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Integrating Physicochemical and Benthic Macroinvertebrate Functional Traits to Assess Ecological Status of Rivers Draining into a Tropical Volcanic Lake

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ABSTRACT

Biological indicators, including benthic macroinvertebrates, complement physicochemical parameters in evaluating the ecological integrity of aquatic ecosystems. Our study aimed to assess river health in rivers surrounding Lake Maninjau, Indonesia, by integrating physicochemical and biological indices. We also examined benthic functional feeding groups (FFGs) and their relationships with environmental factors, and evaluated FFG ratios to reveal ecosystem functional attributes. Macroinvertebrate and physicochemical samples were collected from nine representative sites, comprising seven inflow and two non-inflow rivers. The calculated Water Pollution Index showed that water quality at all sites was classified as good, meeting the criteria for Class 2 of the Indonesian water quality standard. However, macroinvertebrate-based biotic indices such as the Biotilik and $ASPT^{THAI}$ indices revealed variable conditions ranging from clean to rather heavily polluted. Both indices were significantly negatively correlated with nitrite concentration ($r = -0.75$ and -0.76; $p < 0.05$). FFG analysis revealed that collector-gatherers were the dominant group at most sites, except at one site where scrapers prevailed. The FFG ratios suggested that most sites were heterotrophic, with low shredder density, limited availability of TFPOM for collector-filterers, limited habitat stability, and a normal predator–prey interaction across the study area. This study demonstrates that in tropical rivers where physicochemical indicators meet the standards, the functional group structure of benthic animals can still effectively reveal ecological stress caused by agricultural nutrient input. Hence, this highlights its importance for integration into a comprehensive ecological health monitoring framework for lake basins.

1. INTRODUCTION

Water is an essential natural resource that supports all forms of life on Earth. In most developing countries, surface water serves as the primary source, complemented by groundwater from shallow wells [1]. Beyond quantity, surface water quality remains a critical concern amid rapid population growth, which may lead to increased pollution exposure. Degradation often occurs when pollutant loads exceed the natural assimilative capacity of aquatic systems. Therefore, ensuring not only the availability but also the chemical and ecological quality of water is essential for maintaining sustainable aquatic ecosystems. The United Nations' Sustainable Development Goals (SDGs), established in 2015, also emphasize the importance of clean water and sanitation (SDG 6) and life below water (SDG 14) [2].

Surface water quality can be evaluated according to its intended human use, and such assessments are often based on physicochemical parameters that reflect the current condition of the water body [3]. However, biological parameters such as *coliform* bacteria provide limited information, as they fail to represent the cumulative or long-term pressures acting on aquatic systems [4]. The integration of biological indicators that capture both present and past environmental conditions is therefore essential to achieve a more comprehensive and ecologically meaningful assessment of aquatic ecosystem quality.

Macroinvertebrates are invertebrate fauna whose body size exceeds 0.5 mm, associated with surfaces of the channel bottom or other stable surfaces. Macroinvertebrates are one of the most widespread organisms in the river ecosystem, including aquatic arthropods, mollusks, annelids, nematodes, and tubellarians [5]. They represent the trophic link between algae/microorganisms and fish/other vertebrates [6]. Due to their minimal mobility and varying degrees of sensitivity to pollution, they are considered vital bioindicators of aquatic ecosystem health [7]. Other characteristics of these fauna include a relatively long life cycle, easy to collect, and high diversity [8, 9].

Bioassessment using macroinvertebrates can be enhanced through the FFG approach, which provides insights into trophic resource dynamics and ecosystem functioning [10]. FFGs reflect the effects of environmental changes on macroinvertebrate communities based on the types of food resources available and the morphological adaptations related to food acquisition [11]. Macroinvertebrates are generally classified into collector (gatherers and filterers), scrapers, shredders, and predators. Collectors-gatherers consume fine particulate detritus from the riverbed; collectors-filterers acquire fine particulate detritus from the water column. Scrapers harvest benthic algae from substrate surface, shredders utilize coarse particulate organic matter (CPOM), and predators feed on other invertebrates or small vertebrates [12].

Lake Maninjau, one of Indonesia's priority conservation lakes, receives inflows from several rivers that discharge directly into it. These rivers serve as primary channels conveying water from the surrounding catchment area, along with organic and inorganic materials that influence the lake's water quality. Human activities within the watershed can elevate nutrient levels, organic matter, and suspended solids, potentially leading to water quality degradation and threatening the ecological integrity of Lake Maninjau.

The condition of the inflowing rivers is largely determined by the quality of their upstream segments, which are typically less disturbed by human activities. The biological characteristics of minimally disturbed areas serve as reference conditions against which the impacts of anthropogenic activities can be evaluated [13]. Such reference sites are also essential for assessing both the degree of degradation and the potential for recovery in aquatic ecosystems [14].

Environmental changes in upstream areas or headwaters, particularly deforestation, can significantly influence the quantity and quality of downstream water resources [15]. Alterations in water quality may indirectly affect aquatic organisms by modifying food availability, predator–prey dynamics, and habitat development, or even leading to the local extinction of certain species [16]. However, comprehensive assessments of water quality in river systems flowing into Indonesian lakes remain limited, particularly those incorporating the FFG approach of benthic macroinvertebrates as bioindicators. Therefore, the present study aims to: 1) compare river health assessment results based on physicochemical parameters and multiple biological indices; 2) analyze the structure of benthic FFGs and their relationship with environmental factors; and 3) explore the utility of FFG ratios in revealing the functional attributes of these tropical river ecosystems. The findings are expected to provide a scientific basis for the protection and management of river ecosystem health and biodiversity.

2. METHODOLOGY

2.1 Study area and sampling

Lake Maninjau is one of the largest volcanic lakes in West Sumatra Province, Indonesia, covering an area of approximately 9,737 ha. Lake Maninjau receives its water primarily from rivers, with nearly 88 rivers flowing into it. Most of these inflowing rivers are intermittent, while only 34 maintain flow throughout the year [17]. The regions around Lake Maninjau generally experience the rainy season in December, January, March, and April, whereas the dry season occurs in July, August, and September. The transitional period, when rainfall is typically 100–200 mm per month, usually occurs in February, May, June, October, and November.

Table 1. Sampling locations and their coordinates

Labels	Locations	Coordinates	Characteristics
U1	Kurambik	-0.25808, 100.15845	Upstream, forest, rice field
U2	Koto Gadang	-0.25322, 100.16135	Upstream, forest
U3	Koto Kaciak	-0.24123, 100.16527	Upstream, forest, rice field
U4	Kularian	-0.23218, 100.18353	Upstream, forest, rice field
U5	Bancah	-0.32230, 100.22633	Downstream, rice field, settlement
U6	Ranggeh	-0.34282, 100.23857	Upstream, forest, rice field
U7	Batang Air	-0.36150, 100.21877	Downstream, rice field, settlement
U8	Gasang	-0.38832, 100.09025	Midstream, rice field, settlement
U9	Dalko	-0.31452, 100.11568	Upstream, forest

We collected samples twice from seven representative sites in the inflow rivers of Lake Maninjau during March and April 2019, which represent the rainy season. Meanwhile, samples from the non-inflow rivers were collected only once, in April 2019. The seven inflow rivers studied were Kurambik, Koto Gadang, Koto Kaciak, Kularian, Bancah, Ranggeh, and Batang Air, while Gasang and Dalko represented the non-inflow rivers (Table 1 and Figure 1). At each site, three replicate macroinvertebrate samples were collected using a Hess sampler (30 cm diameter, 0.5 mm mesh), with a sampled area of 0.07 m^2 per replicate. The three replicates were combined into a single composite sample prior to analysis. All collected materials were kept in ziplock plastic and preserved in 96% alcohol. In the laboratory, samples were sorted and identified to the family or genus level, most being identified to genus, while Chironomidae were determined to the subfamily level following Zhang et al. [18]. Identification was performed using an Olympus SZ-61 stereomicroscope, with reference to the keys of Yule and Sen [19] and Merritt and Cummins [20]. Then, Macroinvertebrate taxa were classified into six FFGs according to Barbour et al. [11] and Mekong River Commission [21]: collector–gatherers, collector–filterers, scrapers, shredders, predators, and omnivores.

At each sampling site, water temperature (WT), electrical conductivity (EC), turbidity, total dissolved solids (TDS), and pH were recorded onsite using the Water Quality Checker (Horiba U-20). Meanwhile, Dissolved Oxygen (DO) was recorded using a DO-meter (YSI Professional Plus). Other parameters, including total suspended solids (TSS), nitrate, nitrite, ammonia, total nitrogen (TN), and total phosphorus (TP), were measured in the laboratory.

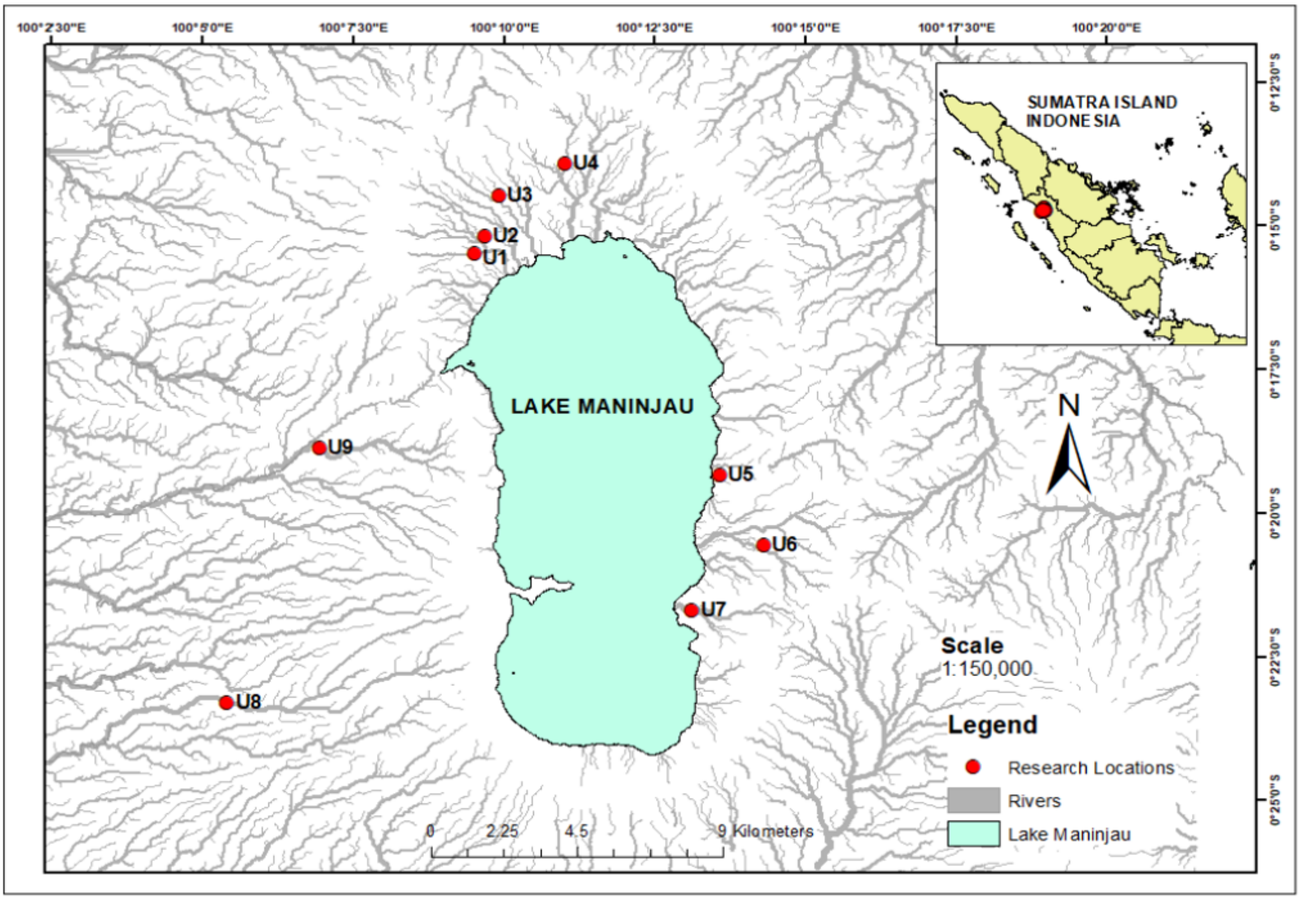

Figure 1. Map showing sampling locations

2.2 Data analysis

Water quality parameters were employed to calculate the Pollution Index, following the Decree of the State Minister of Environment of Indonesia No. 115/2003 [22]. The calculation is based on Indonesian Class II water quality standards, as defined in Government Regulation of the Republic of Indonesia No. 22/2021 [23]. The Pollution Index was computed using Eq. (1), and the water quality criteria are presented in Table 2.

Table 2. Water quality criteria for Pollution index values

Grade	Pollution Index
Unpolluted	$0 < PI_j < 1.0$
Lightly polluted	$1.0 < PI_j < 5.0$
Moderately polluted	$5.0 < PI_j < 10$
Heavily polluted	$PI_j > 10$

$$PI_j = \sqrt{\frac{(C_i/L_{ij})_M^2 + (C_i/L_{ij})_R^2}{2}} \quad (1)$$

where, PI_j is the pollution index, C_i is the measured water quality value, L_{ij} is the water quality standard value, $(C_i/L_{ij})_M$ is the maximum value of C_i/L_{ij}, and $(C_i/L_{ij})_R$ is the average value of C_i/L_{ij}.

The Shannon–Wiener diversity index (H′), Simpson dominance index (D), Pielou's evenness index (J), and Margalef's richness index (R) were calculated using Paleontological Statistics (PAST) software version 4.03 to assess the diversity of benthic macroinvertebrate communities. Furthermore, the PAST software was employed to examine the correlations between water quality parameters, biotic indices, and the FFGs of macroinvertebrates.

To complement the physicochemical assessment, three biotic indices were applied: the Biotilik index [24], which was originally developed in Indonesia; the Average Score Per Taxon-Thailand ($ASPT^{THAI}$) adapted from the BMWP-ASPT (UK) for tropical conditions [25]; and the Stream Invertebrate Grade Number–Average Level (SIGNAL2) developed for temperate and subtropical regions [26]. Their calculation formulas are presented in Table 3.

Table 3. Formulas for biotic indices of macroinvertebrates

Indices	Equation	No.	Description
Biotilik	$Biotilik = \frac{\sum T}{n}$	(2)	T = Tolerance value; n = Number of identified and scored families
$ASPT^{THAI}$	$ASPT^{THAI} = BMWP / n$	(3)	BMWP = Total BMWP index score; n = Number of identified and scored families
SIGNAL2	$SIGNAL2 = \frac{\sum T.F}{\sum F}$	(4)	T = Tolerance value; F = Weight factor based on the abundance of identified families

3. RESULTS AND DISCUSSION

3.1 Water quality

Table 4 summarizes the physicochemical characteristics of the river water observed during the study period. All measured parameters complied with the Indonesian river water quality standards (Class 2), which apply to water used for recreational purposes, aquaculture, livestock, and agricultural irrigation. Higher classification levels (Classes 3–4) indicate progressively lower water quality and more restricted applications, with Class 4 suitable only for agricultural irrigation. Certain parameters, such as EC and turbidity, are not included in the Indonesian standards. Nevertheless, based on the WHO guidelines [27], EC values in this study remained within the acceptable limit of 1.5 mS/cm, while turbidity values were consistently below 5 NTU, except at three sites (U4, U6, and U8).

Conventionally, water quality has also been assessed using the Pollution Index (PI). Figure 2 illustrates the variation in PI values during the observation period. All sampling stations exhibited PI values below 1, indicating that the sites were unpolluted and complied with the Class 2 water quality standard. In general, higher PI values correspond to lower water quality.

Table 4. Physicochemical parameters observed in the rivers surrounding Lake Maninjau

Sites	WT	EC	Turbidity	TDS	TSS	DO	pH	TN	NO^{2}-N	NO^{3}-N	NH^{3}-N	TP
	°C	mS/cm	NTU	g/L	mg/L	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L
U1	24.30	0.37	1.36	0.05	2.20	6.89	7.97	0.17	0.006	0.015	0.01	-
U2	23.20	0.07	1.08	0.05	1.60	7.07	8.12	0.20	0.005	0.018	0.02	0.01
U3	23.45	0.13	2.21	0.09	10.50	6.86	7.94	0.17	0.005	0.015	0.02	-
U4	22.30	0.07	7.04	0.05	11.20	7.21	8.36	0.23	0.006	0.038	0.02	0.01
U5	23.80	0.10	4.25	0.06	10.50	6.71	7.73	0.31	0.006	0.015	0.04	0.04
U6	21.25	0.13	5.34	0.08	14.90	6.97	8.15	0.44	0.005	0.025	0.02	0.03
U7	25.05	0.12	3.32	0.08	7.00	6.43	7.85	0.34	0.006	0.020	0.04	0.05
U8	26.50	0.08	6.03	0.05	1.00	6.65	8.23	0.06	0.004	0.010	0.03	-
U9	24.10	0.08	3.99	0.05	3.20	7.26	7.76	0.13	0.004	0.010	0.03	0.02
Water Quality Standard*	deviation of 3°C	-	-	1	50	4	6-9	15	0.06	10	0.2	0.2

Note: Class 2 river water quality standards as stipulated in Government Regulation of the Republic of Indonesia No. 22 of 2021.

Table 5. Dominant macroinvertebrate taxa: their abundance, tolerance scores, and FFG classifications (T1 = Biotilik; T2 = $ASPT^{THAI}$; T3 = SIGNAL2)

Ordo	Family	Taxa	FFG	Tolerance Score			Density (Individuals/m²)								
				T1	T2	T3	U1	U2	U3	U4	U5	U6	U7	U8	U9
Ephemeroptera	Caenidae	*Caenis*	CG	2	7	4	85	20	52	50	2	10	42	35	5
Ephemeroptera	Heptageniidae	*Heptagenia*	SC	3	10	9	7								
Plecoptera	Nemouridae	*Amphinemura*	SR	4	7	10						7			
Plecoptera	Perlidae	*Neoperla*	PR	4	10	10								75	5
Trichoptera	Hydropsychidae	*Cheumatopsyche*	CF	3	5	6	25	2	45		10	22	167	5	
Trichoptera	Glossosomatidae	*Agapetus*	SC	4		9								5	
Diptera	Simulidae	*Simulium*	CF	2	5	5	2		2		37		12		
Diptera	Chironomidae	*Chironominae*	CG	1	2	3	75	157	52	92	40	32	17	45	10
Diptera	Limoniidae	*Antocha*	CG			3	35	12	50		2	2	272	20	
Hemiptera	Veliidae	*Rhagovelia*	PR	3		3				27					
Coleoptera	Psephenidae	*Psephenus*	SC	3	5	6	7		2					85	
Coleoptera	Dryopidae	*Pelonomus*	SR		5	5			2	2	5	2			
Lepidoptera	Crambidae	*Eoophyla*	SC			2	7	2	22				25	10	

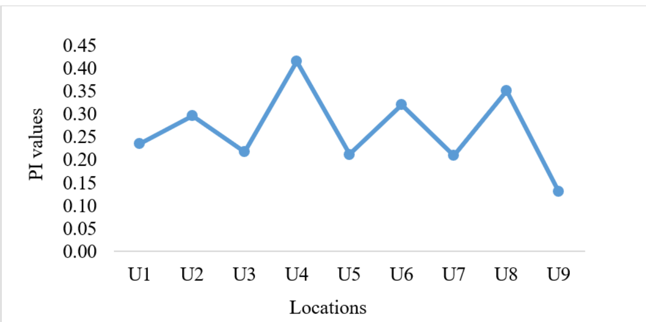

Figure 2. Values of the pollution index in the upstream rivers surrounding Lake Maninjau

The variation in PI values in this study was primarily driven by pH levels. Figure 3 shows a significant positive correlation between PI and pH levels ($r = 0.95$; $p < 0.01$), indicating that higher pH levels contributed to an increase in PI values. pH levels in aquatic ecosystems can be affected by various factors, including geological formations, biological processes, precipitation, and anthropogenic inputs [28]. Generally, pH values below 5 or above 9 are considered detrimental to aquatic organisms. Acidic conditions, in particular, tend to lower the diversity of benthic fauna and enhance the mobilization of heavy metals, which can be toxic to benthic macroinvertebrates [29].

3.2 Macroinvertebrate density and diversity

A total of 1,509 macroinvertebrate individuals, representing 59 taxa from three classes, 11 orders, and 36 families, were collected. Insecta comprised the majority of taxa (57), while Crustacea and Clitellata were represented by one taxon each. Insecta Coleoptera accounted for the highest number of taxa

(17), with Elmidae as the most represented family. Site U8 exhibited the greatest number of taxa (24), mainly composed of Coleoptera, whereas U5 and U9 showed the lowest (8 taxa each), primarily consisting of Diptera and Ephemeroptera, respectively. *Chironominae* (Diptera) and *Caenis* (Ephemeroptera) were the only taxa recorded at all sites (Table 5).

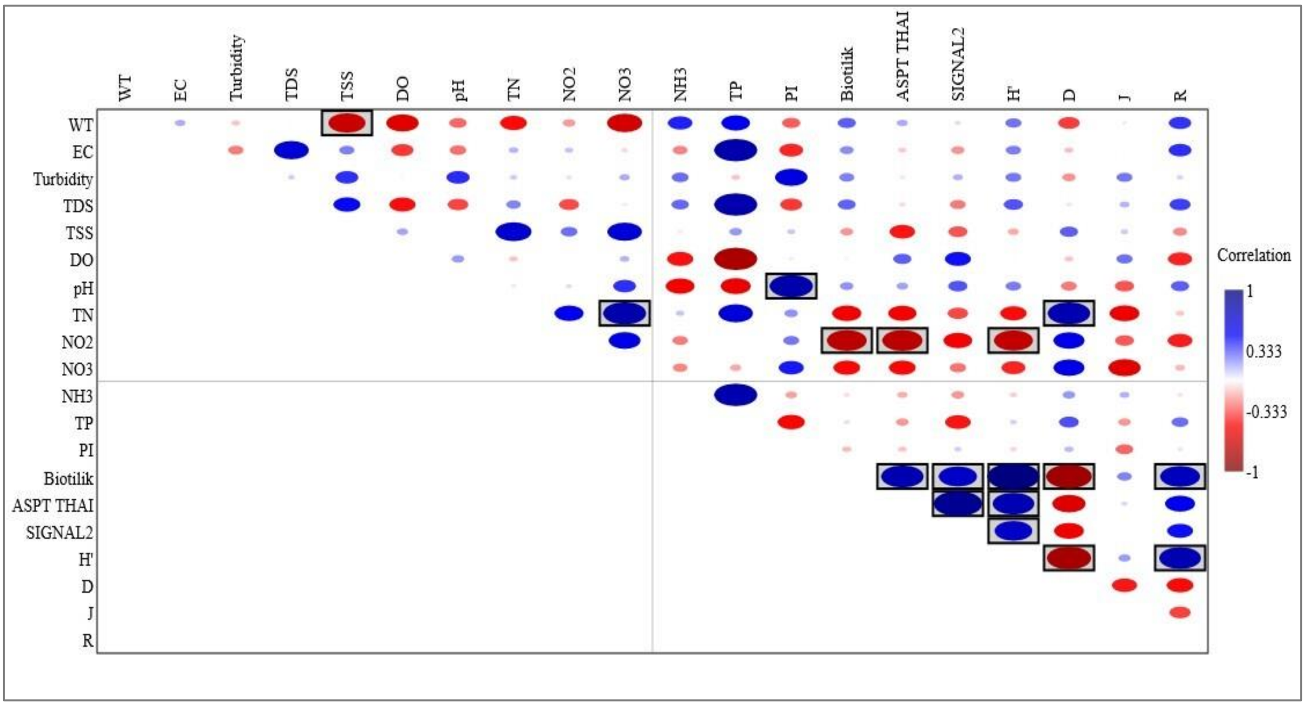

Figure 3. Spearman correlations between biotic indices, water quality parameters, and biodiversity indices

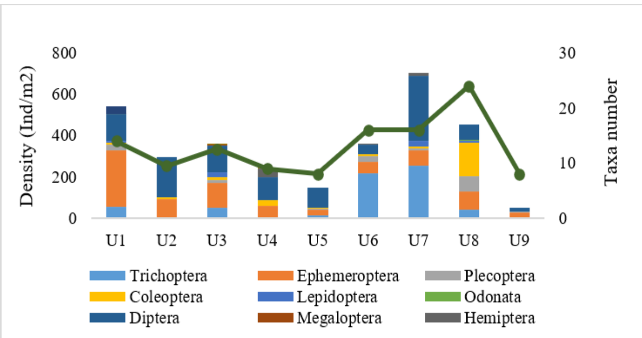

Figure 4. Variation in density and the number of taxonomic groupings in the rivers surrounding Lake Maninjau

Figure 4 illustrates the variation in macroinvertebrate abundance, ranging from 50 ind/m² at site U9 to 703 ind/m² at site U7. Macroinvertebrate communities at five sites (U2, U3, U4, U5, and U7) were dominated by Diptera, whereas Ephemeroptera predominated at sites U1 and U9. In contrast, Trichoptera and Coleoptera were the dominant orders at U6 and U8, respectively. Although site U7 supported the same number of taxa as U6 and fewer than U8 (16 taxa), its higher abundance was mainly attributed to Diptera, particularly *Antocha* (Limoniidae), which reached 272 ind/m² (Table 5). Moreover, Hydropsychidae (Trichoptera) also contributed to the elevated macroinvertebrate abundance observed at this site. Site U9 exhibited the lowest abundance, with the lowest number of taxa recorded among all sites.

Site U8 recorded the highest Shannon–Wiener diversity index (H′) value (2.70), while Site U5 showed the lowest (1.38) (Figure 5). These values were inversely related to the dominance index, with U8 exhibiting the lowest dominance (0.10) and U5 the highest (0.34). Overall, the studied sites indicated low dominance and moderate diversity. The dominance index ranges from 0 to 1, with values near 0 indicating a highly diverse community without dominant species, whereas values approaching 1 suggest that one or a few species dominate the community, resulting in low diversity [30].

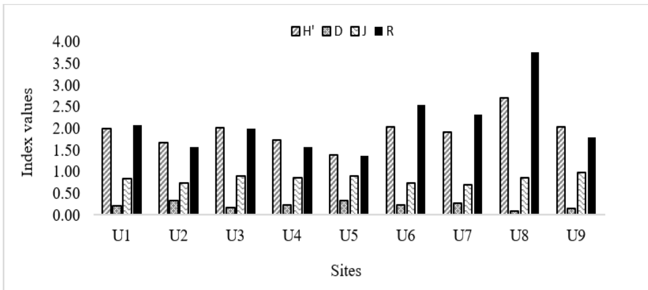

Figure 5. Biodiversity index values of macroinvertebrates in the rivers surrounding Lake Maninjau
H′ = Shannon-Wiener diversity index, D = Simpson dominance index, J = Pielou evenness index, R = Margalef richness index

Pielou's evenness (J) values varied across sites, ranging from the lowest at Site U7 (0.69) to the highest at Site U9 (0.97) (Figure 5). An evenness index value near 1 indicates that species are more evenly distributed, with similar numbers of individuals across taxa. Conversely, values close to 0 suggest that a few species dominate the assemblage [31]. Three sites (U2, U6, and U7) exhibited characteristics of a semi-stable community (J between 0.5 and 0.75). In contrast, the remaining six sites represented stable communities (J > 0.75), where dominance index values tended to be lower [32].

The Margalef index (R) values ranged from 1.37 (U5) to 3.76 (U8) (Figure 5). Sites U6 and U8 showed medium taxa richness ($2.5 < R < 4$), while the other sites were characterized by low taxa richness ($R < 2.5$) [33, 34]. A higher Margalef index value indicates greater species richness relative to the total number of individuals within the assemblage [35].

Table 6. Scores and water quality classifications based on three biotic indices in the rivers surrounding Lake Maninjau

Sites	Biotilik	ASPT^{THAI}	SIGNAL2
U1	2.63 (Mild Pollution)	5.43 (Doubtful quality)	5.01 (Mild Pollution)
U2	2.43 (Moderate Pollution)	5.48 (Doubtful quality)	5.01 (Mild Pollution)
U3	2.67 (Mild Pollution)	5.41 (Doubtful quality)	4.62 (Moderate Pollution)
U4	2.44 (Moderate Pollution)	5.16 (Doubtful quality)	4.68 (Moderate Pollution)
U5	1.71 (Rather Heavy Pollution)	4.08 (Moderate Pollution)	4.29 (Moderate Pollution)
U6	2.96 (Mild Pollution)	5.49 (Doubtful quality)	6.18 (Healthy Habitat)
U7	2.58 (Moderate Pollution)	5.26 (Doubtful quality)	4.63 (Moderate Pollution)
U8	3.20 (Very Mild Pollution)	6.56 (Clean Water)	6.18 (Healthy Habitat)
U9	3.00 (Mild Pollution)	8.14 (Clean Water)	6.75 (Healthy Habitat)

3.3 Ecological water quality based on biotic indices

Table 6 presents the biotic index scores for all sites along with their corresponding water quality classifications. Although the Pollution index indicated good water quality or compliance with Class 2 standards across all sites, the ecological water quality showed considerable variation. This discrepancy highlights that chemical compliance does not necessarily reflect ecological health. Such findings underscore the limitations of water quality standards, which are often designed for human use, and emphasize the importance of biomonitoring to more accurately assess the integrity of aquatic ecosystems.

Based on the Biotilik index values, the water quality in the studied rivers ranged from Very Clean or Very Mildly Polluted to Rather Heavily Polluted. Meanwhile, the ASPT^{THAI} and SIGNAL2 indices indicated conditions ranging from clean water or healthy habitat to moderate pollution. Higher scores from these three indices generally reflect better water quality, indicating the presence of numerous sensitive, high-scoring taxa.

The three biotic indices generally provided comparable assessments of water quality, particularly at sites U1 and U8, which were classified as Mild Pollution and Excellent, respectively. Nevertheless, the Biotilik index indicated lower water quality at U2, U5, and U9 compared with the other indices. The ASPT^{THAI} index reflected higher water quality only at U4 and U7, while the SIGNAL2 index suggested lower quality at U3 but higher quality at U6. These differences likely stem from incomplete tolerance data for some taxa at the studied sites within the selected indices, as well as variations in tolerance scoring across indices. Notably, several taxa, including Psychomyiidae, Elmidae, Dryopidae, and Limoniidae, lacked tolerance scores for the Biotilik calculation. Among the three indices, SIGNAL2 included a more comprehensive set of scored taxa and also incorporated abundance weighting in its calculation, whereas Biotilik and ASPT^{THAI} considered only the number of taxa, without accounting for their abundances.

Among all the sites studied, U8 and U9, which are non-inflow rivers of Lake Maninjau, exhibited the highest ecological water quality, as indicated by at least two of the three biotic indices used. Four other sites (U1, U2, U3, and U6) were classified as lightly polluted, whereas the remaining sites (U4, U5, and U7) were moderately polluted. The decline in water quality was associated with the loss or reduced abundance of sensitive taxa, coupled with an increase in tolerant taxa. In the SIGNAL2 index, water quality was also influenced by the relative abundances of both tolerant and sensitive taxa. Overall, in this study, sensitive taxa were represented by EPT groups such as Leptophlebidae, Heptageniidae, Perlidae, Philopotamidae, and Glossosomatidae, whereas tolerant taxa included Gerridae, Simuliidae, Chironomidae, and Naididae.

The three biotic indices were correlated with water quality and biodiversity parameters (Figure 3). Biotilik and ASPT^{THAI} were negatively correlated with nitrite ($r = –0.75$ and $–0.76$, respectively; $p < 0.05$), indicating that higher nitrite levels corresponded to lower index values, reflecting reduced water quality. These results suggest that both indices are sensitive to nutrient-related stress.

The three biotic indices also showed significant positive correlations with the Shannon–Wiener diversity index, indicating that increased macrozoobenthos diversity was associated with higher biotic index values, reflecting improved water quality. In this study, sites with high H′ values (e.g., U8) also exhibited high values for all three biotic indices, indicative of clean water and healthy habitats, whereas sites with the lowest H′ (e.g., U5) showed correspondingly low biotic index values. The Biotilik index further showed strong and significant correlations with the Margalef index ($r = 0.75$, $p < 0.05$) and the Dominance index ($r = –0.87$, $p < 0.01$). Increased taxa richness was associated with higher Biotilik values, reflecting better water quality, while increased dominance of tolerant taxa, such as Chironomidae, significantly contributed to lower water quality as indicated by the Biotilik index. The presence of Chironomidae larvae has been reported to reflect anthropogenic impacts [36].

3.4 FFG analysis

In total, 59 macroinvertebrate taxa collected during the study period were assigned to six FFGs: collector-gatherers (18 taxa), predators (16 taxa), scrapers (13 taxa), collector-filterers (8 taxa), shredders (3 taxa), and omnivores (1 taxa). Collector-gatherers contributed the highest numbers of taxa, whereas omnivores were the least represented.

Overall, collector-gatherers were the most abundant FFG at almost all sites (40–82.35%), except at site U6, which was dominated by scrapers representing 45.83% of the assemblage (Figure 6). The highest proportion of collector–gatherers (82.35%) was recorded at site U2, a forested upstream area, with an abundance of 245 ind/m². Across all sites, their abundance ranged from 20 ind/m² at U9 to 390 ind/m² at U1 (Figure 7). Collector–gatherers were mainly represented by *Caenis* (Ephemeroptera) at U1 and U3, *Antocha* (Diptera) at

U7, and Chironominae at the remaining sites.

The high proportion of collector-gatherers, particularly at the upstream sites, aligns with findings from the Yellow River [37], the Blyde River [38], and the Steelpoort River [39]. In contrast, this pattern differs from that reported for the Ciliwung River, where collector-filterers are predominant [40], and the Cisadane River, where scrapers dominate [41]. The high proportion of collector-gatherers but scarcity of shredders in the headwater sites (U2 and U9) contradicts the predictions of the River Continuum Concept (RCC). However, a low proportion of shredders is commonly reported in tropical streams [42, 43]. In this study, the relative density of shredders was low across sites, ranging from 0% (U1, U2, U8, and U9) to 3.39% (U5). The genus *Pelonomus* (Coleoptera) was the only representative at U3, U4, and U5. Additionally, *Pelonomus* co-occurred with *Amphinemura* (Plecoptera) at U6.

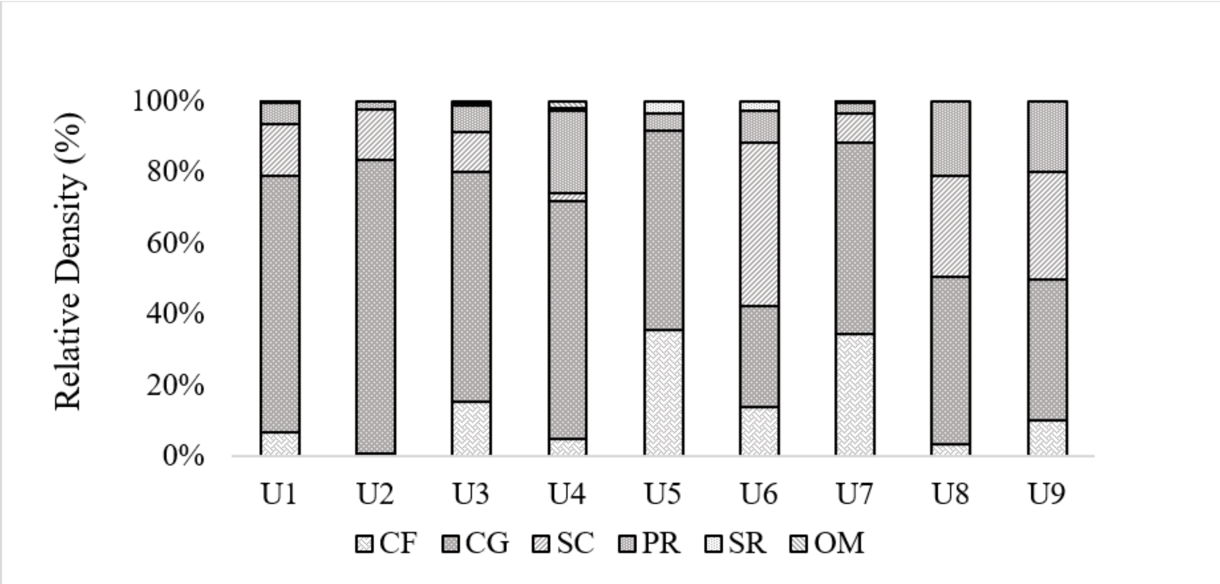

Figure 6. Relative FFG density during observations
CF = collector-filterers, CG = collector-gatherers, SC = scrapers, PR = predators, SR = shredders, OM = omnivore

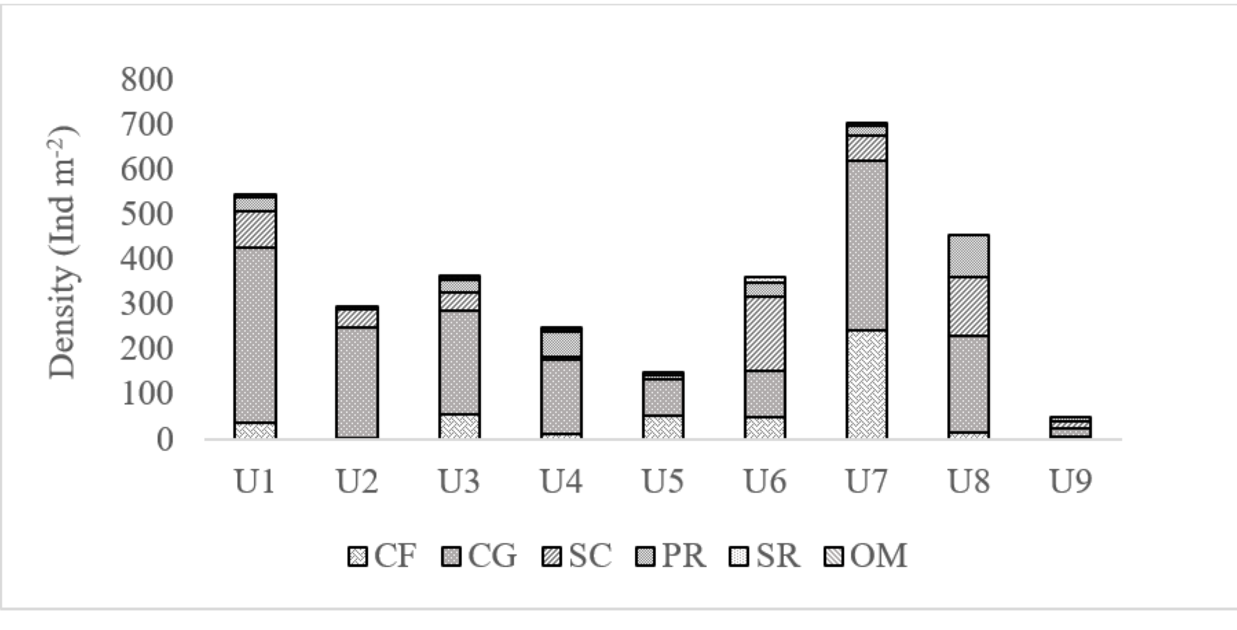

Figure 7. Density of FFG of macroinvertebrates during observations
CF = collector-filterers, CG = collector-gatherers, SC = scrapers, PR = predators, SR = shredders, OM = omnivore

The dominance of collector-gatherers indicates a greater contribution of fine particulate organic matter (FPOM) compared to CPOM. In tropical regions, CPOM input to streams may be reduced because high temperature and humidity accelerate leaf decomposition on land [44, 45]. The low quality of leaf litter, due to the high content of secondary compounds in tropical vegetation, is also thought to contribute to the low abundance of shredders [46]. Shredders were generally scarce, comprising 0–3.39% of the community with abundances of 0–10 ind/m² (Figures 6 and 7). Despite U2 being located upstream within a forested area without adjacent rice fields (Table 2), it lacked shredders (0%), a lower value than other upstream forest sites that were near rice fields (U3, U4, and U6). In this study, shredder abundance showed a significant positive correlation with TSS and TN (Figure 8). Elevated TSS levels may indicate an increased particulate organic matter that supports the presence of shredders, while TN can stimulate microbial conditioning that enhances leaf-litter quality.

Collector dominance may reflect limited food availability for other groups or competition for shared resources [47, 48]. Moreover, most collectors are generalist feeders that utilize a wide variety of food sources and can inhabit diverse streambed environments, enhancing their survival and reproductive success. Collectors also play an important ecological role in repackaging fine particulate organic matter (FPOM) into larger particles after ingestion. Their abundance is likely related to their ability to exploit a broad range of food items compared with more specialized groups such as shredders and scrapers [49]. In addition, collectors are generally tolerant to environmental disturbances occurring in aquatic ecosystems [11].

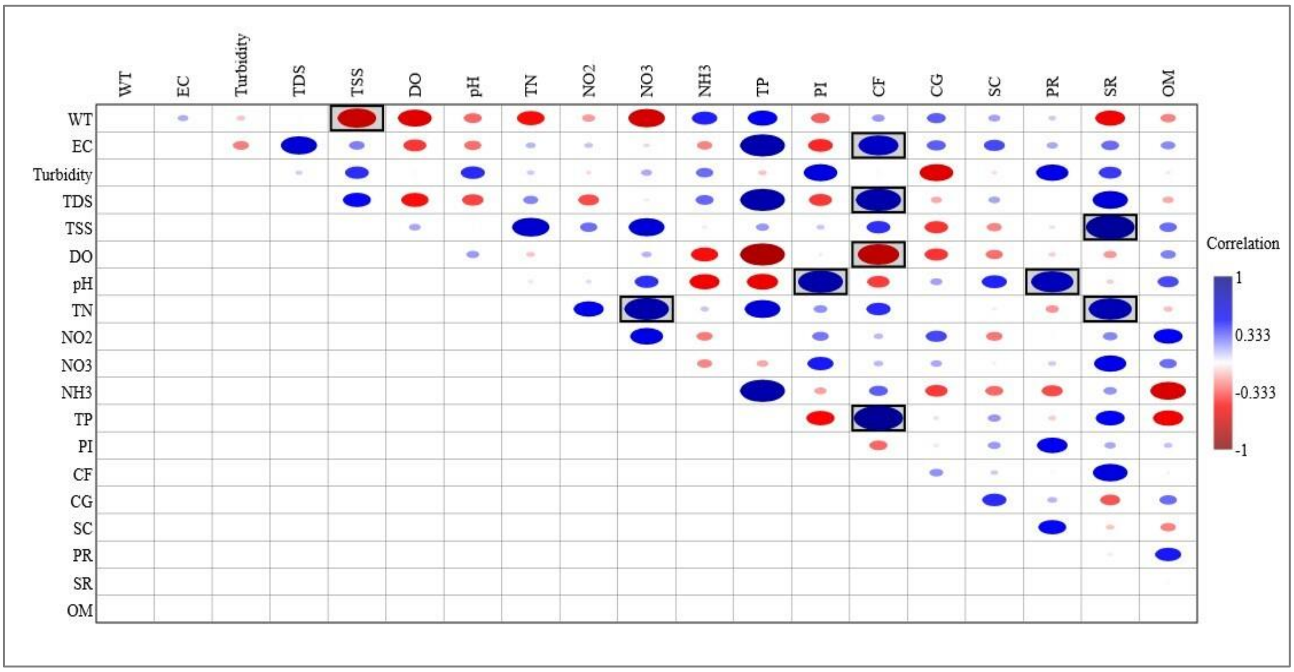

Figure 8. Spearman correlations between FFG abundances and water quality parameters

Collector-filterers were the second most dominant FFG at sites U3, U5, and U7, where *Cheumatopsyche* (Trichoptera) dominated at U3 and U7, and *Simulium* (Diptera) at U5. These two taxa have also been reported as representative collector-filterers in the Upper Ciliwung River [40]. In this study, collector-filterers showed higher proportions at two downstream sites (U5 and U7), accounting for 35.59% and 34.52%, respectively. The combined abundance of collector-filterers and collector-gatherers reached 91.53% at U5 and 88.26% at U7, consistent with the River Continuum Concept (RCC), which predicts collectors as the predominant group in downstream reaches. Similar findings were reported for the Ranggeh River, where the proportion of collectors increased downstream from areas with intensive agricultural practices [50].

The abundance of collector-filterers showed significant positive correlations with EC, TDS, and TP, and a significant negative correlation with DO (Figure 8). The positive relationship between CF and TDS agrees with Uwadie [51] but contrasts with Doong et al. [52]. Increased TDS due to fine organic matter input likely enhances food availability for collector-filterers. Similarly, Zhang et al. [53] reported that higher conductivity promotes an increase in pollution-tolerant macroinvertebrates, consistent with the presence of *Cheumatopsyche* and *Simulium* in this study. The positive CF–TP correlation suggests nutrient enrichment promotes collector-filterer proliferation, indicating a disturbed condition in the study area [37].

Scrapers dominated at site U6, composed mainly of *Agapetus* (Trichoptera) with a density of 165 individuals/m². At four other sites (U1, U2, U8, and U9), scrapers were the second most abundant FFG, accounting for 14.75%, 14.29%, 28.57%, and 30% of individuals, respectively. Scrapers at U8 were represented by *Psephenus* (Coleoptera), while at the other three sites, they were represented by *Heptagenia* (Ephemeroptera). The high density of scrapers at U6 may be related to the open canopy, which increases light intensity and primary production, thereby enhancing algal growth as a food resource for scrapers [54]. Additionally, their abundance was supported by riffle habitat conditions [55].

Predators were present at all study sites, with proportions ranging from 2.52% to 23.23%, corresponding to 7-95 individuals/m². During the observation period, only site U4 showed predators as the second most abundant FFG, represented by *Rhagovelia* (Hemiptera) with a density of 27 individuals/m². Their abundance depends on prey availability and intra-guild competition for food [56]. Our results also indicated that predator abundance was positively correlated with pH, which may be associated with higher prey availability under slightly alkaline water conditions.

3.5 Attributes of the aquatic ecosystem

The P/R ratio is commonly used to represent the relative energy contribution of primary producers, with values across ecosystems serving as proxies for the proportion of allochthonous versus autochthonous organic matter [57, 58]. In this study, the P/R ratio identified only one site (U6) as autotrophic, while the remaining eight sites were heterotrophic, depending largely on allochthonous riparian organic matter input. Five upstream sites (excluding U6) conformed to the predictions of the River Continuum Concept

(RCC) with P/R < 1. Similarly, the downstream sites (U5 and U7) also showed P/R < 1 (Table 7). In contrast, the midstream site (U8) deviated from RCC expectations, which predict P/R > 1. This discrepancy is likely due to elevated turbidity (Table 4), which can reduce algal production and thus limit food availability for scrapers.

Table 7. The value of the river ecosystem attributes

Sites	P/R	CPOM/FPOM	TFPOM/BFPOM	Substrate Stability	Predator Prey Ratio
	> 0.75	**> 0.5**	**> 0.5**	**> 0.5**	**0.10-0.15**
U1	0.10	0.00	0.05	0.16	0.03
U2	0.23	0.00	0.02	0.26	0.02
U3	0.31	0.00	0.12	0.45	0.28
U4	0.01	0.01	0.04	0.06	0.26
U5	0.00	0.51	0.33	0.32	0.03
U6	1.01	0.07	0.49	1.93	0.09
U7	0.10	0.00	1.15	1.37	0.04
U8	0.57	0.00	0.07	0.67	0.26
U9	0.60	0.00	0.25	1.00	0.25

The CPOM/FPOM ratio indicated low shredder density at all sites except U5, where values slightly exceeded the CPOM/FPOM threshold. This pattern contrasts with RCC predictions, which anticipate higher shredder abundance in upstream reaches. CPOM appears to contribute more to the high density of shredders than FPOM. The filtering collector index, expressed as the TFPOM/BFPOM ratio, was below the threshold (< 0.5) at all sites except U7, indicating that most sites were unsuitable for collector-filterers due to limited transport of FPOM. Site U7, however, supported a macroinvertebrate CF population dominated by *Cheumatopsyche.*

Based on substrate stability, only four sites (U6–U9) provided stable habitats with abundant attachment sites for macroinvertebrates, while the remaining five sites exhibited higher abundance of collector-gatherers. The pronounced channel stability at U6–U9 reflects the presence of suitable substrates, including bedrock, boulders, large cobbles, and coarse woody debris, offering stable surfaces for filter-feeding and scraping macroinvertebrates [58]. Based on the predator-prey ratio, only four sites (U3, U4, U8, and U9) exhibited high predator densities relative to prey, while the remaining sites showed lower predator abundance compared to prey.

4. CONCLUSIONS

The present study indicates that rivers surrounding Lake Maninjau are generally unpolluted based on physicochemical assessments, as reflected by the Pollution Index. However, ecological water quality varied from good to moderately polluted according to the Biotilik and $ASPT^{THAI}$ indices, which were positively correlated with macroinvertebrate diversity and showed sensitivity to nutrient stress, particularly nitrite concentrations. Macroinvertebrate diversity was moderate, with low dominance and a relatively stable community structure. Collector–gatherers dominated the FFG at most sites, followed by scrapers, collector–filterers, predators, shredders, and omnivores. The FFG ratios indicated that most sites were heterotrophic, implying that energy inputs were primarily allochthonous. In tropical volcanic lake basins, routine water quality physicochemical monitoring may mask early signs of ecosystem degradation. Benthic bioindices, particularly their sensitivity to nitrite, and functional feeder structure (such as the absolute dominance of gatherers), provide more sensitive and ecologically significant tools for detecting nutrient stress and ecosystem functional simplification caused by agricultural activities. Further research encompassing wider spatial and temporal scales is recommended to improve understanding of ecological dynamics in these tropical streams.

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