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Assessing the Ecological Status of the Curug Tilu Leuwi Opat Waterfall Using Macroinvertebrates and Physicochemical Parameters

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Abstract. *Anthropogenic activities increasingly threaten freshwater availability. The Curug Tilu Leuwi Opat waterfall in the Cimahi River, an important water source for surrounding communities and a popular tourist site, requires an ecological assessment to support effective water management. This study aims to provide an initial overview of the ecological status of waters through an integrative approach that combines benthic macroinvertebrates and physicochemical parameters. Sampling was conducted in two waterfall streams, Kacapi and Aseupan, which are part of the Curug Tilu Leuwi Opat waterfall system. Physicochemical parameters measured included temperature, flow velocity, pH, dissolved oxygen, conductivity, and total dissolved solids. Benthic macroinvertebrates were collected using a Surber net and identified to the lowest feasible taxonomic level, typically morphospecies with some taxa at the family level, and subsequently analyzed using the Shannon–Wiener index, Simpson's dominance, the Family Biotic Index (FBI), and Canonical Correspondence Analysis. Results indicated excellent water quality (FBI at Kacapi = 4.17; Aseupan = 4.24), driven by the presence of pollution-sensitive taxa from Leptophlebiidae, Tipulidae, and Perlidae, while the slightly higher FBI at Aseupan reflected several moderately tolerant families such as Physidae and Simuliidae. Benthic macroinvertebrate diversity was moderate with no dominant species, indicating stable community structure. Most measured parameters that met established standards met Class I criteria, while dissolved oxygen, conductivity, and flow velocity emerged as the dominant variables shaping community structure. Overall, the aquatic ecological status was excellent, highlighting the role of aquatic biodiversity as a scientific basis for sustainable environmental management.*

Keywords*: biodiversity, bioindicator, limnology, macroinvertebrates, physicochemical*

Citation
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INTRODUCTION

The availability of freshwater is a fundamental aspect of natural resource management and environmental sustainability. Globally, freshwater accounts for only about 2.5% of Earth's total water volume, with the largest share locked in polar ice and deep groundwater that is difficult to access (Mishra, 2023). This condition renders freshwater a vital resource that demands integrated and sustainable management. The pressure on its quality and availability continues to increase due to population growth, land-use change, tourism activities, waste discharge, and climate change, all of which cumulatively accelerate the degradation of aquatic ecosystems (Wang et al., 2019; Jones et al., 2023). In response to these challenges, evaluating the ecological status of water bodies through an integrated approach combining physicochemical parameters and biological indicators has become a strategic and representative means of assessing actual ecosystem conditions and their responses to environmental pressures (Martinez-Haro et al., 2015).

Benthic macroinvertebrates are one of the most widely used biological indicators in ecological assessments of aquatic systems. These aquatic invertebrates, ≥1 mm in size, inhabit the bottom substrate and are relatively immobile, enabling them to reflect localized environmental conditions (Fachrul, 2012) accurately. Differences in taxa' tolerance to variations in physicochemical parameters make the structure of macroinvertebrate communities a sensitive and representative biological indicator of water quality (Tampo et al., 2021). These organisms are distributed across a wide range of aquatic ecosystems, both lentic and lotic, making them applicable in diverse contexts for aquatic ecological studies (Buffagni, 2021).

The Curug Tilu Leuwi Opat waterfall is part of the regional hydrological system in West Bandung Regency, supplied by Situ Lembang and several mountain springs. This area serves important ecological functions as a natural habitat and utilitarian functions as a source of clean water for local communities, while also functioning as a nature-based tourism destination, making it a critical area to evaluate and conserve. However, excessive water use and intensified tourism activities may threaten the quality of aquatic ecosystems in Curug Tilu Leuwi Opat. To date, no scientific studies have assessed the ecological status of water bodies in this area. This study was conducted in two waterfall segments, Kacapi and Aseupan, to provide an initial overview of the ecological status of the water bodies through an integrative approach combining macroinvertebrate community analysis and physicochemical parameters, in support of efficient, adaptive, and evidence-based environmental management.

MATERIALS AND METHODS

Study Site

This research was conducted at Curug Tilu Leuwi Opat, a natural complex consisting of three waterfalls located in the upper reaches of the Cimahi River (6°47′15.014″S, 107°34′56.238″E) in West Bandung Regency, West Java Province, Indonesia. Based on accessibility, tourism intensity, and proximity to residential areas, two waterfalls were selected as study sites: Aseupan (upstream; sites A1–A3) and Kacapi (downstream; sites K1–K3). At each waterfall, three sampling sites were established based on distance from the plunge pool. At Aseupan, A1 was located 5 m from the waterfall, while A2 and A3 were 10 m and 15 m downstream, respectively, all with sandy–rocky substrates. At Kacapi, site K1 (5 m) had predominantly rocky substrates with abundant pebbles, K2 (10 m) had muddy substrates with scattered pebbles and rocks, and K3 (15 m) had mixed muddy–rocky substrates with noticeable pebble presence (Figure 1).

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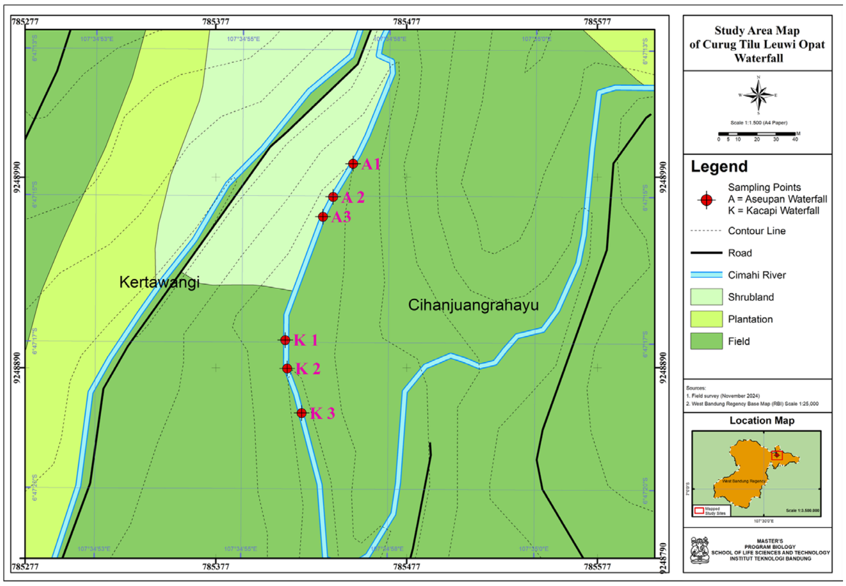

Figure 1. Study area map of Curug Tilu Leuwi Opat along the Cimahi River, West Bandung Regency. The map shows the distribution of sampling points at Aseupan Waterfall (A1–A3) and Kacapi Waterfall (K1–K3)

Field surveys were conducted twice during the early rainy season, with one sampling campaign in late November and another in mid-December 2024. Benthic samples were collected using a Surber net, and water samples were taken simultaneously at each site to assess physicochemical conditions. According to the Meteorology, Climatology, and Geophysics Agency (BMKG), West Java received moderate to heavy rainfall (100–500 mm) during this period, indicating elevated stream discharge typical of early-wet-season hydrology.

Physicochemical Water Analysis

At each location, physical and chemical factors were measured: water temperature, flow velocity, Dissolved Oxygen (DO), Total Dissolved Solids (TDS), conductivity, and pH. Water sampling was carried out using dark bottles at a depth of 10–30 cm, and the samples were measured in situ using a water quality meter (AZ 86031) provided by the Ecology Laboratory, School of Life Sciences and Technology, Institut Teknologi Bandung. Flow velocity was measured using the method described by Razak et al. (2024), with a buoy and the distance traveled per unit time. Measurements of physicochemical parameters were carried out between 07.00 and 09.00 local time.

Benthic Macroinvertebrate Analysis

Benthic macroinvertebrates were collected using a Surber net (250 µm mesh; 25×40 cm opening) positioned on the stream substrate. At each site, the substrate within the frame was hand-disturbed to dislodge organisms into the net, after which samples were manually sorted. One Surber sample was collected per site during each sampling campaign, yielding three replicates per waterfall per period. All specimens were preserved in 70% alcohol for laboratory identification (Hussen et al., 2019).

Sample Identification

The collected macroinvertebrate samples were examined under a stereo microscope (Nikon SMZ445) at the Ecology Laboratory, School of Life Sciences and Technology, Institut Teknologi Bandung. Identification was carried out to the morphospecies level using Smith et al. (2019) and the online resource gbif.org.

Data Analysis:

All calculations for macroinvertebrate density, Shannon–Wiener diversity, Simpson dominance, and the Family Biotic Index were performed in Microsoft Excel 2024. Pearson correlation and Canonical Correspondence Analysis (CCA) were conducted in R version 4.4.2 using the vegan package.

Macroinvertebrate Density

At each location, macroinvertebrate density (individuals m⁻²) was calculated using the following equation (Zhao et al., 2015):

$$N = \frac{O}{S} \times 10000 \qquad (1)$$

where O is the number of individuals counted per sample and S is the area of the Surber net in cm².

Community Structure:

At each site, variation and community structure of macroinvertebrates was assess using Shannon-Wiener diversity index (H'). The calculation was based on the relative proportion of each taxon (Kunakh et al., 2023), combining species and family levels due to taxonomic identification limitations. This approach was also applied by Retnaningdyah et al. (2023) under similar constraints. The H' value was interpreted as a supporting indicator of water quality and community structure stability.

$$H' = -\sum pi \times \ln \times pi \qquad (2)$$

where p_i is the proportion of individuals of taxon i to the total (n_i/N), and ln is the natural logarithm. To determine the presence of dominant taxa in the macroinvertebrate community, the Simpson dominance index was calculated. The index was calculated as follows (Fedor & Zvaríková, 2019):

$$D = \left(\frac{ni}{N}\right)^2 \qquad (3)$$

where n_i is the total number of individuals of taxon i, and N is the total number of individuals in the community. A value approaching 1 indicates the dominance of a single macroinvertebrate taxon.

Family Biotic Index (FBI)

To assess water quality, Family Biotic Index (FBI) was used based on the tolerance values of each macroinvertebrate family to organic pollution (Hilsenhoff, 1988; Mandaville, 2002). The FBI was chosen for its ability to provide a quick and simple assessment in a preliminary study. The tolerance values were used without modification due to limited local data. Tolerance values range from 0 to 10, where lower values represent pollution-sensitive families and higher values indicate more pollution-tolerant taxa. Consequently, higher average tolerance values increase the resulting FBI score, which reflects poorer water quality. For long-term monitoring, adjustments to the FBI based on Indonesian-specific conditions are recommended. The FBI was calculated as follows:

$$FBI = \frac{\sum_{ni \times ti}}{\sum_{N}} \qquad (4)$$

where n_i is the number of individuals of family i, t_i is the family's tolerance value, and N is the total number of individuals. Interpretation of FBI values followed the classification by Hilsenhoff (1988), as cited in Mandaville (2002): 0.00–3.75: excellent water quality, no pollution; 3.76–4.25: very good, very low organic pollution; 4.26–5.00: good, moderate organic pollution; 5.01–5.75: fair, substantial organic pollution; 5.76–6.50: poor, high organic pollution; 6.51–7.25: very poor; 7.25: extremely poor, generally unsuitable for aquatic life.

Environmental Correlation and Ordination Analysis

Prior to ordination, Pearson's correlation analysis was applied to examine potential multicollinearity among environmental parameters. Highly correlated variables (r≥ 0.8) were excluded to minimize redundancy and ensure the independence of explanatory factors. The selection of variables for ordination was guided by both statistical independence and ecological relevance, emphasizing parameters that represent major physicochemical gradients influencing aquatic biota.

Canonical Correspondence Analysis (CCA)

Canonical Correspondence Analysis (CCA) was employed to investigate the relationships between macroinvertebrate assemblages and the selected environmental variables. Community data were standardized prior to analysis, and the ordination was based on a species–environment biplot. Arrows representing environmental variables indicate both the direction and strength of their influence on community distribution, while species positions reflect their ecological affinities along the measured gradients.

RESULTS AND DISCUSSION

Physicochemical Water Quality

Based on the physicochemical analysis, the water conditions at both Kacapi and Aseupan waterfalls are relatively similar (Table 1). Dissolved oxygen (DO) levels at both sites were relatively high and met the Class I water quality standards. The elevated DO concentrations were likely influenced by oxygen diffusion from the atmosphere, enhanced by the fast-flowing nature of the stream and the relatively shallow water depth of approximately 50 cm (Filter et al., 2017). The low organic matter content may also have contributed to the high DO levels by reducing microbial respiration activity (Hertika et al., 2022). In addition, turbulence generated by strong surface currents likely contributed to increased oxygen diffusion (Bullee et al., 2024). DO concentrations above 5 mg/L are highly supportive of benthic macroinvertebrate life, as they sustain aerobic respiration (Arfiati et al., 2025).

Water temperatures at both sites met the Class I water quality standard, which requires that the difference between water and ambient air temperatures does not exceed 3°C. The measured differences were minimal (Kacapi: 0.10°C; Aseupan: 0.23°C), indicating thermally stable conditions during sampling. The recorded water temperatures (19–22°C) were relatively low due to rainy-season conditions. This temperature is slightly below the optimal range for maximum macroinvertebrate activity, which is 25–32°C (Basyuni et al., 2018).

Conductivity values at both sites were low, indicating minimal dissolved ion content. Although World Health Organization (WHO) does not specify a numerical threshold for electrical conductivity, the observed values were substantially lower than those typically reported for tropical freshwater systems (150–270 µS/cm; Retnaningdyah et al., 2023), suggesting very low ionic loads. In contrast, Total Dissolved Solids (TDS) can be directly compared with international and national standards. The measured TDS levels (≈26–27 mg/L) were far below the WHO guideline for drinking water (<500 mg/L) (WHO, 2008). These values were also well within the Indonesian Class I water quality standard, which requires very low dissolved-solids content for high-quality surface waters. Taken together, the low EC and TDS values provide strong evidence that the water quality at both sites was excellent (Basyuni et al., 2018).

The measured pH values ranged from 6.7 to 7.1, falling within the Class I standard range (6–9) and within the optimal range for benthic macroinvertebrates (5–9) (Wang et al., 2019). Streamflow velocity at Kacapi was observed to be higher than at Aseupan, likely due to its lower elevation and upstream contribution from Aseupan. The substrate at Kacapi, dominated by pebbles with only a few scattered boulders, may have also contributed to the higher water flow velocity observed at this site. Substrate characteristics are known to play an important role in shaping local flow field conditions, with riverbed particle size influencing hydrodynamic patterns (Xu et al., 2024).

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Government Regulation No. 22/2021, all observed physicochemical parameters at Curug Tilu Leuwi Opat fell within the Class I water quality standards, indicating that the water has the potential to be utilized as a raw water source for domestic purposes by the surrounding community.

Benthic macroinvertebrates

The benthic macroinvertebrates collected at both sites were identified up to the morphospecies level, with some taxa only identifiable to the family level. Table 2 presents the density of each benthic macroinvertebrate taxon at both sites during the sampling period.

The identification results revealed a total of 23 benthic macroinvertebrate taxa belonging to 10 orders, 5 classes, and 4 phyla: Arthropoda (Insecta and Malacostraca), Mollusca (Gastropoda), Annelida (Clitellata), and Platyhelminthes (Turbellaria). Arthropods were the dominant phylum in terms of taxonomic richness, particularly Trichoptera, Ephemeroptera, and Plecoptera. Taxonomic diversity was higher at Aseupan Waterfall (21 taxa) than at Kacapi (18 taxa). Several taxa were shared between sites, indicating community similarity, although differences in density and composition were evident. Total benthic macroinvertebrate density reached 328 ind m^{-2}, with slightly higher density at Aseupan. These differences were likely influenced by environmental conditions such as higher dissolved oxygen and lower flow velocity at Aseupan, which favor taxa less tolerant of strong currents. Furthermore, Aseupan's rocky substrate offered various benthic macroinvertebrate groups more stable microhabitats and attachment surfaces.

Five benthic macroinvertebrate taxa were found exclusively at Aseupan: *Macrobrachium rosenbergii*, Leptophlebiidae, Pyralidae, *Byrsopteryx mirifica*, and Simuliidae. Among these taxa, Leptophlebiidae is the only sensitive group (tolerance value = 2; Mandaville, 2002), indicating that Aseupan provides physicochemical conditions favorable for pollution-intolerant organisms. The exclusive presence of this family is consistent with the expectation that higher-quality habitats support sensitive taxa (Smith et al., 2019). Nevertheless, the occurrence of Simuliidae, a moderately tolerant family (tolerance value = 6; Mandaville, 2002), suggests that the site also supports taxa with a broader tolerance range, reflecting a naturally mixed assemblage under relatively good conditions. At both sites, Hydropsychidae exhibited the highest density and is considered a moderately tolerant family, with a tolerance value of 4 (Mandaville, 2002). The bright (white) body coloration of Hydropsychidae observed in this study suggests an absence of heavy-metal accumulation (Ratia et al., 2012).

Table 1. Water Physicochemical Parameters at Kacapi and Aseupan Waterfalls

Parameter	Location ($\bar{x} \pm$ SD)		Water Quality Standard			
	Kacapi	**Aseupan**	1	2	3	4
Dissolved Oxygen (mg/l)	7.5 ± 0.29	7.75 ± 0.18	6	4	3	1
Water Temperature (°C)	19.72 ± 0.95	19.78 ± 0.89	Dev 3	Dev 3	Dev 3	Dev 3
Conductivity(µS/cm)	51.73 ± 0.9	51.53 ± 0.78				
Total Dissolved Solid (mg/l)	26.23 ± 0.88	26.25 ± 0.89	1000	1000	1000	2000
pH	6.76 ± 0.44	7.07 ± 0.53	6-9	6-9	6-9	6-9
Flow Velocity (m/s)	0.71 ± 0.36	0.66 ± 0.36				
Water Quality Class	**Class 1**	**Class 1**				

Note: Water quality standards were referenced from Government Regulation of Indonesia No. 22/2021

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Table 2. Benthic macroinvertebrates of Kacapi and Aseupan Waterfalls

Order	Family	Species	Kacapi (ind m⁻²)	Aseupan (ind m⁻²)
Coleoptera	Elmidae		5	8
	Psephenidae	*Psephenus faili*	3	0
		Psephenus herricki	3	7
Decapoda	Palaemonidae	*Macrobrachium lanatum*	5	5
		Macrobrachium rosenbergii	0	5
		Macrobrachium sintangense	10	3
Diptera	Simulidae		0	3
	Tipulidae		3	8
Ephemeroptera	Baetidae	*Baetis sp*	13	13
	Heptageniidae	*Heptagenia sp*	7	5
	Lephtophlebiidae	*Deleatidium sp*	0	10
Basommatophora	Physidae	*Physa sp*	3	10
Lepidoptera	Pyralidae		0	3
Lumbriculida	Lumbriculidae		7	7
Plecoptera	Eustheniidae	*Stenoperla sp*	5	3
	Nemouridae		3	0
	Perlidae		7	8
Trichoptera	Conoesucidae	*Pycnocentrodes sp*	5	5
	Hydrobiosidae		5	3
	Hydropsychidae	*Hydropsyche sp*	62	37
	Hydroptilidae	*Byrsopteryx mirifica*	0	3
	Polycentropodidae		5	7
Tricladida	Planariidae	*Planaria sp*	8	13

Based on Figure 2, the Shannon–Wiener diversity index shows that Aseupan Waterfall had a higher diversity value (2.82) than Kacapi (2.14), both falling into the moderate category, with no single taxon dominating. This indicates a balanced taxonomic distribution and a stable community composition. The lower diversity at Kacapi is presumably due to the higher flow velocity (0.71 m/s), which favors only those organisms capable of withstanding strong flows, such as Hydropsychidae. This finding supports the results of Smith et al. (2019), who reported high abundances of Hydropsychidae in fast-flowing, rocky-substrate streams. Additionally, increased accessibility to Kacapi Waterfall may increase human activity, potentially impacting the benthic community.

The Family Biotic Index (FBI) was used to assess water quality based on the tolerance of benthic macroinvertebrate families to organic pollution. The FBI values were 4.17 at Kacapi and 4.24 at Aseupan (Figure 3), both classified as “very good,” indicating low levels of organic enrichment. These low scores are consistent with the dominance of low-tolerance families such as Leptophlebiidae (tolerance value/TV=2), Perlidae (TV=1), Tipulidae (TV=3), Hydropsychidae (TV=4), and Baetidae (TV=4) (Mandaville, 2002). The slightly higher FBI at Aseupan may reflect the presence of families with moderate to high tolerance, particularly Simuliidae (TV=6) and Physidae (TV=8). However, the magnitude of this difference remains ecologically small.

These results are in line with other studies in tropical lotic ecosystems. Retnaningdyah et al. (2023) reported good to excellent FBI values in Bawean Island waterfalls, primarily driven by the strong representation of EPT taxa, even where nutrient levels varied. Likewise, Wijeyaratne & Kalaotuwawe (2017) demonstrated that the FBI effectively separated undisturbed upstream segments dominated by sensitive families from downstream sections with higher proportions of tolerant taxa such as Tubificidae and Pilidae. The consistent presence of EPT orders at both Kacapi and Aseupan in the present study supports the interpretation that both sites maintain good ecological integrity, with no indication of substantial organic pollution (Hamid & Rawi, 2017).

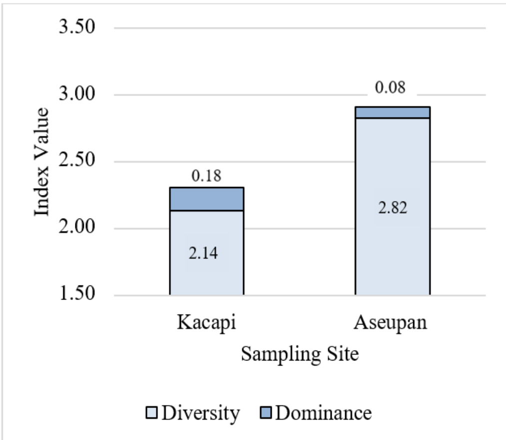

Figure 2. Diversity and dominance indices of benthic macroinvertebrates at Kacapi and Aseupan Waterfalls

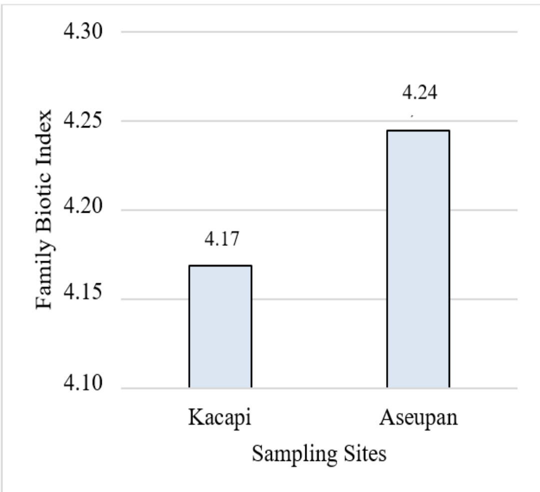

Figure 3. Family Biotic Index (FBI) of benthic macroinvertebrates at Kacapi and Aseupan Waterfalls.

Canonical Correspondence Analysis (CCA) was performed to examine the relationship between benthic macroinvertebrate community structure and environmental gradients across the two study sites. Prior to the analysis, Pearson's correlation was applied to assess interrelationships among environmental parameters to avoid multicollinearity. The results showed strong correlations among several variables, particularly between temperature and conductivity (r=–0.95) and temperature and pH (r=–0.87). Total Dissolved Solids (TDS) also exhibited a moderate correlation with conductivity (r =0.57). These high correlations indicated redundant information among variables; therefore, only three representative parameters were retained for the final model: Dissolved Oxygen (DO), conductivity, and flow velocity, representing oxygenation, ionic concentration, and hydrodynamic energy, respectively. These parameters are recognized as key factors influencing macrozoobenthic community structure (Elexová & Némethová, 2003; Azis & Abbas, 2021).

The CCA results (Figure 4) showed that the first two axes, CCA1 and CCA2, together explained 89.5% of the variation in macrozoobenthic community structure, with CCA1 accounting for 62.9% and CCA2 for 26.6%. This high cumulative variance indicates that the model effectively captures the influence of environmental variables on taxon distributions at both waterfalls. CCA1 was mainly associated with conductivity and DO, while CCA2 was influenced by flow velocity. The direction and magnitude of the environmental vectors in the CCA biplot highlight the relative influence of each parameter on community structure. Flow velocity showed the most substantial contribution, with Hydropsychidae and, to a lesser extent, Heptageniidae aligning closely with this vector. Their distribution reflects a preference for fast-flowing, well-oxygenated habitats, consistent with their morphological adaptations, such as streamlined bodies and strong tarsal claws, that allow them to maintain position on coarse substrates. This pattern aligns with Mandaville (2002), who classifies these taxa as sensitive to pollution and dependent on stable, high-flow conditions. Hydropsychidae, in particular, require steady currents for filter feeding and net construction, supporting findings by Ficsór and Csabai (2021) that current velocity is a primary determinant of their longitudinal zonation.

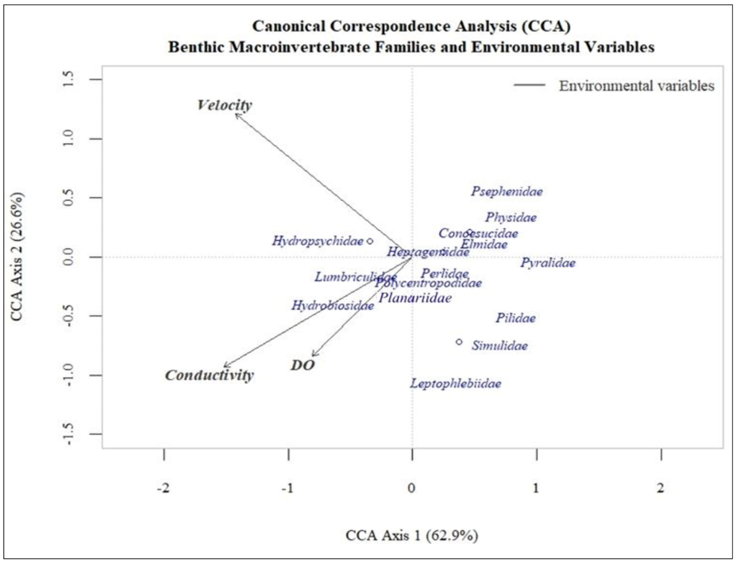

Figure 4. The relationship between benthic macroinvertebrate families and environmental variables at Kacapi and Aseupan Waterfalls

Conductivity was oriented toward the lower left quadrant, where Lumbriculidae, Hydrobiosidae, and Planariidae were positioned closest to the vector. Their association with elevated ionic concentrations suggests a higher tolerance to osmotic stress, a pattern consistent with broader evidence that ion-rich conditions act as environmental filters favoring taxa with strong physiological resilience (Kaczmarek et al., 2024). These groups are commonly encountered in slower, depositional habitats where ionic accumulation is more pronounced. In contrast, dissolved oxygen was associated with Leptophlebiidae and Hydrobiosidae, reflecting their reliance on oxygenated, fast-moving waters. This is consistent with Everaert et al. (2014), who reported that higher dissolved oxygen concentrations were positively associated with the occurrence of Leptophlebiidae across the tropical river basins studied, and noted that sensitive taxa, including several Trichoptera families, tended to occur within narrower ranges of dissolved oxygen. Taxa such as Physidae, Psephenidae, Conoesucidae, and Pyralidae occupied more central or right-center positions in the biplot, indicating weaker responses to individual gradients and suggesting generalist ecological strategies. Overall, the CCA results demonstrate that stream macroinvertebrate assemblages are shaped jointly by flow dynamics, oxygen availability, and ionic concentration. These interacting gradients form a multidimensional environmental template that structures taxonomic composition along the studied stream continuum.

CONCLUSION

This study indicates that the aquatic ecosystem of Curug Tilu Leuwi Opat, particularly at Kacapi and Aseupan Waterfalls, is in excellent ecological status. The stable structure of benthic macroinvertebrate communities, low Family Biotic Index (FBI) values, and physicochemical parameters meeting Class I water quality standards confirm that the ecosystem continues to function optimally and supports both clean water provision and conservation-based tourism. Given the initial assessment's limited spatial and temporal coverage, this research recommends further studies with expanded sampling and refined tropical biotic indices. Overall, these findings provide a scientific foundation for sustainable and adaptive management, especially in anticipation of increasing anthropogenic pressures.

AUTHOR CONTRIBUTION

H.S.P. collected the samples and drafted the manuscript. **T.S.S.** and **D.R.** designed the project, revised the manuscript critically, and provided constructive feedback. All authors read and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest related to this study.

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