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Spatial Analysis of Fish Diversity, Evenness, and Dominance During the Seasonal Transition Period for Ecosystem Health Assessment

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Abstract

Freshwater ecosystems, particularly small lakes, play a crucial role in maintaining biodiversity and supporting essential ecological functions, yet they are highly vulnerable to environmental disturbances. Small lakes are increasingly exposed to anthropogenic pressures such as land use change, nutrient enrichment, and declining water quality, making biological assessment essential for detecting ecosystem degradation. This study aimed to identify segment level patterns of fish diversity, evenness, and dominance during the seasonal transition period and to determine whether these patterns can distinguish relatively balanced ecological zones from priority stress zones for ecosystem management. An ecologically based quantitative descriptive approach was applied using spatial zoning of inlet, middle, and outlet segments. Fish assemblages were assessed using the Shannon–Wiener diversity index (H′), Evenness (E), and Simpson's dominance index (D). The results revealed clear spatial variation in community structure among sampling segments. Some systems exhibited strong internal ecological gradients characterized by decreasing diversity and increasing dominance toward downstream segments, whereas others showed more transitional or relatively uniform patterns. Community composition analysis indicated assemblage compression and potential biotic homogenization driven by a limited number of dominant taxa. Exploratory analyses further suggested that higher alkalinity, hardness, and chlorine levels were associated with lower diversity and greater dominance. These findings demonstrate that fish community indices provide effective biological indicators of ecosystem condition and can support spatially targeted monitoring, conservation, and management of small freshwater ecosystems. The study also highlights the importance of incorporating spatially explicit community assessments into ecosystem health evaluation frameworks.

Keywords: biological indicators; ecosystem health; fish community structure; freshwater acosystems; spatial assessment

INTRODUCTION

Freshwater ecosystems support a disproportionately high level of global biodiversity while providing essential ecosystem services, including water supply, nutrient cycling, fisheries, and climate regulation. Despite their ecological and socioeconomic importance, freshwater habitats are experiencing rapid degradation due to increasing anthropogenic pressures such as pollution, eutrophication, habitat fragmentation, hydrological alteration, and biological invasions (Dudgeon, 2019; Thierry, 2022; Sayer *et al.*, 2025). Among freshwater environments, small lakes are particularly vulnerable because their relatively limited water volume and restricted hydrological buffering capacity make them highly sensitive to environmental disturbances originating from surrounding catchments. Consequently, nutrient enrichment, sedimentation, and land-use changes can rapidly alter ecological processes, reduce biodiversity, and impair ecosystem functioning (Danurrachman *et al.*, 2023; Gu *et al.*, 2024; Tammeorg *et al.*, 2024).

The vulnerability of small lakes is especially pronounced in urban and peri-urban regions where rapid population growth and land use transformation intensify environmental stress. Increased runoff, domestic wastewater discharge, shoreline modification, and agricultural inputs frequently contribute to declining water quality and habitat degradation. Previous studies in Indonesia have reported substantial ecological changes in urban lakes, including eutrophication, declining water quality, and alterations in aquatic community composition associated with anthropogenic activities (Maresi *et al.*, 2020; Lanuza *et al.*, 2023). Similarly, investigations conducted in West Java and the Ciliwung watershed have documented considerable spatial and temporal variability in water-quality conditions, highlighting the need for effective monitoring approaches capable of detecting ecological degradation before irreversible ecosystem damage occurs (Dina *et al.*, 2022; Sulastri & Akhdiana, 2022). Therefore, reliable biological indicators are essential for supporting evidence-based conservation and management of freshwater ecosystems (Britton, 2022; Torralva *et al.*, 2023).

Fish communities are widely recognized as effective bioindicators of freshwater ecosystem health because they integrate environmental conditions over time, occupy multiple trophic levels, and respond sensitively to habitat alteration and water quality changes (Yang *et al.,* 2025; Djarang *et al.,* 2026). Ecological disturbances commonly result in shifts in fish assemblage structure characterized by reduced species richness, declining diversity, and increasing dominance of disturbance tolerant taxa (Britton, 2022; Gkenas *et al.,* 2024). Within the framework of biological integrity assessment, community-based metrics such as the Shannon–Wiener diversity index, Pielou's evenness index, and Simpson's dominance index provide complementary information regarding species composition, abundance distribution, and ecological balance (Prihatini, 2018; Gu *et al*., 2024). When applied together, these indices offer a comprehensive assessment of community structure and can reveal ecological changes that may not be apparent from physicochemical measurements alone.

However, freshwater ecosystems are inherently spatially heterogeneous. Environmental conditions often differ substantially among inlet, middle, and outlet sections due to variations in hydrological connectivity, nutrient inputs, habitat complexity, and human disturbance (Sulastri & Akhdiana, 2022; Thorø *et al.,* 2023). Consequently, assessments based solely on lake wide averages may overlook localized areas experiencing ecological degradation or, conversely, zones that continue to function as biodiversity refugia. Spatially explicit approaches are therefore necessary to identify ecological hotspots, understand within lake variability, and support targeted management interventions. Such approaches provide a more detailed understanding of how environmental gradients influence biological communities across different lake zones. They also facilitate the detection of site specific ecological pressures that may not be apparent in broad scale assessments. Furthermore, incorporating spatial variation into ecosystem evaluations can improve the accuracy of conservation planning and enhance the effectiveness of lake management strategies aimed at maintaining ecological integrity and biodiversity (Larentis *et al*., 2022; Gu *et al.*, 2024).

Although numerous studies have examined fish diversity, invasive species occurrence, and ecological conditions in Indonesian freshwater ecosystems, most have focused on species inventories, individual lakes, or overall community indices without integrating spatial zonation and ecosystem health assessment within a unified framework (Prihatini, 2018; Tambunan *et al.*, 2021; Gustiano *et al.*, 2023; Nurfadillah *et al*., 2025). Existing studies have rarely combined inlet–middle–outlet spatial analysis, diversity–evenness–dominance metrics, native versus alien fish composition, and physicochemical gradients across multiple lakes simultaneously. As a result, knowledge remains limited regarding how fish community structure varies spatially within and among small urban lakes and how these patterns can be translated into practical ecosystem health indicators.

To address this knowledge gap, the present study investigated fish community structure in Tonjong lake, Tunggilis lake, and Suradita lake using a spatially explicit approach based on inlet, middle, and outlet zonation. In addition, the relationship between fish community patterns and selected physicochemical characteristics was examined to better understand the environmental factors influencing fish assemblages across different lake zones. The findings are expected to contribute to the development of fish-based ecosystem health assessment frameworks and provide practical information for freshwater conservation and sustainable lake management in Indonesia. The aim of this study was to evaluate the spatial variation of fish diversity, evenness, and dominance during the seasonal transition period as indicators of ecosystem health and to identify lake segments that may function as ecological refugia or priority stress zones.

METHOD

This study employed an ecologically based quantitative descriptive approach to evaluate fish community structure as an indicator of ecosystem health in three small lakes in West Java, Indonesia, namely Tonjong lake, Tunggilis lake, and Suradita lake. The locations of the study lakes are presented in Figure 1. A quantitative descriptive approach was selected because it enables the systematic measurement and comparison of biological community attributes across different spatial units while providing an objective basis for ecosystem assessment (Magurran, 2021; Sayer *et al.*, 2025). The approach was further considered appropriate because fish assemblages integrate environmental conditions over time and provide reliable biological indicators of freshwater ecosystem quality (Magurran, 2021; Larentis *et al*., 2022). A spatial zoning design was applied by dividing each lake into three ecological segments representing the inlet, middle, and outlet areas. This zoning framework was used to capture spatial heterogeneity within each lake and to assess how fish community characteristics vary among ecological segments. Therefore, segment-based analysis provides a more detailed assessment of ecosystem condition than evaluations conducted at the whole lake scale.

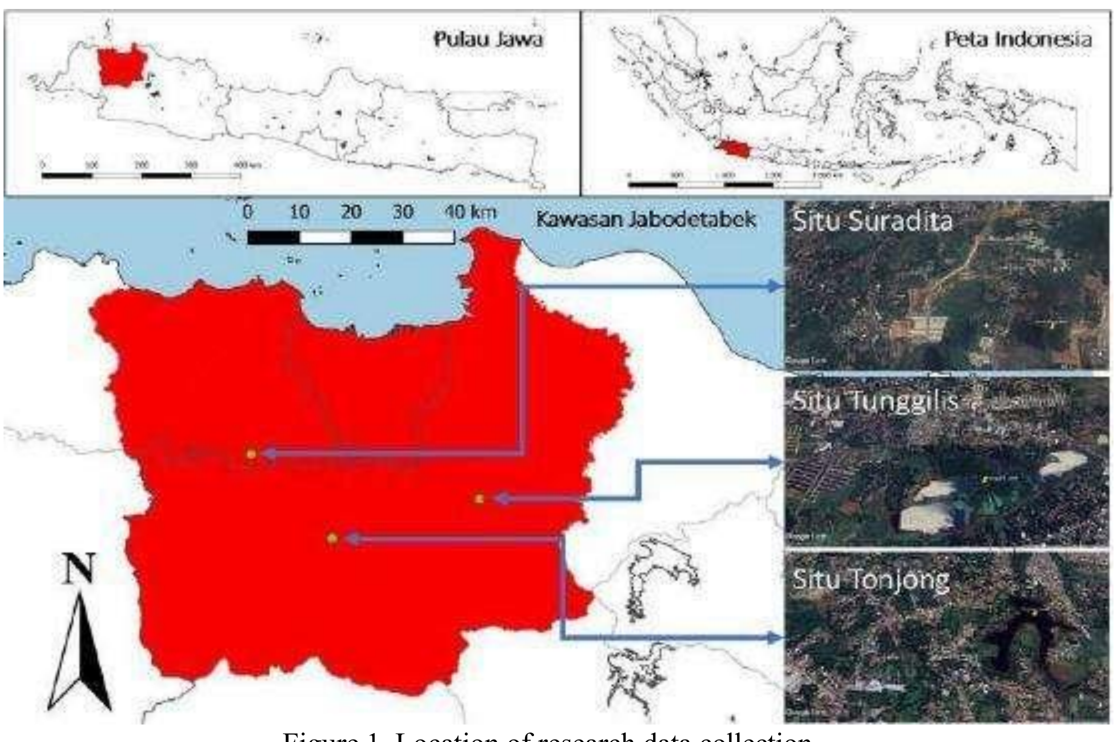


Figure 1. Location of research data collection

The study was conducted during the seasonal transition period. Each lake was divided into three sampling segments (inlet, middle, and outlet), and three plot-level replicates were established within each segment, resulting in a total of 27 sampling units (3 lakes × 3 segments × 3 replicates). Each sampling plot covered an area of approximately 60 × 20 m, adjusted according to shoreline morphology and field accessibility. The zoning system was designed to capture potential ecological gradients associated with water flow, habitat characteristics, and varying levels of anthropogenic influence. The seasonal transition period was selected because fluctuations in hydrological conditions during this time may influence fish distribution and community structure across lake segments. The use of replicated sampling units within each segment was intended to improve data reliability and reduce the influence of local scale variability on ecological assessments.

The research focused on fish communities inhabiting the three lakes. Study sites were selected using purposive sampling based on their ecological characteristics and differences in environmental pressure. Fish sampling was conducted using a combination of umbrella traps, cast nets, and traditional fishing lines to maximize species detection across different habitat types and microhabitats. Sampling effort was standardized among segments as much as possible with respect to sampling duration, gear deployment, and observation procedures. Sampling activities were carried out between 10:00 and 15:00 Western Indonesian Time. All captured individuals were counted, identified to species level, and morphologically documented. Species identification was conducted using standard ichthyological references and verified through the FishBase database.

Water quality measurements were conducted simultaneously with fish sampling to provide environmental context for community assessment. The measured parameters included Dissolved Oxygen (DO), water temperature, pH, Total Dissolved Solids (TDS), ammonia (NH_3), nitrite (NO_2), nitrate (NO_3), carbonate hardness (dKH), total hardness, and chlorine. Measurements were taken in each sampling segment using portable water quality instruments and test kits following standard field procedures. Fish community structure was assessed using the Shannon–Wiener diversity index (H′), Pielou's evenness index (E), and Simpson's dominance index (D) (Magurran, 2021). To further characterize assemblage composition, relative abundance and relative frequency were calculated for each species. Relative abundance was used to determine the proportional contribution of species to total fish abundance, whereas relative frequency was used to evaluate the consistency of species occurrence among sampling plots.

Spatial patterns of fish community structure were examined descriptively through comparisons among inlet, middle, and outlet segments and among lakes. Segment-based ecological profiles and spatial visualizations were generated to identify potential ecological refugia and priority stress zones. In addition, chi square analysis was applied to evaluate differences in native and alien fish composition among sampling zones. Exploratory simple linear regression analyses were performed to examine relationships between fish community indices (H′, E, and D) and selected physicochemical variables. These analyses were intended to determine whether variations in environmental conditions were associated with observed differences in fish-community structure across sampling segments. All analyses were conducted using Microsoft Excel and statistical software packages, and results were interpreted at a significance level of $\alpha = 0.05$.

RESULT AND DISCUSSION

Tonjong lake is located in Bojonggede District, Bogor Regency, West Java Province, Indonesia, and represents a small freshwater lake within an increasingly urbanized landscape. The geographical locations of the three study lakes, namely Tonjong lake, Tunggilis lake, and Suradita lake, are presented in Figure 2. The lake covers approximately 7.65 ha and is characterized by an irregular shoreline with four distinct embayments. Based on regional topographic data, the lake is situated at an elevation of approximately 130–180 m above sea level (masl). Water depth varies across the lake, with a maximum depth of about 5.7 m and an average depth of approximately 2.0 m, resulting in an estimated water volume of 152.982 m^3. Its relatively shallow morphology promotes frequent water column mixing, which may influence nutrient distribution, primary productivity, and overall limnological processes. However, the ecological condition of the lake is potentially affected by anthropogenic pressures from the surrounding watershed, including residential development, agricultural activities, and domestic waste inputs that may contribute to water quality degradation.

Figure 2. Condition of Tonjong, Tunggilis and Suradita Lakes

Tunggilis lake is located in Situsari Village, Cileungsi District, Bogor Regency, West Java Province, Indonesia, and is one of the largest small lakes in the study area. The lake covers approximately 35–35.5 ha and is situated at an elevation of about 263.15 m above sea level. Water depth reaches a maximum of 15.7 m, with an average depth of approximately 3.9 m, resulting in an estimated water volume of around 1.4 million m^3. The lake serves multiple ecological and socio economic functions, including water storage, water resource provision, fisheries, and recreational activities for local communities. Aquatic macrophytes, including lotus (*Nelumbo nucifera*), are distributed across several parts of the lake, contributing to habitat heterogeneity and providing refuge for aquatic organisms. However, the lake is subject to increasing environmental pressures, including waste inputs, excessive growth of aquatic vegetation, and land use changes within the surrounding catchment area, all of which may influence local water quality and ecosystem condition.

Suradita lake is located in Suradita Village, Cisauk District, Tangerang Regency, Banten Province, Indonesia. The lake originated partly from a former sand mining area that subsequently developed into a permanent freshwater body. Currently, it is utilized for fish farming activities and community-based ecotourism. The lake covers an estimated area of approximately 25–30 ha and is situated in a lowland region at an elevation of about 40–50 m above sea level. Water depth varies considerably, with a maximum depth of approximately 20.7 m and an average depth of around 7.6 m. These morphometric characteristics create diverse aquatic habitats that may influence the distribution and composition of fish communities. In addition, the combination of aquaculture activities and tourism development may contribute to local environmental pressures that affect ecosystem condition.

To ensure consistent spatial coverage among lakes, each study site was divided into three ecological zones representing the inlet, middle, and outlet segments. This zoning approach was designed to capture potential variation in hydrological conditions, habitat characteristics, and anthropogenic influences across different parts of each lake. The inlet zones generally receive direct inflows and external nutrient inputs from the surrounding catchment area, whereas the outlet zones are more strongly influenced by water discharge processes. Meanwhile, the middle zones represent transitional areas where physical and biological conditions may reflect interactions between upstream and downstream influences. Such spatial differentiation is important for identifying ecological patterns that may not be evident when lakes are evaluated as single homogeneous units. The number of sampling points assigned to each zone, together with a description of the sampling locations in Tonjong lake, Tunggilis lake, and Suradita lake, is presented in Table 1.

Table 1. Number of sampling points/zones (inlet–middle–outlet) and description of each location from Tonjong, Tunggilis and Suradita Lakes

Station	Station Name	Coordinate	Area Description
Tonjong Lake			
Plot 1 (inlet)	Tajurhalang, Bogor	6°29'48.0"S 106°45'57.7"E	Peri-urban lakeshore characterized by a mixture of aquatic plants and moderate levels of surrounding human activities.
Plot 2 (middle)		6°29'41.8"S 106°45'50.4"E	Shallow lakeside zone dominated by open water, with sparse vegetation and close proximity to residential settlements.
Plot 3 (outlet)		6°29'32.8"S 106°45'54.8"E	Narrow inlet section with relatively calm water conditions and a mosaic of shrub and grass vegetation along the shoreline.
Suradita Lake			
Plot 1 (inlet)	Cisauk, Tangerang, Banten	6°21'10.5"S 106°37'34.8"E	Artificial lowland lake margin featuring open water areas, limited vegetation cover, and active recreational use.
Plot 2 (middle)		6°21'07.9"S 106°37'27.7"E	Mid-lake edge zone with moderate water turbidity, influenced by surrounding residential developments.
Plot 3 (outlet)		6°21'03.3"S 106°37'33.3"E	Sheltered shallow shoreline affected by adjacent residential and small-scale agricultural activities.
Tunggilis Lake			
Plot 1 (inlet)	Cibarusah, Bekasi	6°25'23.9"S 107°01'13.1"E	Lowland lake margin bordering agricultural land, with a moderate presence of aquatic macrophytes.
Plot 2 (middle)		6°25'09.0"S 107°01'25.2"E	Open-water shoreline with minimal riparian vegetation and nearby rural housing.
Plot 3 (outlet)		6°25'09.5"S 107°01'50.2"E	Shallow cove area surrounded by croplands, showing increased sediment input into the lake.

Referring to Figure 2 and Table 1, the three study lakes were organized using a common spatial framework consisting of inlet, middle, and outlet zones. This zonation scheme was applied to ensure consistency in sampling design and to facilitate comparisons of fish community characteristics both within and among lakes. Although Tonjong lake, Tunggilis lake, and Suradita lake are located in different administrative regions, all three lakes are situated within lowland landscapes and are influenced by varying degrees of human activity. The inlet zones generally receive water and material inputs from the surrounding catchment area, whereas the outlet zones are associated with water discharge processes. Meanwhile, the middle zones represent transitional areas between these two hydrological extremes. The characteristics of each sampling location and the distribution of sampling points across zones are summarized in Table 1, providing the spatial basis for subsequent ecological analyses.

A total of 1.375 fish individuals were recorded across the three study lakes, comprising 685 native individuals (49.8%) and 690 alien individuals (50.2%). This distribution indicates a nearly balanced composition between native and alien fish, with a slight predominance of alien species. The number of individuals varied among lakes, with Tunggilis lake supporting the highest abundance (577 individuals), followed by Suradita lake (419 individuals) and Tonjong lake (379 individuals). These differences suggest spatial variation in fish community structure among lakes, reflecting potential differences in habitat conditions, resource availability, and levels of anthropogenic disturbance. The relatively high contribution of alien fish across the study sites further indicates that non-native species have become established components of the local fish assemblages. Detailed information on the abundance of native and alien fish in each lake is presented in Table 2 and Figure 3.

Table 2. List of fish species and their abundance in Tonjong, Tunggilis and Suradita Lakes

No	Local Name	Species	Station/Plots									Total	Native	Alien
			Tonjong			Tunggilis			Suradita					
			(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)			
1	Paray Danau	*Rasbora argyrotaenia*	22	1	0	5	0	1	5	2	0	36	√	
2	Benteur	*Barbodes binotatus*	9	0	0	0	0	10	2	0	0	21	√	
3	Nilem	*Osteochillus vittatus*	2	0	0	0	0	0	4	0	0	6	√	
4	Mercoca	*Systomus rubriphinnis*	4	0	0	0	0	0	0	0	0	4	√	
5	Seren	*Cyclocheilicthys Apogon*	1	0	0	0	0	0	0	0	0	1	√	
6	Keting	*Mystus nigriceps*	0	0	4	0	0	0	0	0	0	4	√	
7	Lele Dumbo	*Clarias gariepinus*	0	0	1	0	0	0	0	0	0	1		√
8	Sapu-sapu	*Pterygoplichthys pardalis*	0	2	0	0	0	3	1	0	0	6		√
9	Nila	*Oreochromis niloticus*	11	9	3	147	33	14	108	23	63	411		√
10	Jaguar Cichlid	*Parachromis managuensis*	0	0	0	0	0	0	3	10	8	21		√
11	Balzani	*Geophagus balzani*	1	0	0	0	0	0	0	0	0	1		√
12	Red Devil	*Amphilopus labiatus*	13	50	54	20	21	25	10	9	15	217		√
13	Sili jawa	*Macrognathus maculatus*	0	1	0	0	0	0	0	0	0	1	√	
14	Sisik Melik	*Aplocheilus armatus*	19	3	5	12	6	9	16	3	17	90	√	
15	Cere	*Gambusia affinis*	0	2	1	11	0	0	12	4	0	30		√
16	Guppy	*Poecillia reticulata*	0	0	3	0	0	0	0	0	0	3		√
17	Julung-julung	*Dermogenys pusilla*	10	2	10	0	0	0	2	0	0	24	√	
18	Betok	*Anabas testudineus*	0	2	0	0	0	0	0	0	0	2	√	
19	Sepat	*Trichogaster trichopterus*	2	3	2	31	5	53	13	2	6	117	√	
20	Cupang sawah	*Trichopsis vittata*	43	11	3	44	4	22	31	14	20	192	√	
21	Gabus	*Channa striata*	4	1	0	0	0	1	0	0	0	6	√	
223	Gabus Jujung	*Channa lucius*	10	1	0	55	0	0	0	0	0	66	√	
23	Betutu	*Oxyeleotris marmorata*	1	0	0	1	0	0	3	0	4	9	√	
24	Menga	*Brachygobius xanthomelas*	0	0	0	0	0	0	4	0	4	8	√	
25	Gobi Kaca	*Gobiopterus chuno*	0	2	0	0	0	0	0	0	0	2	√	
26	Kaca-kaca	*Parambassis siamensis*	26	12	0	7	0	0	1	0	0	46	√	
27	Ikan Padi	*Oryzias hubbsi*	1	12	0	34	0	3	0	0	0	50	√	
Individu/Plot			179	114	86	367	69	141	215	67	137	1375	685	690
Individu/Stasiun					379			577			419			

Description: (1). inlet, (2) middle, (3) outlet

Table 2 indicates that the fish community was unevenly distributed among taxa, with a relatively small number of species contributing a large proportion of the total abundance, while several other taxa were represented by comparatively few individuals. This pattern suggests a tendency toward community imbalance, where dominant species exert a strong influence on overall assemblage structure. Such conditions are commonly observed in small freshwater ecosystems experiencing varying degrees of environmental pressure, including habitat modification, nutrient inputs, and other anthropogenic disturbances. Under these circumstances, species with greater ecological tolerance and adaptive capacity may become more abundant than less tolerant taxa, leading to shifts in community composition. Consequently, the fish assemblage may become increasingly characterized by the numerical dominance of a limited number of species and reduced representation of less abundant taxa. The proportions of native and alien fish based on both abundance and species richness across lakes and sampling zones are presented in Table 3.

Table 3. Proportion of native and alien fish by abundance and species richness in each lake and zone

Lake	Zone	Native individuals (n)	Alien individuals (n)	Total individuals (n)	Native (%)	Alien (%)	Native species (S)	Alien species (S)	Total species (S)	Alien species (%)
Tonjong	Inlet	154	25	179	86.03	13.97	14	3	17	17.65
Tonjong	Middle	51	63	114	44.74	55.26	12	4	16	25.00
Tonjong	Outlet	24	62	86	27.91	72.09	5	5	10	50.00
Tunggilis	Inlet	189	178	367	51.50	48.50	8	3	11	27.27
Tunggilis	Middle	15	54	69	21.74	78.26	3	2	5	40.00
Tunggilis	Outlet	99	42	141	70.21	29.79	7	3	10	30.00
Suradita	Inlet	81	134	215	37.67	62.33	10	5	15	33.33
Suradita	Middle	21	46	67	31.34	68.66	4	4	8	50.00
Suradita	Outlet	51	86	137	37.23	62.77	5	3	8	37.50
Tonjong total	All zones	229	150	379	60.42	39.58	18	7	25	28.00
Tunggilis total	All zones	303	274	577	52.51	47.49	10	4	14	28.57
Suradita total	All zones	153	266	419	36.52	63.48	10	5	15	33.33

The proportion of alien and native fish differed markedly among lakes and sampling zones. At the lake level, Suradita showed the highest alien contribution by abundance (63.48%), followed by Tunggilis (47.49%) and Tonjong (39.58%). At the zonal level, alien dominance was not consistently highest at the outlet. In Tonjong, the outlet had the highest alien proportion (72.09%), whereas in Tunggilis and Suradita the middle zone showed the greatest alien contribution (78.26% and 68.66%, respectively). When all lakes were combined, the middle zone had the highest proportion of alien individuals (65.20%), followed by the outlet (52.20%) and inlet (44.28%). A chi-square test confirmed that the native–alien composition differed significantly among zones ($\chi^2 = 33.74$, df = 2, $p < 0.001$). These findings suggest that spatial heterogeneity within lakes may influence the distribution of native and alien fishes, resulting in distinct community compositions among inlet, middle, and outlet segments.

Table 3 reveals clear differences among the three lakes in the balance between native and alien fish, indicating that invasion pressure was not distributed uniformly across sites. At the whole lake level, Suradita showed the highest overall alien contribution, making it the most alien dominated system in cumulative terms, whereas Tonjong and Tunggilis displayed more mixed native–alien structures. However, the zonal pattern was not consistent among lakes. In Tonjong, alien dominance was strongest at the outlet**,** whereas in Tunggilis and Suradita the highest alien contribution occurred in the middle zone. When all lakes were pooled, the middle zone showed the highest overall proportion of alien individuals, exceeding both inlet and outlet segments. This means that the native–alien pattern was not uniformly outlet driven and that the common assumption that the outlet automatically represents the main “stress core” is not universally supported by the data.

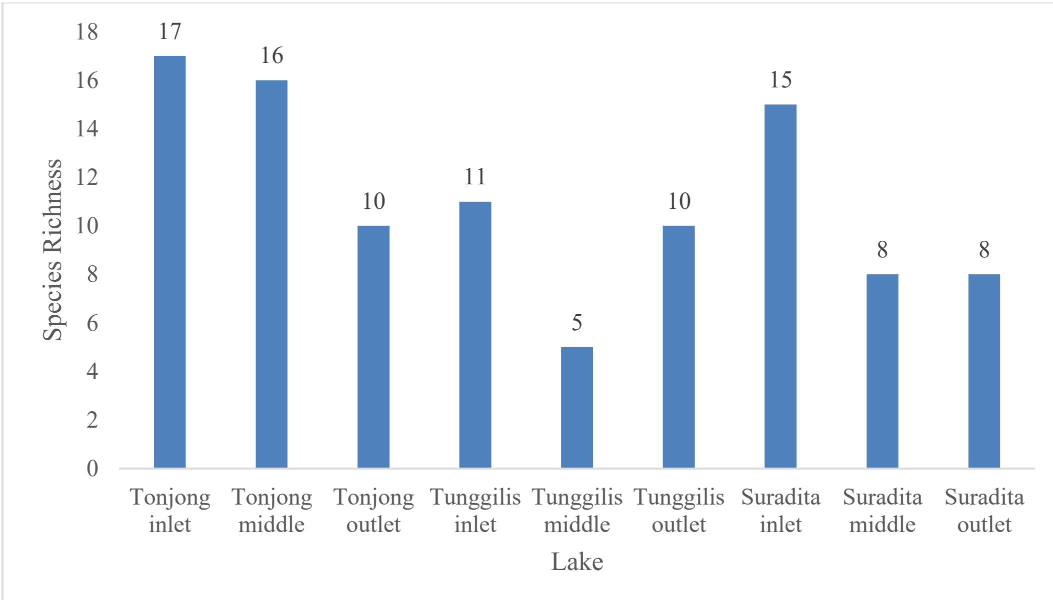


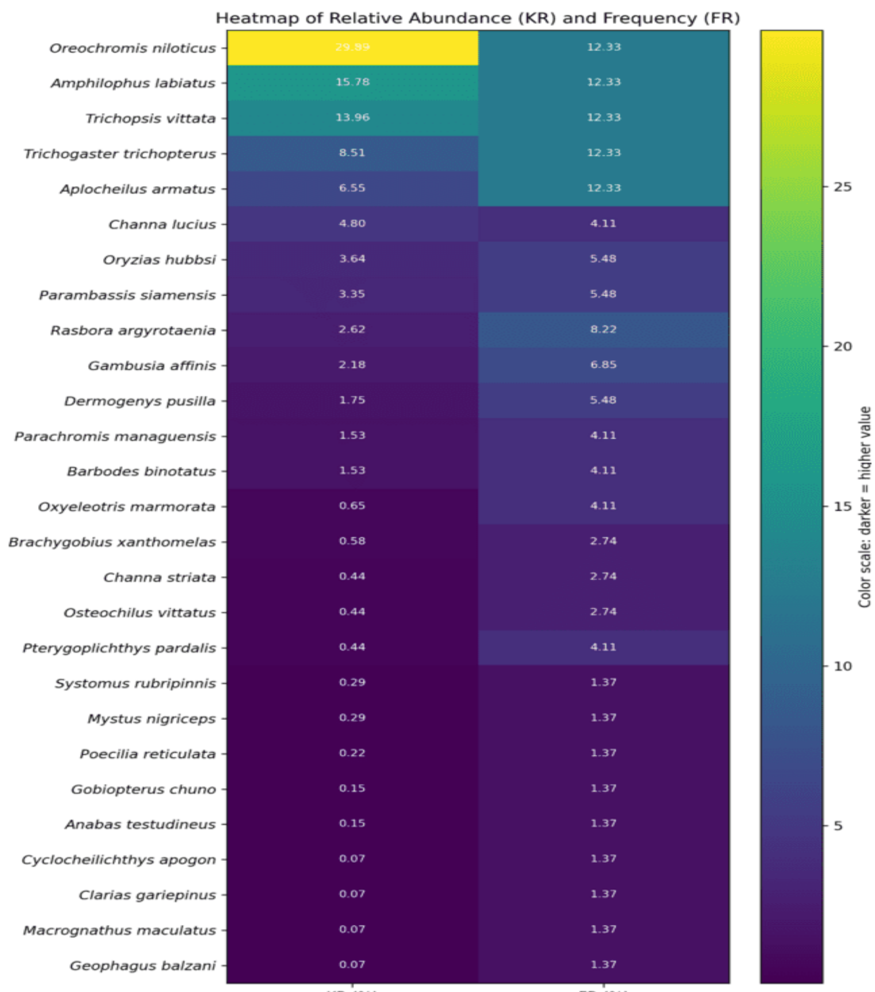
Figure 3. The value of species richness by lake in Tonjong, Tunggilis and Suradita

Figure 3 shows a clear spatial pattern in species richness across the three lakes, and these differences are consistent with variation in habitat quality and shoreline disturbance. Tonjong had the highest richness overall, especially at the inlet and middle, which is ecologically plausible because these sections remain relatively natural, are surrounded by garden vegetation, and are strongly influenced by spring water that helps maintain better water quality than household discharge. In contrast, richness declined at the Tonjong outlet, where shoreline concrete reinforcement, periodic clearing of aquatic vegetation, roadside location, and intensive human activity from sports fields and food stalls likely reduce habitat complexity and make conditions less favorable for a wider range of species. Tunggilis showed a different pattern, with moderate richness at the inlet, a strong decline in the middle, and then an increase again at the outlet.

The relatively good richness at the inlet is likely supported by natural vegetation and surrounding gardens, while the middle section may represent a less heterogeneous zone with fewer suitable microhabitats; the recovery at the outlet suggests that, although this section is affected by embankment construction, cafés, and a major interprovincial road, some species may still persist or concentrate there under local habitat conditions. Suradita showed the highest richness at the inlet and lower but relatively similar values in the middle and outlet. Although the lake is generally still natural and surrounded by rice fields, its large water volume, considerable depth, and relatively stable conditions as a former sand-mining lake may create a more even internal environment, limiting strong spatial contrasts except for the inlet, which likely provides greater habitat heterogeneity and resource input. Overall, species richness appears highest in segments with more natural habitat, better vegetation cover, and lower direct disturbance, whereas concrete shorelines, vegetation removal, and intense human activity are associated with lower richness.

A clear dominance rarity gradient was observed within the fish assemblage, in which a small number of taxa contributed disproportionately to total abundance and occurrence, while many others remained infrequent and numerically minor. *Oreochromis niloticus*, *Amphilophus labiatus*, and *Trichopsis vittata* were the most prominent taxa, exhibiting high relative abundance and frequency, indicating that the assemblage was not evenly distributed across species. This pattern is consistent with dominance by a limited number of taxa rather than a broadly balanced community structure. At the same time, numerous species occurred at low relative abudance and low relative frequency values, suggesting a long tail of rare or localized taxa. Such a configuration may reflect assemblages dominated by disturbance tolerant species and could indicate an ongoing process of biotic homogenization, particularly where the same dominant taxa recur across multiple segments while rarer taxa contribute relatively little to overall community structure. However, the present data demonstrate patterns of dominance and unevenness rather than direct evidence of competitive exclusion or competition as a tested mechanism.

When interpreted together with the spatial analyses, differences in species composition and abundance further suggest ecological differentiation among the three lakes. Tonjong lake exhibited the strongest zonal gradient, with outlet segments characterized by lower diversity, higher dominance, and a greater contribution of alien fishes. Tunggilis lake showed more moderate contrasts among zones, whereas Suradita lake appeared comparatively homogeneous across sampling segments. Nevertheless, such homogeneity should be interpreted cautiously because it may reflect either relatively stable environmental conditions or a more widespread simplification of assemblage structure. Overall, these patterns indicate that fish community organization differed not only in diversity level but also in the extent to which assemblages were concentrated around a limited number of recurrent taxa. The dominance rarity distribution and relative contribution of each species are illustrated in Figure 4.



· Figure 4. Heatmap of Relative Abundance (RA/KR) and Relative Frequency (RF/FR) of species per zone

The three lakes differed not only in the absolute values of fish community indices, but also in the strength of their internal zonal gradients. Among all segments, Tonjong inlet had the highest mean diversity (H′ = 1.9040 ± 0.1769) and the lowest dominance (D = 0.1956 ± 0.0475), indicating the most balanced assemblage among the sampled sites. In contrast, Tonjong outlet had the lowest diversity (H′ = 1.0466 ± 0.5322) and the highest dominance (D = 0.4761 ± 0.2734), suggesting a much more simplified assemblage. Compared with Tonjong, Tunggilis showed intermediate values, with lower diversity at the middle segment and a slight increase toward the outlet. Suradita displayed relatively similar values across inlet, middle, and outlet, indicating a more even internal distribution of community structure. Thus, from an among-lake perspective, Tonjong showed the strongest internal differentiation, Tunggilis showed a moderate zonal shift, and Suradita appeared comparatively more uniform. Detailed values of diversity (H′), evenness (E), and dominance (D) for each lake and sampling segment are provided in Appendix 1.

From a zonal perspective, Tonjong exhibited the clearest internal ecological gradient: H′ declined consistently from inlet to middle to outlet, while D increased in the same direction, and evenness also became lower at the outlet. This pattern is consistent with progressive community simplification along the inlet–middle–outlet axis and suggests that ecological pressure may have been more concentrated toward the outlet. In Tunggilis, the pattern was less directional. Diversity dropped from inlet to middle and then increased slightly at the outlet, while dominance rose in the middle and decreased slightly at the outlet, producing a more transitional profile rather than a strongly degraded outlet pattern. In Suradita, differences among segments were smaller overall: H′, E, and D remained within relatively narrow ranges, indicating higher internal homogeneity than in Tonjong or Tunggilis.

Ecologically, these patterns suggest that the three lakes were structured by different degrees of internal spatial heterogeneity. In Tonjong, the strong decline in diversity together with increasing dominance toward the outlet is consistent with a community under stronger local pressure, where a smaller number of taxa contributed disproportionately to total abundance. In Tunggilis, the middle segment appeared to represent a transitional zone where community balance was reduced, but the outlet did not continue this trend as strongly, indicating that internal ecological pressure was present but less uniformly organized. In Suradita, the more stable index values across segments may indicate either relatively even environmental conditions or a more system wide community structure with weaker zonal contrast. Therefore, Table 4 supports the interpretation that fish community condition should be assessed not only across lakes but also within lakes, because the inlet–middle–outlet gradient can reveal different ecological profiles, ranging from sharp zonal differentiation to more homogeneous internal organization.

Segment-based spatial visualization and zonal ecological profiles of H′, E, and D in Tonjong, Tunggilis, and Suradita Lakes is provided in Appendix 2. It provides a segment-based spatial view of fish community structure and shows that Tonjong had the strongest internal ecological differentiation among the three lakes. In Tonjong, the inlet segment was characterized by the highest Shannon–Wiener diversity and relatively high evenness, while dominance increased markedly toward the middle and especially the outlet. This pattern indicates that the inlet supported a more balanced assemblage, whereas the downstream segments became progressively less even and more concentrated in a smaller number of taxa. In contrast, Tunggilis showed a more transitional pattern, with diversity declining at the middle segment and then slightly recovering at the outlet, while dominance was elevated in the middle and remained moderate at the outlet. Suradita appeared more spatially uniform, with relatively similar H′, E, and D values across inlet, middle, and outlet segments, indicating weaker internal zonal contrast than in Tonjong.

Ecologically, the figure suggests that inlet segments tended to support more diverse and balanced fish assemblages, whereas middle and outlet segments in some lakes were associated with higher dominance. However, this pattern was not identical across all lakes, which reinforces the interpretation that internal ecological pressure was site specific rather than uniformly outlet driven. The relative uniformity observed in Suradita should also be interpreted cautiously, because spatial uniformity does not automatically indicate better ecological condition. A system may appear internally uniform either because its environmental conditions are relatively even or because community structure has already been broadly simplified across segments. For this reason, the spatial profile should be read together with the native–alien composition and physico chemical data, especially where alien dominance and chemical enrichment may alter the meaning of "uniformity."

In the study**,** relative refugia can be defined as segments with comparatively higher H′ and E and lower D, whereas priority stress segments refer to segments with comparatively lower H′ and E and higher D. Under this definition, using an operational definition, segments with comparatively higher H′ and E and lower D may be interpreted as relative refugia, whereas segments with lower H′ and E and higher D may be treated as priority stress segments. Tunggilis and Suradita, by contrast, show more moderate or transitional profiles rather than sharply separated ecological extremes. Thus, the zonal ecological interpretation indicates that fish community structure varies meaningfully within lakes, but the location and intensity of ecological pressure differ among systems. Further details are provided in Appendix 2.

The spatial gradients observed across the three lakes indicate early warning signals of ecological imbalance relevant to freshwater fish conservation. Declining diversity and evenness combined with localized dominance hotspots are consistent with habitat simplification and proliferation of disturbance tolerant or non-native taxa, a pattern widely reported in disturbed urban and human modified freshwater systems (Gkenas *et al.*, 2024; Yang *et al*., 2025). Such spatial compression of diversity can reduce functional redundancy and weaken ecosystem resilience, making fish communities more vulnerable to additional disturbance and environmental change (Dudgeon, 2019; Stefani *et al*., 2024). Collectively, these spatial index gradients function as biological indicators of ecosystem health because they integrate the cumulative effects of multiple interacting stressors operating across lake zones, including land use change, pollution, habitat alteration, and invasive species pressure (Dudgeon, 2019; Gkenas *et al*., 2024).

The relatively stable structure observed in Suradita further suggests the importance of habitat heterogeneity and moderated disturbance in sustaining more equitable fish assemblages, in line with recent evidence showing that connectivity and heterogeneous habitats support higher freshwater fish richness and conservation value. In this context, spatially explicit diversity mapping, as applied here, provides a practical diagnostic tool for identifying priority conservation zones, especially inlet refugia that may function as biodiversity reservoirs and downstream sectors requiring restoration or invasive-species management; recent richness-mapping studies likewise show that spatial biodiversity patterns can directly inform conservation prioritization (Yousefi *et al*., 2023; Stefani *et al*., 2024). These findings reinforce the importance of spatial planning in lake conservation strategies to maintain fish biodiversity, ecological function, and long-term management effectiveness. The observed patterns of fish-community structure were further interpreted in relation to environmental conditions. A summary of the physicochemical characteristics recorded across all sampling zones can be seen in Table 4.

Table 4. Ranges of physico-chemical water quality parameters across inlet, middle, and outlet plots in Tonjong, Tunggilis, and Suradita Lakes during the August–October seasonal transition period

Segment	Plot	DO (ppm)	Tempt(°C)	pH	TDS (ppt)	NH_3	NO_2	NO_3	dKH	Hardness	Klorin
Tonjong	Inlet	3,40–4,22	30,0–31,6	6,10–6,43	0,024–0,054	0,0–0,0	0–10	0–0	0–0	40–50	0–0
Tonjong	Middle	4,45–5,02	31,2–31,8	7,10–7,77	0,071–0,089	0,0–0,5	0–10	0–1	40–40	50–100	0–1
Tonjong	Outlet	5,02–5,65	31,7–32,2	7,00–7,22	0,088–0,092	0,5–1,0	10–25	5–5	80–80	100–100	3–3
Tunggilis	Inlet	3,01–4,23	30,4–32,9	6,07–7,14	0,091–0,126	0,0–0,0	0–25	0–5	40–40	50–100	0–3
Tunggilis	Middle	5,01–5,87	31,0–31,2	7,26–7,97	0,121–0,143	0,0–0,5	0–25	1–10	40–80	50–100	1–3
Tunggilis	Outlet	6,65–7,12	31,3–31,8	7,87–8,48	0,122–0,181	1,0–1,0	25–25	5–10	40–80	50–100	3–3
Suradita	Inlet	7,28–9,73	30,1–32,8	8,52–8,88	0,126–0,141	0,0–0,0	0–25	0–5	40–40	50–100	0–3
Suradita	Middle	7,10–8,26	28,9–30,1	6,41–7,33	0,092–0,098	0,0–0,5	0–25	1–10	40–80	50–100	1–3
Suradita	Outlet	7,14–7,77	31,1–31,9	7,46–7,89	0,211–0,291	1,0–1,0	25–25	5–10	40–80	100–100	3–3

Table 4 indicates a consistent spatial gradient in water quality across the inlet–middle–outlet sequence, particularly for variables associated with dissolved materials and chemical enrichment. In general, outlet segments tended to show higher TDS, NH_3, NO_2, NO_3, dKH, hardness, and chlorine than inlet segments, especially in Tonjong and Tunggilis, suggesting greater downstream accumulation of dissolved substances and nitrogen related compounds during the seasonal transition period. This pattern provides an important environmental context for the community results, because segments with elevated chemical loads also tended, in several cases, to coincide with lower diversity and higher dominance. The pattern was especially evident in Tonjong, where the outlet combined higher nitrogen-related values, higher alkalinity related parameters, and higher chlorine with a simplified fish assemblage.

At the same time, the physico chemical data also show that community condition cannot be explained by any single parameter alone. Suradita generally exhibited the highest dissolved oxygen values, particularly at the inlet and middle segments, which could be interpreted as relatively favorable from the perspective of oxygen availability. However, Suradita also showed strong alien representation in other parts of the dataset, indicating that a seemingly favorable value for one variable does not automatically translate into a more balanced or less invasion prone fish community. This means that physico chemical factors provide essential context, but they do not fully account for all observed biological patterns. Instead, the results support the view that fish community indices are complementary to physico chemical measures: water quality variables help characterize the environmental setting, while diversity, evenness, and dominance reveal how fish assemblages integrate those conditions through changes in community structure. The relationships between fish community indices and selected physicochemical variables were further examined using exploratory simple linear regression analysis, the results of which can be seen in Table 5.

Table 5. Exploratory simple linear regression between fish community indices and selected physico-chemical variables across the nine sampling segments

Response variable	Predictor	Regression equation	Slope (β)	R²	P-value	Interpretation
Shannon–Wiener diversity (H′)	dKH	H′ = 1.860 − 0.0104(dKH)	-0.0104	0.899	<0.001	Diversity decreased strongly with increasing dKH
Shannon–Wiener diversity (H′)	Hardness	H′ = 2.208 − 0.0111(Hardness)	-0.0111	0.526	0.027	Diversity decreased with increasing hardness
Shannon–Wiener diversity (H′)	Chlorine	H′ = 1.654 − 0.1655(Chlorine)	-0.1655	0.527	0.027	Diversity decreased with increasing chlorine
Evenness (E)	Chlorine	E = 0.800 − 0.0235(Chlorine)	-0.0235	0.336	0.102	Evenness tended to decrease with chlorine, but not significantly
Evenness (E)	Temperature	E = 1.863 − 0.0354(Temperature)	-0.0354	0.336	0.102	Evenness tended to decrease with higher temperature, but not significantly
Evenness (E)	Hardness	E = 0.876 − 0.00155(Hardness)	-0.00155	0.322	0.111	Evenness showed a weak negative relationship with hardness
Dominance (D)	dKH	D = 0.207 + 0.00303(dKH)	0.00303	0.860	<0.001	Dominance increased strongly with increasing dKH
Dominance (D)	Hardness	D = 0.080 + 0.00356(Hardness)	0.00356	0.611	0.013	Dominance increased with increasing hardness
Dominance (D)	Chlorine	D = 0.271 + 0.0461(Chlorine)	0.0461	0.463	0.044	Dominance increased with increasing chlorine

The spatial variation in diversity, evenness, and dominance observed among inlet, middle, and outlet segments indicates differences in ecosystem condition across the three study lakes. In general, segments characterized by higher diversity and evenness together with lower dominance reflected more balanced fish assemblages, whereas areas with lower diversity and greater dominance suggested ecological stress. These findings support the use of fish community metrics as practical indicators of ecosystem health because fish communities integrate environmental conditions over relatively long periods and respond to multiple ecological pressures simultaneously. Such patterns are commonly associated with ecological stress because environmental disturbance tends to reduce the number of species capable of persisting while simultaneously favoring tolerant or opportunistic taxa (Britton, 2022; Gkenas *et al.*, 2024). Similar patterns have been documented in various Indonesian freshwater ecosystems, where habitat degradation, water quality decline, and anthropogenic disturbances contributed to reductions in fish diversity and shifts in community composition (Fitriani *et al*., 2022; Hidayat *et al*., 2023; Yalindua *et al*., 2023).

The strongest ecological gradient was observed in Tonjong lake, where diversity progressively declined from inlet to outlet while dominance increased. Comparable responses have been reported in tropical freshwater ecosystems experiencing habitat simplification and environmental stress, resulting in reduced species richness and increased dominance of a limited number of tolerant taxa (Paujiah *et al*., 2019; Larentis *et al.*, 2022; Laga *et al*., 2025). The observed differences among segments further demonstrate that small lakes cannot be considered ecologically homogeneous systems. Habitat complexity, hydrological connectivity, and local environmental gradients can generate substantial variation in fish community structure even within the same water body (Maghfiriadi *et al.*, 2023; Yalindua *et al.*, 2023).

Inlet zones generally exhibited more favorable community characteristics than middle and outlet zones. These areas receive biological inputs from surrounding catchments and often provide greater habitat heterogeneity through shoreline vegetation and aquatic macrophytes. Consequently, inlet segments may function as ecological refugia that support higher biodiversity and ecological stability, whereas segments characterized by lower diversity and higher dominance may represent priority stress zones requiring management attention (Thorø *et al.*, 2023; Laga *et al.*, 2025). The relatively balanced proportion of native and alien fish recorded across the three lakes indicates that nonnative species have become established components of local fish assemblages. The slight predominance of alien individuals suggests that biological invasions may play an important role in shaping community structure and ecosystem functioning within these freshwater systems.

The ecological implications of alien species dominance have been extensively documented. Introduced species can alter trophic interactions, compete with native fishes for resources, and modify habitat utilization patterns, ultimately affecting native biodiversity (Milardi *et al.*, 2019; Britton, 2022). Similar concerns have been reported in Indonesian inland waters, where increasing abundance of non-native fishes has been associated with changes in fish assemblage structure and reduced ecological stability (Wahyudewantoro, 2018; Fitriani *et al.*, 2022). The recurring dominance of several alien taxa across the three lakes may therefore indicate an ongoing process of biotic homogenization, whereby ecological communities become increasingly similar because a small number of widespread species dominate multiple habitats (Wahyudewantoro, 2018; Dina *et al.*, 2022; Gavioli *et al.*, 2022).

Such processes have been identified as important drivers of biodiversity decline because they reduce ecological distinctiveness and increase community similarity among freshwater ecosystems. Although the present study did not directly assess interactions between native and alien fishes, the observed patterns emphasize the importance of continued monitoring and management efforts to maintain native biodiversity and ecological resilience. The regression analyses indicated that several physicochemical variables were associated with variation in fish community structure across sampling segments. H′ index generally decreased with increasing concentrations of chlorine, hardness, and dKH, whereas D exhibited the opposite trend. These relationships suggest that environmental quality may influence the composition and stability of fish assemblages within the study lakes.

The response of E was weaker than that of H′ and D. Although evenness tended to decline with increasing chlorine, temperature, and hardness, none of these relationships was statistically significant. This suggests that while the number of effectively represented taxa and the degree of dominance were responsive to the chemical gradient, the relative distribution of individuals among species was more stable and less sensitive within the range of conditions observed. Ecologically, this means that changes in community structure were expressed more clearly through reduced diversity and elevated dominance than through a strong breakdown of evenness. Thus, H′ and D appear to be the more responsive indicators in this dataset.

At the same time, the interpretation of Table 5 should remain cautious. Because the analysis was based on only nine sampling segments ($n = 9$) and used segment level environmental summaries, the regressions are best viewed as exploratory relationships rather than definitive causal models. Even so, the consistency of the direction across dKH, hardness, and chlorine strengthens the interpretation that chemical gradients likely contributed to the observed biological pattern. Overall, these results suggest that increasing chemical loading or mineral related enrichment was associated with lower diversity and greater dominance, but these relationships should be treated as hypothesis generating evidence that complements, rather than replaces, broader ecological interpretation. Previous studies have demonstrated that changes in water chemistry can alter habitat suitability for freshwater fishes by affecting physiological tolerance, food availability, and ecological interactions. Similar findings have been reported from Indonesian freshwater ecosystems, where nutrient enrichment, increasing dissolved substances, and declining water quality were associated with changes in fish community composition and biodiversity patterns (Paujiah *et al.,* 2019; Yalindua *et al*., 2023; Laga *et al.,* 2025).

This interpretation is consistent with a growing body of freshwater research showing that fish community structure responds strongly to environmental gradients, habitat alteration, and invasion pressure rather than to spatial position alone. Studies conducted in tropical aquatic ecosystems have demonstrated that hydrological conditions, habitat heterogeneity, and water quality gradients collectively influence fish diversity and assemblage structure (Jusmaldi *et al*., 2019; Hidayat *et al*., 2023; Maghfiriadi *et al.,* 2023). At broader freshwater scales, human disturbance has been associated with habitat simplification, compositional turnover, and increasing dominance of tolerant or nonnative species (Côte *et al.*, 2022; Gavioli *et al*., 2022; Thorø *et al*., 2023). This pattern is ecologically relevant because invasive freshwater fishes can reduce native richness and abundance through competition, predation, habitat alteration, and other ecological processes that ultimately increase community imbalance.

Severe exotic species invasions have also been linked to reduced functional diversity in freshwater fish communities, reinforcing the view that assemblage simplification is a common outcome of ecological pressure (Milardi *et al.*, 2019; Britton, 2022). Within the Indonesian context, increasing environmental pressure and the spread of invasive fishes continue to pose significant challenges for biodiversity conservation and ecosystem resilience. Evidence from the Ciliwung River has similarly demonstrated dynamic changes in fish diversity and increasing abundance of invasive fish species under conditions of anthropogenic disturbance (Ainy *et al.*, 2024; Mujadid *et al.*, 2025). Taken together, the present results suggest that chemical enrichment should be viewed not only as a local water quality issue, but also as part of a broader ecological process that may accelerate community imbalance, favor dominance by fewer taxa, and reduce the resilience of freshwater biodiversity. Integrating fish community metrics with physicochemical measurements therefore provides a more comprehensive framework for ecosystem health assessment and supports the development of evidence-based management strategies for small tropical lakes.

CONCLUSION

The study shows that fish community structure in three small lakes in West Java varies among lakes and across inlet, middle, and outlet zones. Tonjong has the clearest zonation, with decreasing diversity and increasing dominance toward the outlet. Tunggilis shows a more gradual pattern, while Suradita is relatively uniform across segments. These patterns indicate that fish community indices reflect ecological differences linked to habitat conditions and environmental pressure. However, the most stressed segment is not consistently the outlet across all lakes. Exploratory analysis suggests that higher dKH, hardness, and chlorine are associated with lower diversity and higher dominance, while evenness is less responsive. Although limited in scope, the results show that fish-based indices can complement physico chemical data for assessing lake condition. Overall, this study provides a simple baseline framework using diversity, evenness, and dominance for small lake monitoring. At the national level, this approach offers a low cost tool for Indonesia to detect ecological stress, identify refugia, and support lake restoration and biodiversity conservation planning.

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