longitudinal gradient of rivers have been explained primarily based on stream order and size in the absence of anthropogenic disturbances [2,82–84]. Similar to other studies [85,86], Republic of Korean rivers typically exhibit high fish diversity in the 3rd–5th order streams owing to microhabitat diversity. In streams below the 2nd order, limited environmental flow and monotonous microhabitats support communities dominated by a few pelagic and benthic organisms [54]. Thus, although the distribution of sensitive species may be higher upstream, the number of species is generally lower. Contrary to these general patterns, stream order showed minimal differences among the cluster groups based on the similarity of fish communities in the Geumgang River watershed and exhibited the lowest correlation with FAI among the eight variables. Urban streams, even those with low stream order, tend to be dominated by tolerant and omnivorous species such as *Z. platypus*, *C. auratus*, *C. carpio*, and *Misgurnus mizolepis* because of pollutant inflows [52,78], suggesting that water quality disturbances can significantly alter fish community composition regardless of stream size.

Altitude emerged as the variable most strongly correlated with fish community distribution and FAI among all environmental variables assessed in the current study. Altitude is generally associated with water temperature and influences the distribution of cold-water species [87–89]. However, the maximum altitude of the sampling sites was 300 m, which, according to Min and Kong [48], classifies them as highland and not mountain streams (>450 m). Therefore, in the present study, altitude likely reflects the longitudinal gradient of the river more accurately than stream order rather than influencing the distribution of cold-water species. Altitude thus serves as a multi-indicator variable reflecting the patterns of fish community distribution in response to changes in land use and water quality up- to downstream within the watershed [39,78,80].

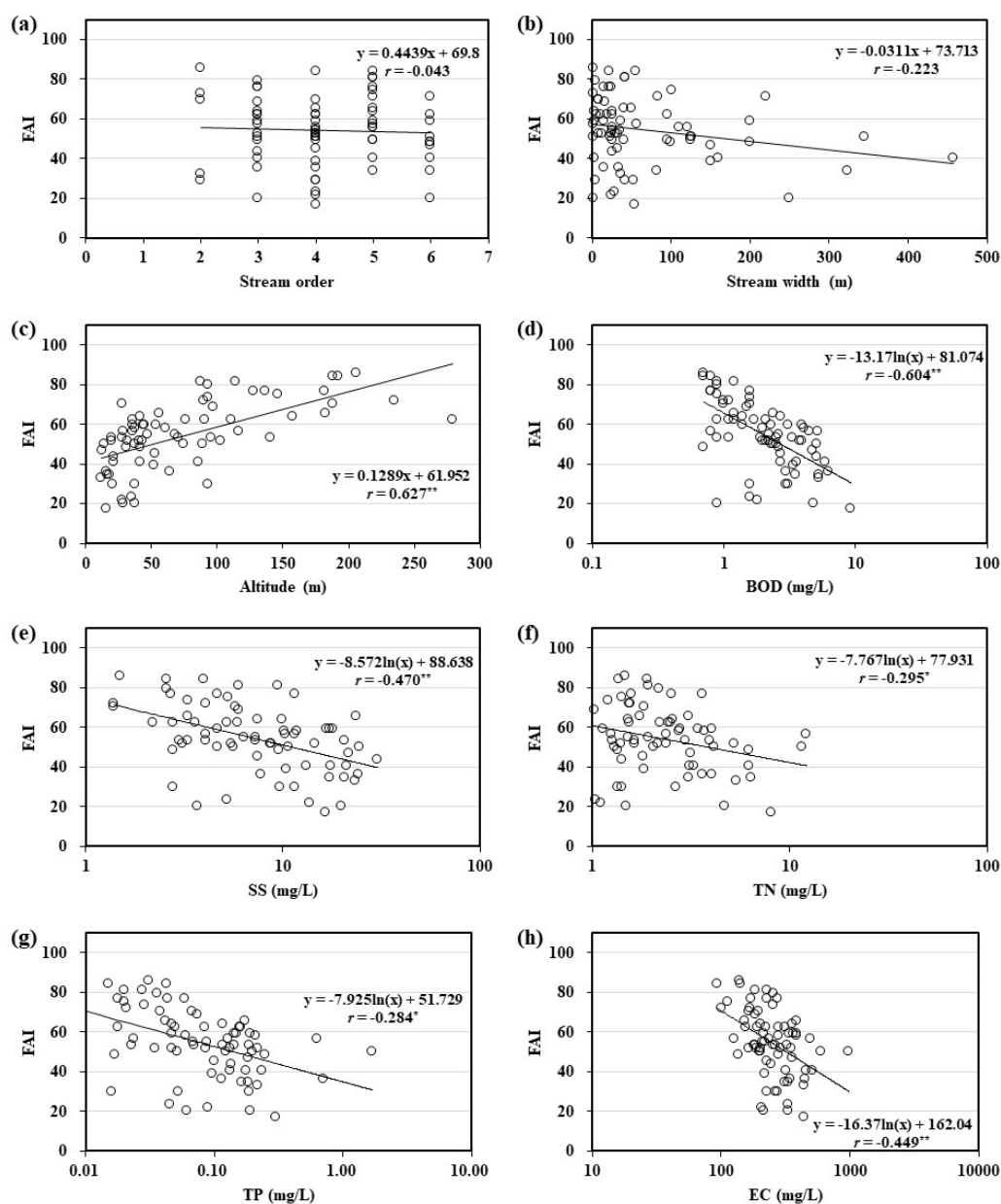


Figure 7. Relationship between fish assessment index (FAI) and (a) stream order, (b) stream width, (c) altitude, (d) biological oxygen demand 5-day test (BOD₅), (e) suspended solids (SS), (f) total nitrogen (TN), (g) total phosphorus (TP), and (h) conductivity (EC). r indicates the Pearson correlation coefficient between each variable and FAI, and the superscript symbol indicates the statistical significance of p -values less than 0.05 (*) or 0.01 (**).

4. Conclusions

This study analyzed the relationship between fish communities and environmental variables in mainstream and tributary sites of the Geumgang River from 2008 to 2009, before the installation of weirs. Although the elevation in the upper watershed was not high, high forest coverage resulted in good water quality. However, in the middle and lower reaches, the increasing proportion of agricultural land and urbanization led to a gradual deterioration in water quality. Across all sites, the background concentration of nitrogen was high, making the nutrient status relatively higher than that of organic pollution. In areas with intensive agricultural activity, the increase in nutrients such as TN and TP was pronounced, while rivers passing through urban areas showed marked increases in organic pollution and conductivity, indicating differences in the degree of disturbance caused by land-use factors. While both stream order and width can represent the size of a stream, the number

of sites in the transitional zone between small and large streams was high based on stream order, whereas many sites were classified as small streams based on stream width, indicating differences in scale depending on the variables used.

Zacco platypus was the most commonly found species throughout the Geumgang River basin, and species with high frequency and occurrence changed from sensitive-insectivores to tolerant-omnivores in response to changes in the aquatic environment. Although fish community changes are typically determined by scale and functional changes, such as stream order, the present study found that water quality disturbances played a major role. This trend was also observed in the evaluation of the biological health of rivers using FAI and the classification of fish communities into 1) tolerance guilds, 2) trophic guilds, 3) indicator species by cluster group, and 4) overall FAI.

Although FAI is a multi-metric index developed based on the scale of streams, its correlation with stream order was very low, whereas its correlation with BOD₅ was the highest. This indicates that water quality disturbances significantly affect fish community distribution. Generally, conductivity varies greatly with salinity, and elevation is closely related to water temperature, potentially affecting the distribution of cold-water species. However, the current study reflected the pollution gradient based on the longitudinal characteristics of the stream, suggesting that elevation may serve as a multi-indicator variable capable of determining fish communities and water quality variables.

The current study was conducted in the Geumgang River watershed; therefore, it may be important to conduct research on fish communities and environmental variables in each watershed and assess environmental management results for each watershed by comparing them with the current status.

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