

Research Article

Macrozoobenthos as Bioindicators of Water Quality in a Managed and Restored Tropical River: A Case Study of the Upper Citarum River

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Abstract

Macrozoobenthos and physicochemical water parameters were sampled at five stations along an upstream–downstream gradient from July to September 2025. Community structure was assessed based on taxonomic composition, abundance, and diversity indices, while spatial patterns were explored using non-metric multidimensional scaling (nMDS), hierarchical cluster analysis, and SIMPER. Associations between macrozoobenthos metrics and environmental variables were examined using Spearman's rank correlation. The results revealed pronounced spatial variation in water quality and macrozoobenthos assemblages along the river. Upstream sections were characterized by higher dissolved oxygen, coarser substrates, and the presence of environmentally sensitive insect taxa, indicating relatively good ecological condition. Midstream sections exhibited transitional conditions with mixed assemblages of sensitive, semi-tolerant, and facultative taxa. In contrast, downstream sections were dominated by highly tolerant taxa with low diversity and high dominance, reflecting degraded ecological conditions associated with organic loading, suspended solids, nutrient enrichment, and reduced dissolved oxygen. These findings demonstrate clear ecological structuring of macrozoobenthos assemblages along environmental gradients and reinforce their applied value for ecological monitoring within managed tropical river systems.

Keywords: macrozoobenthos, bioindicator, water quality, Upper Citarum River, tropical river

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1. Introduction

Rivers are vital freshwater ecosystems that support biodiversity and provide essential ecosystem services, including nutrient cycling, water purification, and habitat connectivity (Teristiandi & Yuliana, 2025). However, rivers are among the most threatened ecosystems globally, as anthropogenic activities increasingly degrade water quality (Stoll et al., 2016). Pressures from industrial effluents, agricultural runoff, and urban wastewater inputs alter physicochemical conditions, disrupt aquatic habitats, and ultimately lead to biodiversity loss and overall ecosystem degradation (Gavrilaş et al., 2025). In response to these pressures, river management and restoration programs have been widely implemented to improve water quality and ecological conditions, particularly in heavily impacted river systems.

Macrozoobenthos are widely used as bioindicators in the assessment of aquatic ecosystem health due to their high taxonomic diversity, low mobility, relatively long life cycles, and varying tolerance to pollution (França et al., 2025; Hellen et al., 2020). Because different taxa exhibit contrasting sensitivities to environmental stressors, the presence of sensitive macrozoobenthos generally indicates relatively good water quality, whereas the dominance of tolerant taxa reflects degraded conditions. Their abundance and diversity are strongly influenced by water quality and substrate characteristics, enabling macrozoobenthos assemblages to integrate environmental conditions over time and reflect cumulative impacts of pollution and habitat alteration (Balqish et al., 2024; Wawrzynkowski et al., 2023). In addition, the relative ease of sampling and identification makes macrozoobenthos highly effective for biomonitoring applications (Muntalif et al., 2023).

The presence and distribution of macrozoobenthos are closely associated with surrounding environmental conditions, particularly physicochemical water parameters and habitat characteristics that determine species occurrence and community structure (Balqish et al., 2024). Physical parameters such as water temperature, total suspended solids (TSS), flow velocity, depth, and turbidity directly influence habitat suitability, substrate composition, and physiological stress experienced by macrozoobenthos (Aulia et al., 2020; Hellen et al., 2020; Johan & Ediwarman, 2011; Norhidayah et al., 2016). Chemical parameters, including dissolved oxygen (DO), pH, nitrate, phosphate, and chemical oxygen demand (COD), play a critical role in regulating metabolic processes, oxygen availability, and nutrient dynamics, thereby affecting macrozoobenthos survival and community composition (Amin et al., 2023; Hellen et al., 2020; Setiawan et al., 2013). Changes in physicochemical water properties also influence sediment conditions, which function as the primary substrate for benthic organisms and further shape macrozoobenthos community structure (Balqish et al., 2024).

The Upper Citarum River is part of the Citarum watershed, one of the most important river systems in West Java, Indonesia. The upper catchment originates from Mount Wayang and has a critical role in regulating hydrological and ecological processes within the watershed (Anggraini et al., 2024; Halimatusadiah et al., 2012). The Upper Citarum catchment has experienced significant ecological pressure due to land-use change and domestic and industrial activities, resulting in declining water quality and habitat degradation (Ekasari et al., 2022; Imansyah, 2012; Rosdiana et al., 2022). In response to these pressures, restoration efforts have been implemented under the “Citarum Harum” program to improve water quality and ecological conditions. In this context, the use of biological indicators such as macrozoobenthos provides an effective approach for describing current ecological and water quality conditions under post-restoration management.

Despite the recognized value of macrozoobenthos as bioindicators, most assessments in tropical river systems, including the Citarum River, have primarily emphasized physicochemical parameters or descriptive diversity metrics. Limited studies have integrated biological community patterns with spatial environmental variation in managed tropical rivers. Understanding how environmental variables shape macrozoobenthos assemblages is therefore essential for supporting river management and conservation strategies under increasing anthropogenic pressure (Munyai et al., 2025). This study contributes by combining physicochemical measurements, sediment characteristics, and macrozoobenthos community metrics to provide an integrated assessment of ecological condition in the Upper Citarum River. Accordingly, this study aims to examine spatial variation in macrozoobenthos assemblages in relation to environmental parameters within a managed tropical river system, with emphasis on their applied relevance for ecological monitoring and river management.

2. Methodology

2.1 Study area

The study was conducted in the Upper Citarum River, West Java, Indonesia, a managed tropical river system experiencing varying degrees of anthropogenic pressure. The Upper Citarum is part of the Citarum Harum restoration program, which operates across 23 sectors throughout the watershed, including approximately 8 sectors within the upper basin. All sampling stations (S1–S5) are located within these upper-basin sectors. This study does not differentiate among sector-specific interventions nor apply a before–after restoration design, but instead examines spatial ecological variation within a restoration-managed river system. Five sampling stations were purposively selected along the upper catchment to represent a gradient of

environmental conditions and land-use intensity. The upstream station near the Cikoleberes spring flowing into Lake Cisanti represented relatively minimal anthropogenic disturbance, while the remaining stations were increasingly influenced by domestic, agricultural, industrial, and wastewater-related activities. Field sampling was conducted from July to September 2025.

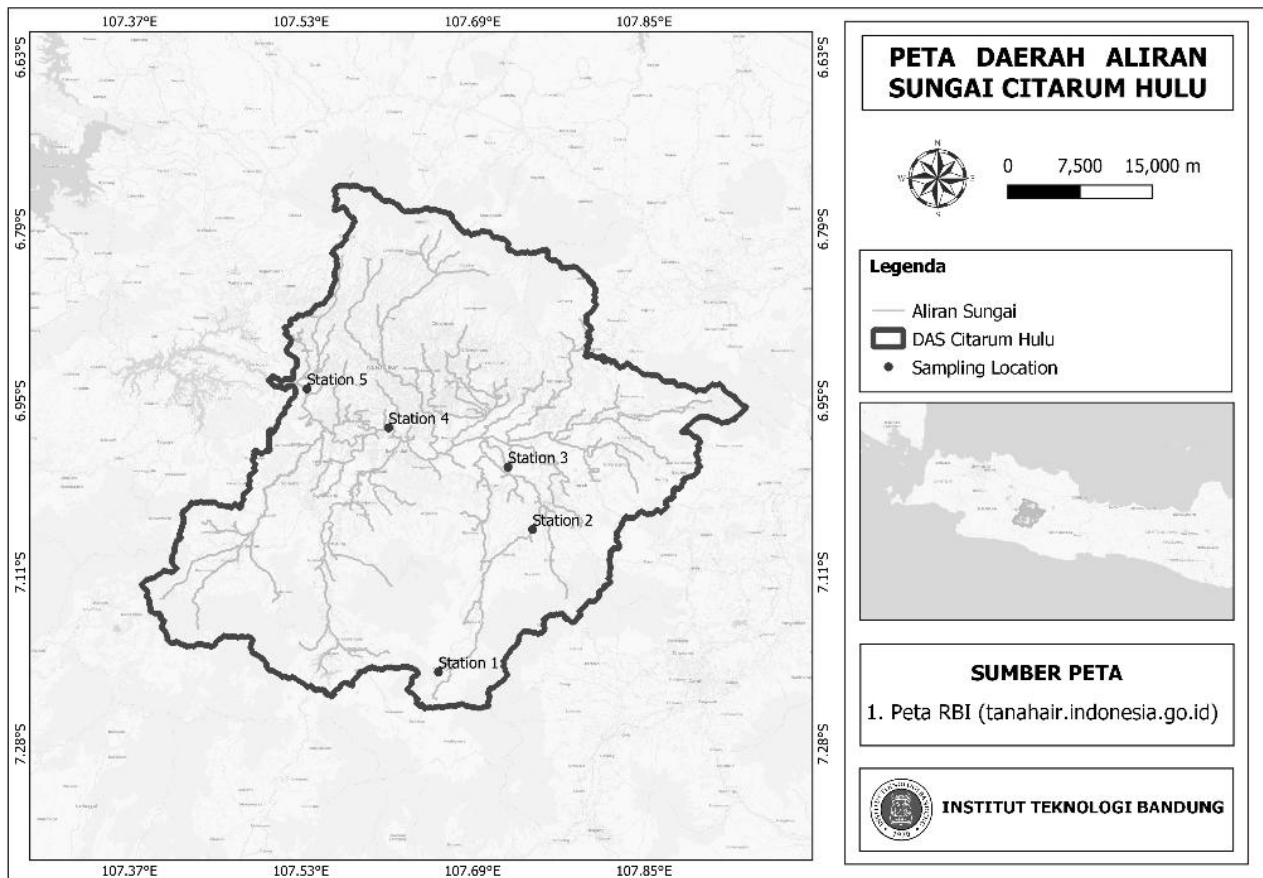


Figure 1. Research location

Table 1. Description of sampling stations and environmental conditions in the Upper Citarum River

Station	Coordinates	Width (m)	Flow velocity (m/s)	Environmental conditions
I	07°12'30" S 107°39'35.37" E	0.8 ± 0.02	0.211 ± 0.006	Forested area; dense riparian vegetation; natural flow with woody debris and leaf litter
II	07°04'26.8" S 107°44'54.7" E	27.08 ± 0.10	0.578 ± 0.051	Residential–agricultural area; sand and gravel extraction; open riparian zone with large stones
III	07°00'55.1" S 107°43'31.0" E	17.15 ± 0.05	0.326 ± 0.069	Mixed land use (residential, industrial); bamboo-dominated riparian zone; semi-open channel
IV	06°58'42.1" S 107°36'46.0" E	69.13 ± 0.06	0.263 ± 0.032	Downstream of WWTP; residential and agricultural areas; open channel with mixed vegetation
V	06°56'29.8" S 107°32'09.1" E	31.73 ± 0.25	0.480 ± 0.152	Dense residential–industrial area; bamboo and tall grasses; solid waste and woody debris

2.2 Macrozoobenthos sampling and identification

Macrozoobenthos sampling was carried out using a Surber net (25 × 40 cm, mesh size 0.5 mm). At each sampling station, sampling was conducted within a river reach of approximately 20 m, where three to five replicate samples were collected depending on substrate heterogeneity. During sampling, bottom substrates were disturbed using the toe of a boot for approximately 2 minutes to dislodge both mobile and sessile taxa, allowing organisms to be transported by the current into the net (Muntalif et al., 2023). Collected organisms were placed in labeled vials and preserved in 70% ethanol or 4–5% formalin prior to laboratory analysis. Macrozoobenthos identification was conducted in the laboratory using a binocular stereomicroscope (Olympus) and carried out to the genus level based on standard taxonomic references by McCafferty & Provonsa, 1983. Genus-level identification was selected because it effectively represents broader environmental conditions and ecological gradients, whereas species-level identification tends to reflect highly localized conditions specific to individual sampling sites (Chzanah, 2018).

2.3 Measurement of environmental variables

Environmental variables were characterized through physicochemical water measurements and sediment sampling at each station. Surface water samples were collected using the grab sampling method in accordance with SNI 6989.57:2008. Water quality analyses were divided into in situ and ex situ measurements. In situ parameters included water temperature, flow velocity, turbidity, pH, and dissolved oxygen (DO), which were measured directly at each sampling station. Ex situ laboratory analyses included total suspended solids (TSS) (SNI 06-6989.3:2004), chemical oxygen demand (COD) (SNI 6989.73:2019), ammonium (NH_3^-) (SNI 06-6989.30:2005), nitrate (NO_3^-) (SNI 06-2480:1991), total phosphorus (TP) (SNI 6989-31:2021), and total nitrogen (TN) (SNI 06-6989.52:2005). Water samples were preserved at approximately 4°C and analyzed in the laboratory following standard procedures. Sediment samples were collected as composite samples from riverbank and mid-channel areas at each station using a shovel and Ekman grab, respectively. Approximately 1 kg of sediment was collected per station and transported to the laboratory for further analysis. Measured physicochemical parameters and sediment characteristics were used to describe environmental conditions and to support the interpretation of macrozoobenthos community structure in the Upper Citarum River.

2.4 Data analysis

Macrozoobenthos community structure was evaluated based on abundance and taxonomic composition at each sampling station. Relationships between physicochemical water parameters and macrozoobenthos abundance were examined using Spearman's rank correlation analysis. Multivariate analyses were applied to explore community structure patterns across stations. Non-metric multidimensional scaling (nMDS) based on Bray–Curtis similarity was used to visualize macrozoobenthos community ordination, supported by hierarchical clustering (UPGMA) and similarity percentage (SIMPER) analysis to identify key taxa contributing to community dissimilarity. All statistical analyses were performed using PAST and R software.

3. Result and Discussion

3.1 Physicochemical water quality and habitat characteristics

Physicochemical water quality and habitat characteristics in the Upper Citarum River varied spatially across sampling stations, reflecting differences in land use, anthropogenic pressure, and river morphology (Table 2 and Table 3). These environmental conditions provide an important ecological context for interpreting macrozoobenthos community responses along the upstream–downstream gradient.

Dissolved oxygen (DO) concentrations ranged from 3.97 to 7.47 mg/L, with higher values observed at upstream stations and lower values at midstream and downstream stations. Several measurements approached or fell slightly below the Class II standard (≥ 4 mg/L), particularly at Station V. Reduced DO levels may impose physiological stress on oxygen-sensitive taxa and promote the dominance of tolerant organisms. Spatial variation in DO was partly associated with increasing water temperature (20.40–28.04 °C), which reduces oxygen solubility (Amin et al., 2023).

Table. 2 Water quality parameters at each sampling station in the Upper Citarum River

No.	Parameter	Unit	Station					Class II Water Quality Standard (PP No. 22 of 2021)
			ST I	ST II	ST III	ST IV	ST V	
1	Temperature	°C	20.40 ± 0.83	25.01 ± 1.66	28.04 ± 2.47	27.08 ± 2.24	25.42 ± 0.55	-
			7.73 ± 0.03	7.99 ± 0.23	6.90 ± 0.15	6.95 ± 0.11	7.09 ± 0.07	
2	pH	-	7.73 ± 0.03	7.99 ± 0.23	6.90 ± 0.15	6.95 ± 0.11	7.09 ± 0.07	6-9
			7.73 ± 0.03	7.99 ± 0.23	6.90 ± 0.15	6.95 ± 0.11	7.09 ± 0.07	
3	Electrical Conductivity (EC)	µS/cm	219 ± 12.49	181.67 ± 6.23	641.33 ± 200.35	600.67 ± 79.29	505.56 ± 79.29	-
			219 ± 12.49	181.67 ± 6.23	641.33 ± 200.35	600.67 ± 79.29	505.56 ± 79.29	
4	TDS	mg/L	110.33 ± 6.01	93.22 ± 2.78	319.22 ± 94.59	297.67 ± 40.92	247 ± 41.79	1000
			110.33 ± 6.01	93.22 ± 2.78	319.22 ± 94.59	297.67 ± 40.92	247 ± 41.79	
5	DO	mg/L	6.76 ± 0.51	7.47 ± 0.70	5.97 ± 0.21	4.14 ± 0.72	3.97 ± 0.37	≥ 4
			6.76 ± 0.51	7.47 ± 0.70	5.97 ± 0.21	4.14 ± 0.72	3.97 ± 0.37	
6	Turbidity	NTU	7.38 ± 0.64	175.33 ± 55.65	133.22 ± 53.40	109.78 ± 22.88	133.89 ± 12.58	-
			7.38 ± 0.64	175.33 ± 55.65	133.22 ± 53.40	109.78 ± 22.88	133.89 ± 12.58	
7	TSS	mg/L	7.83 ± 0.52	175.08 ± 49.75*	119.83 ± 32.30*	59.17 ± 40.49*	95.00 ± 7.57*	50
			7.83 ± 0.52	175.08 ± 49.75*	119.83 ± 32.30*	59.17 ± 40.49*	95.00 ± 7.57*	
8	COD	mg/L	9.40 ± 1.13	16.74 ± 0.91	37.44 ± 7.09*	36.69 ± 7.75*	46.28 ± 7.80*	25
			9.40 ± 1.13	16.74 ± 0.91	37.44 ± 7.09*	36.69 ± 7.75*	46.28 ± 7.80*	
9	Nitrate	mg/L	0.20 ± 0.26	1.61 ± 1.22	1.12 ± 0.60	0.92 ± 0.20	0.44 ± 0.08	10
			0.20 ± 0.26	1.61 ± 1.22	1.12 ± 0.60	0.92 ± 0.20	0.44 ± 0.08	
10	Ammonia	mg/L	0.02 ± 0.00	0.02 ± 0.00	3.09 ± 4.64*	4.83 ± 2.51*	4.50 ± 1.36*	0.2
			0.02 ± 0.00	0.02 ± 0.00	3.09 ± 4.64*	4.83 ± 2.51*	4.50 ± 1.36*	
11	Total Phosphorus (Total P)	mg/L	0.31 ± 0.13	0.29 ± 0.11	0.35 ± 0.08*	0.52 ± 0.14*	0.45 ± 0.19*	0.2
			0.31 ± 0.13	0.29 ± 0.11	0.35 ± 0.08*	0.52 ± 0.14*	0.45 ± 0.19*	
12	Total Nitrogen (Total N)	mg/L	2.62 ± 2.20	4.37 ± 0.91	10.67 ± 0.62	9.87 ± 1.16	8.70 ± 0.43	15
			2.62 ± 2.20	4.37 ± 0.91	10.67 ± 0.62	9.87 ± 1.16	8.70 ± 0.43	

Turbidity (7.38–175.33 NTU) and total suspended solids (TSS) (7.83–175.08 mg/L) showed elevated values at Stations II–V, indicating increased sediment input and physical disturbance. High suspended solids can alter substrate composition, reduce habitat stability, and impair feeding and respiration in benthic organisms (Hellen et al., 2020), thereby reducing suitability for sensitive taxa and favoring tolerant groups. Organic pollution also exhibited clear spatial variation. COD concentrations ranged from 9.40 to 46.28 mg/L, with higher values at midstream and downstream stations, reflecting increased organic loading. Elevated COD indicates greater oxygen demand during decomposition processes and may contribute to reduced DO availability, indirectly promoting tolerant taxa (Pratiwi & Mirwan, 2022).

Nutrient concentrations further indicated environmental pressure. Nitrate remained below the Class II standard at all stations, whereas ammonia (0.02–4.83 mg/L) exceeded the standard at several midstream and downstream stations. Total phosphorus (0.29–0.52 mg/L) also surpassed the regulatory threshold in impacted sections. Elevated ammonia and phosphorus levels are associated with organic enrichment and may contribute to ecological stress and community simplification through enhanced oxygen consumption and habitat degradation (Dauhan et al., 2014; Hellen et al., 2020).

Sediment characteristics further modulated macrozoobenthos responses. Upstream stations dominated by coarser substrates (gravelly sand and sand) provided more stable habitats with greater oxygen exchange,

supporting higher diversity. In contrast, downstream sections characterized by finer sediments (silt and clay) likely experienced reduced permeability and oxygen penetration, favoring burrowing and pollution-tolerant taxa. These substrate differences interact with water quality conditions to structure macrozoobenthos assemblages along the river continuum (Irmawan et al., 2010).

Table 3. Substrate composition and texture at each sampling station in the Upper Citarum River

Station	Substrate fraction				Texture
	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	
I	11.62	86.92	NA	NA	Gravelly sand
II	0.31	98.06	NA	NA	Sand
III	NA	34.13	52.2	13.67	Silty sand
IV	4.5	46.52	34.35	14.62	Sandy loam
V	1.18	84.92	7.96	5.95	Sand

3.2 Macrozoobenthos community structure and composition

Macrozoobenthos assemblages in the Upper Citarum River exhibited pronounced spatial variation among sampling stations, as reflected by differences in taxonomic composition at the order level and community metrics. A total of 11 macrozoobenthos orders were recorded across the study area, including Ephemeroptera, Trichoptera, Diptera, Odonata, Coleoptera, Hemiptera, Architaenioglossa, Hygrophila, Tubificida, Rhynchobdellida, and Isopoda (Table 4).

Table 4. Taxonomic composition of macrozoobenthos identified at each sampling station in the Upper Citarum River

Order	Genus	S1	S2	S3	S4	S5
Ephemeroptera	<i>Baetis</i> sp.	+	+	-	-	-
	<i>Ephemera</i> sp.	+	-	-	-	-
Trichoptera	<i>Hydropsyche</i> sp.	+	+	+	-	-
Diptera	<i>Chironomus</i> sp.	-	+	+	-	-
	<i>Ormosia</i> sp.	+	-	-	-	-
Odonata	<i>Enallagma</i> sp.	-	+	-	-	-
	<i>Libellula</i> sp.	-	+	+	-	-
Coleoptera	<i>Stenelmis</i> sp.	+	-	-	-	-
	<i>Agabus</i> sp.	-	+	+	-	-
	<i>Hydrocanthus</i> sp.	-	+	+	-	+
Hemiptera	<i>Belostoma</i> sp.	+	-	-	-	-
Architaenioglossa	<i>Sulcospira</i> sp.	+	-	-	-	-
Hygrophila	<i>Lymnaea</i> sp.	-	+	+	-	-
	<i>Physastra</i> sp.	-	+	+	-	-
	<i>Gyraulus</i> sp.	-	-	+	-	-
	<i>Filopaludina</i> sp.	-	-	+	-	-
	<i>Pila</i> sp.	-	-	+	-	-
Tubificida	<i>Lumbriculus</i> sp.	+	-	-	-	-
	<i>Tubifex</i> sp.	-	-	+	+	+
Rhynchobdellida	<i>Hirudinaria</i> sp.	-	+	+	-	-
	<i>Helobdella</i> sp.	-	+	+	+	+
Isopoda	<i>Asellus</i> sp.	+	-	-	-	-

Notes: + = present; - = absent.

Upstream stations, particularly Station 1 (S1), were characterized by the presence of insect orders commonly associated with relatively good water quality and well-oxygenated habitats, especially Ephemeroptera and Trichoptera (Table 4). These orders are widely recognized as environmentally sensitive taxa with low tolerance to physicochemical disturbances, particularly reductions in dissolved oxygen and increased organic enrichment (Wilhm, 1975 cited in Faza, 2015). Insect taxa constituted the majority of individuals at S1, indicating that environmentally sensitive groups dominated the assemblage under low environmental stress. This quantitative pattern is reflected in moderate diversity ($H' = 1.48$) and relatively low dominance ($D = 0.36$) values (Table 5), suggesting a relatively balanced community structure consistent with low environmental stress. Such assemblages are typically associated with stable benthic habitats and limited anthropogenic disturbance.

Table 5. Macrozoobenthos community metrics in the Upper Citarum River

Station	Taxa (S)	Individuals (total)	Shannon (H')	Simpson ($1-D$)	Dominance (D)	Evenness (J)
S1	11	251	1.48 ± 0.21	0.64 ± 0.07	0.36 ± 0.07	0.67 ± 0.03
S2	14	207	2.15 ± 0.04	0.83 ± 0.01	0.17 ± 0.01	0.84 ± 0.03
S3	13	180	1.93 ± 0.53	0.76 ± 0.18	0.24 ± 0.18	0.78 ± 0.21
S4	2	714	0.23 ± 0.01	0.12 ± 0.01	0.89 ± 0.01	0.33 ± 0.01
S5	3	376	0.32 ± 0.04	0.15 ± 0.02	0.85 ± 0.01	0.33 ± 0.03

Station 2 (S2) exhibited the highest order richness and supported a heterogeneous assemblage comprising both insect and non-insect orders, including Ephemeroptera, Trichoptera, Diptera, Odonata, Coleoptera, Gastropoda, and Hirudinea (Table 4). The coexistence of environmentally sensitive insect orders with taxa exhibiting intermediate tolerance suggests transitional environmental conditions between upstream and downstream reaches. Several taxa recorded at S2 belong to the semi-tolerant group, characterized by the ability to persist across a broader range of environmental conditions than strictly intolerant taxa, while still requiring relatively good water quality (Wilhm, 1975 cited in Faza, 2015). This mixed assemblage is consistent with the high diversity ($H' = 2.15$) and evenness ($J = 0.84$) values observed at S2 (Table 5), indicating moderate ecological disturbance rather than severe degradation. The balanced contribution of sensitive and semi-tolerant taxa reflects intermediate stress intensity, where environmental pressures are present but not yet sufficient to cause strong community simplification.

At Station 3 (S3), macrozoobenthos composition began to shift toward increased representation of taxa with higher tolerance to environmental stress. In addition to several insect orders, S3 was consistently characterized by the presence of Gastropoda and Oligochaeta (Tubificida). Several gastropod taxa recorded at this station can be categorized as facultative organisms capable of inhabiting a wide range of environmental conditions, from relatively good water quality to moderately polluted waters (Aulia et al., 2020). This compositional shift corresponds with reduced diversity ($H' = 1.93$) and increased dominance compared to S2 (Table 5), indicating early signs of community restructuring under moderate environmental pressure. The increasing representation of facultative and tolerant taxa suggests progressive ecological filtering associated with elevated organic loading and nutrient enrichment.

In contrast, downstream stations (S4 and S5) exhibited markedly simplified macrozoobenthos assemblages dominated by highly tolerant taxa, particularly Oligochaeta (Tubificida) and Hirudinea (Rhynchobdellida) (Table 4). Species within Tubificida, such as *Tubifex* sp., are well known for their high tolerance to low dissolved oxygen conditions and elevated organic matter due to their deposit-feeding behavior and physiological adaptability (Aulia et al., 2020). The numerical dominance of these tolerant taxa is reflected in extremely low diversity values ($H' < 0.35$), high dominance ($D > 0.85$), and low evenness ($J = 0.33$) despite high total abundance (Table 5). Such community structures are characteristic of environments experiencing sustained organic enrichment, reduced oxygen availability, and habitat degradation, where only a limited number of highly tolerant taxa are able to persist. This pattern indicates strong ecological simplification under elevated stress conditions.

These combined patterns of taxonomic composition (Table 4) and community metrics (Table 5) demonstrate a clear longitudinal transition from diverse, insect-dominated assemblages in upstream reaches to simplified, tolerance-dominated communities in downstream sections. This spatial structuring reflects increasing environmental stress along the river continuum, demonstrating how increasing environmental stress constrains community complexity toward downstream sections.

3.3 Spatial patterns and associations with environmental variables

Spatial ordination using non-metric multidimensional scaling (nMDS) based on Bray–Curtis dissimilarity revealed clear separation of macrozoobenthos assemblages among sampling stations along the Upper Citarum River (Figure 2). Replicates from the same station clustered closely together, indicating consistent community composition within stations, while distinct separation was observed among upstream, midstream, and downstream stations. This pattern reflects a longitudinal gradient in macrozoobenthos community structure corresponding to changes in environmental conditions along the river.

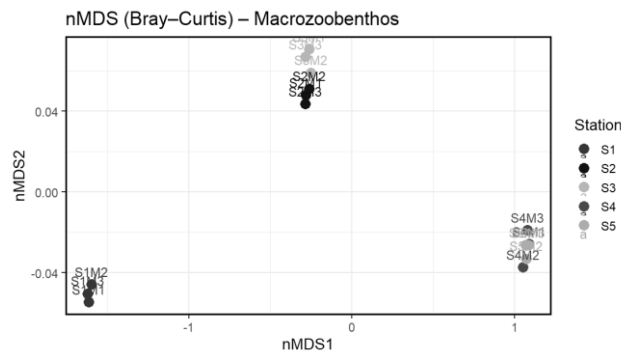


Figure 2. Non-metric multidimensional scaling (nMDS) ordination of macrozoobenthos communities based on Bray–Curtis similarity across sampling stations in the Upper Citarum River

The nMDS pattern was further supported by hierarchical cluster analysis (HCA), which grouped sampling stations into distinct clusters representing upstream (S1), midstream (S2–S3), and downstream (S4–S5) sections (Figure 3). The clustering pattern highlights strong similarity among replicates within each station and clear dissimilarity between river sections, particularly between upstream and downstream reaches, indicating pronounced spatial structuring of macrozoobenthos assemblages.

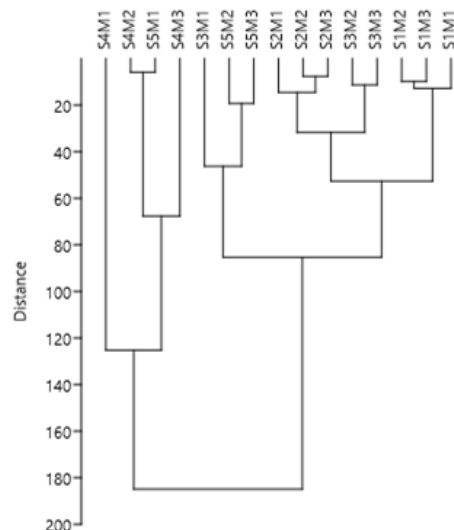


Figure 3. Hierarchical cluster analysis (UPGMA) of macrozoobenthos communities based on Bray–Curtis similarity across sampling stations in the Upper Citarum River

Spearman rank correlation analysis demonstrated that macrozoobenthos community metrics were closely associated with physicochemical parameters related to oxygen availability, suspended solids, organic loading, and nutrient enrichment (Figure 4). Dissolved oxygen showed positive associations with taxa richness and diversity, consistent with its essential role in supporting macrozoobenthos metabolism, growth, and survival

(Amin et al., 2023; Valentino et al., 2022). In contrast, turbidity and total suspended solids were generally associated with reduced diversity, reflecting their influence on light penetration, oxygen availability, and benthic habitat quality (Hellen et al., 2020; Muzammil et al., 2021). Elevated COD and nutrient concentrations, particularly ammonia and total phosphorus, indicate organic enrichment that enhances oxygen consumption and promotes tolerant taxa (Hellen et al., 2020; Irmawan et al., 2010; Pratiwi & Mirwan, 2022). These correlations further support the role of oxygen depletion and organic enrichment as primary drivers of community simplification in downstream reaches.

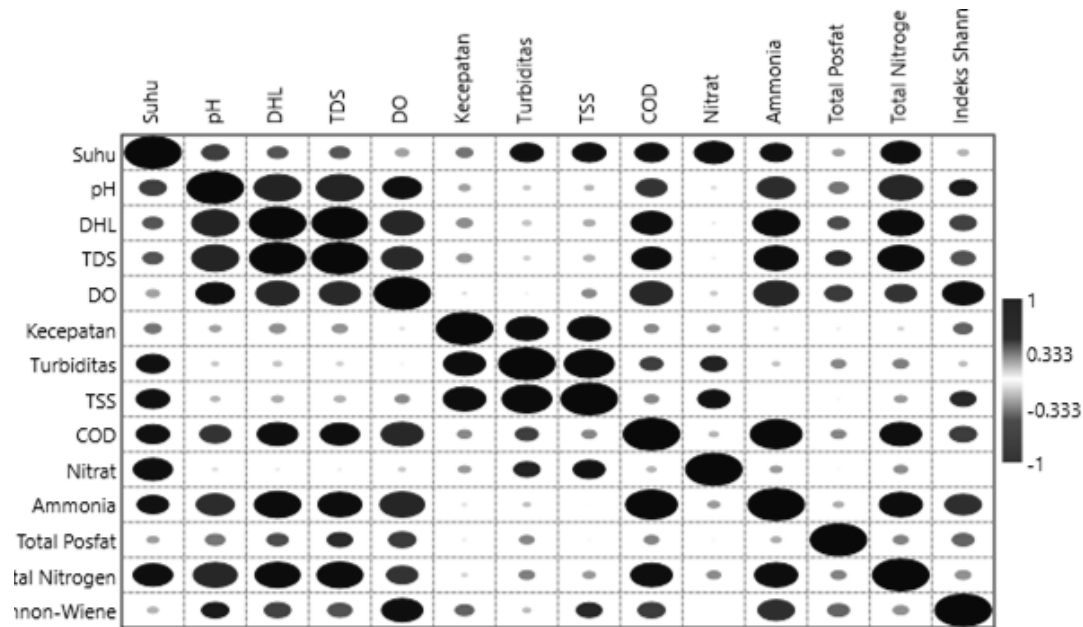


Figure 4. Spearman rank correlation matrix between physicochemical water parameters and macrozoobenthos metrics in the Upper Citarum River

SIMPER analysis provided further insight into the biological drivers of community dissimilarity among station pairs (Figure 5). Differences involving downstream stations were primarily driven by high contributions from a limited number of tolerant taxa, particularly *Tubifex sp.* and *Helobdella sp.*, which are known to thrive under conditions of elevated organic matter, low dissolved oxygen, and fine sediment substrates. In contrast, dissimilarities between upstream and midstream stations were more strongly influenced by insect taxa associated with better water quality, reflecting shifts from sensitive to more tolerant assemblages along the river continuum.

SIMPER Contribution Heatmap (Top 10 Taxa per Pair)

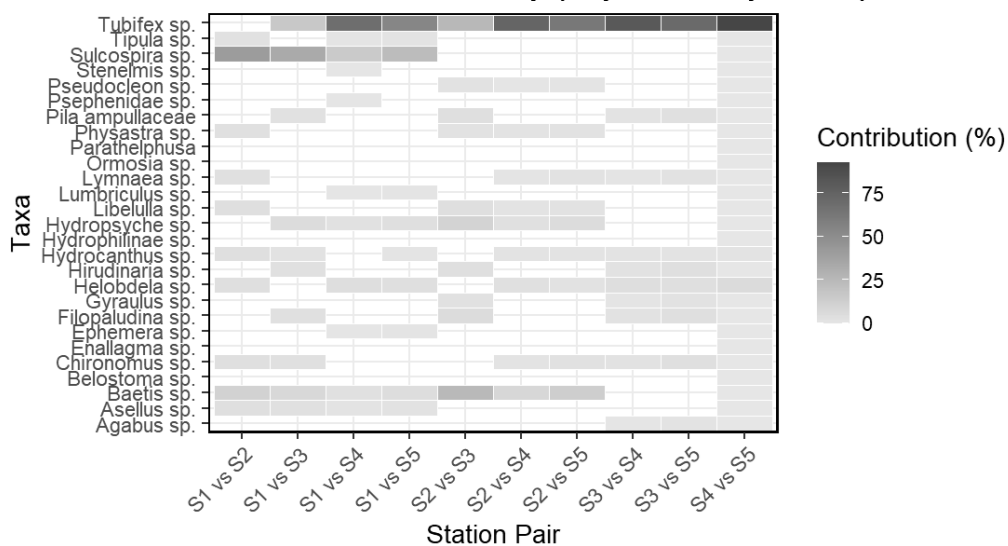


Figure 5. SIMPER contribution heatmap showing the top taxa contributing to dissimilarities in macrozoobenthos community composition among station pairs in the Upper Citarum River

The integrated results of ordination, clustering, correlation, and SIMPER analyses demonstrate that spatial variation in macrozoobenthos assemblages along the Upper Citarum River is strongly structured by gradients in water quality and habitat conditions. These analyses collectively indicate a transition from relatively diverse, insect-dominated assemblages in upstream reaches to simplified, tolerance-dominated communities in downstream sections, providing robust biological evidence of spatial heterogeneity in ecological condition across the river system. The consistent clustering pattern further confirms that macrozoobenthos assemblages respond predictably to spatial variation in environmental stress intensity.

3.4 *Bioindicator-based interpretation of ecological condition*

The integrated assessment of taxonomic composition, community metrics, and spatial analyses demonstrates clear spatial differentiation in ecological condition along the Upper Citarum River. Macrozoobenthos assemblages responded consistently to gradients in oxygen availability, organic loading, suspended solids, and nutrient enrichment, indicating strong ecological structuring under spatially variable environmental stress.

Upstream reaches, particularly Station 1 (S1), exhibited relatively good ecological integrity, characterized by environmentally sensitive insect taxa (e.g., Ephemeroptera and Trichoptera), moderate diversity, and low dominance. Such assemblages are typically associated with well-oxygenated and minimally disturbed habitats (Hellen et al., 2020), suggesting lower ecological stress in upstream sections. Midstream stations (S2 and S3) reflected transitional ecological conditions, as the coexistence of sensitive, semi-tolerant, and facultative taxa indicates moderate environmental pressure. These assemblages suggest partially impacted habitats that remain functionally capable of supporting diverse communities but are increasingly influenced by organic inputs and sediment disturbance. In contrast, downstream stations (S4 and S5) displayed pronounced ecological degradation. Communities were dominated by highly tolerant taxa, particularly Oligochaeta (Tubificida) and Hirudinea (Rhynchobdellida), accompanied by very low diversity and high dominance despite elevated total abundance. Such simplified assemblages are widely recognized as characteristic of systems experiencing sustained organic enrichment and oxygen stress (Pratiwi & Mirwan, 2022; Wawrzynkowski et al., 2023), where increasing environmental stress constrains community complexity and resilience. These findings suggest that reducing organic loading, nutrient inputs, and suspended solids remains essential for improving ecological condition in downstream sections. Macrozoobenthos-based assessment thus provides an integrative biological framework for identifying priority intervention zones within managed tropical river systems.

3.5 *Implications for managed and restored river systems*

Although this study does not employ a before–after restoration design, the observed spatial differentiation in macrozoobenthos assemblages provides insight into ecological structuring within the restoration-managed Upper Citarum River. The dominance of tolerant taxa in downstream sections suggests that organic enrichment and suspended solids continue to influence ecological conditions across river segments. These findings highlight the importance of integrating biological community assessment into restoration monitoring frameworks. In contexts where long-term pre-restoration data are limited, macrozoobenthos-based assessment can serve as a complementary tool for tracking ecological trajectories under ongoing watershed management.

4. Conclusion

This study demonstrates that macrozoobenthos communities effectively reflect spatial variation in water quality and ecological condition along the Upper Citarum River. Upstream reaches exhibited relatively good ecological condition, characterized by the presence of environmentally sensitive insect orders, moderate diversity, and low dominance, while midstream sections showed transitional conditions with mixed assemblages of sensitive, semi-tolerant, and facultative taxa. In contrast, downstream reaches were dominated by highly tolerant taxa, accompanied by very low diversity and high dominance, indicating degraded

ecological conditions associated with elevated organic loading, suspended solids, nutrient enrichment, reduced dissolved oxygen, and finer sediment substrates. These results highlight a clear upstream–downstream gradient in ecological condition and support the use of macrozoobenthos as reliable bioindicators for assessing water quality in managed tropical river systems.

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