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Benthic Macroinvertebrates as Bioindicators of Water Quality of Krueng Aceh Watershed Based on the BMWP-ASPT Method

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ABSTRACT

The Krueng Aceh watershed, vital to Banda Aceh and Aceh Besar, is increasingly threatened by ecological disruption from land-use changes that cause erosion, turbidity, and increased runoff. This study aimed to analyze the quality conditions of the Krueng Aceh River using benthic macroinvertebrates as bioindicators of BMWP-ASPT. The analysis was conducted from March to August 2024 and used a purposive sampling method. Observation stations were distributed at 10 points along the river, representing the upstream, middle, and downstream sections of the river. The upstream and middle sections of the river used surber nets, while the downstream section used PVC pipes to collect benthic macroinvertebrates. The assessment was based on community structure, the Biological Monitoring Working Party-Average Score Per Taxon (BMWP-ASPT) method, and physicochemical parameters of water and substrate. We recorded 29 macroinvertebrate families: 15 are in the original BMWP, and 14 additional families were incorporated to adapt the index. River health showed a clear longitudinal gradient, with upstream good, midstream moderate, and downstream poor, consistent with physicochemical patterns and downstream pressures. It is concluded that BMWP-ASPT is effectively adapted for diagnosing the condition of the Krueng Aceh watershed.

1. Introduction

The Krueng Aceh River plays a crucial role for the people of Aceh, serving not only as a water source for agriculture but also as a source of clean water for domestic needs, including drinking water. The primary water source of the Krueng Aceh Watershed is rainfall, which becomes surface water and groundwater (Ferijal *et al.* 2016; Satriyo *et al.* 2017). Field observations indicate that the Krueng Aceh watershed is suspected to have experienced ecological disturbances, leading to a decline in water quality. These ecological disturbances include land conversion for agricultural use, plantations, and settlements along the Krueng Aceh watershed, all carried out without regard for soil conservation principles. This causes a decrease in groundwater supply, flooding during the rainy season, drought during the dry season, the threat of future water scarcity, and river silting due to sedimentation (Devianti *et al.* 2021; Basri *et al.* 2023). Suboptimal water management, including dam and drainage construction (Muis 2019), as well as the pressure of heavy metal pollution (Saputri 2016; Hadi *et al.* 2018), is a serious threat to the biota inhabiting the Krueng Aceh watershed.

The ecological challenges lead to reduced river biodiversity and negatively impact the health of communities that depend on the river. Therefore, accurate, integrated information on the current condition of the Krueng Aceh Watershed is essential to guide effective restoration and mitigation strategies. Currently,

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two major methods are commonly used to assess water health status, namely physicochemical and biological. The physicochemical method, as defined in the Decree of the Minister of Environment No. 115 of 2003, is widely used (Ujianti & Androva 2019). However, this method has several weaknesses, including not measuring the concentration of pollutants in water, being less effective in detecting pollutants at low concentrations, having spatial and temporal variations (Lionetto *et al.* 2019; Mikosch *et al.* 2021), only reflecting conditions when the measurement was made, while water pollution occurs continuously, and requiring adequate equipment and relatively high costs (Danelon *et al.* 2021; Harmel *et al.* 2023). Therefore, water-quality assessment based on physicochemical parameters is less effective at describing the overall condition of river ecosystems. Water quality assessment using a biological approach is considered cost-effective, time-consuming, and effort-effective. One biological indicator of water health is the presence of benthic macroinvertebrates. Benthic macroinvertebrates are considered good bioindicators of river health because they reflect the impacts of both short- and long-term pollution events (Singh & Sharma 2020).

As crucial components of river food webs, benthic macroinvertebrates are known to exhibit high intolerance to habitat changes and pollution, making them important indicators of river health (Ojija *et al.* 2017; López-López *et al.* 2019; Natsir & Dillenia 2023). Purcell *et al.* (2002) explained that the use of biotic indices could reveal aspects that physicochemical variables may not. The Biological Monitoring Working Party (BMWP) score method, formulated and developed by the Department of the Environment (National Water Council 1981) (Hawkes 1979, 1998), is one of the biotic indices frequently used to assess water health status (Medupin 2019; Ochieng *et al.* 2020). This system was originally developed to assess river health in subtropical climates. Therefore, applying the BMWP outside these climates requires adjustments (Hawkes 1998; Ochieng *et al.* 2020), for example, by adding new families and changing some sensitivity values (Mustow 2002). In this research, the adjustments made were the addition of newly discovered families and the assignment of sensitivity scores without changing the original scores after the research was conducted (Alba-Tercedor & Sánchez-Ortega 1978; Hawkes 1998).

The BMWP assessment method has several advantages, including not requiring high taxonomic precision, thereby saving time and economic resources. The process is simple and easy to apply (Huh & Lee 2023), as it only requires taxonomic identification of macroinvertebrates to the family level and, in certain cases, to the order or class level. This index summarizes the presence or absence of taxa and the tolerance to pollution. Several physical and chemical parameters that significantly correlate with benthic community structure are used to predict community structure in unimpacted environments (Uherek & Pinto Gouveia 2014).

Although BMWP-ASPT is widely used, the index was developed outside tropical contexts and remains insufficiently calibrated for Indonesian rivers. Family composition and tolerance to pollution can differ substantially, so an unmodified application risks a biased diagnosis. For the Krueng Aceh watershed in particular, longitudinal macroinvertebrate assessments explicitly validated against key physicochemical gradients (e.g., clarity, dissolved oxygen, TDS, conductivity, sediment fractions, C-organic, and total N) are limited, and standard BMWP family lists do not include several families that actually occur locally.

To address this gap, we adapt BMWP-ASPT to Indonesian tropical conditions by integrating families observed locally and assigning context-appropriate sensitivity scores while retaining the original framework. We then map community patterns along the upstream–downstream gradient, summarize river status using BMWP-ASPT, and examine associations with key physicochemical parameters to evaluate ecological coherence. The novelty of this study lies in delivering a locally calibrated BMWP-ASPT for Indonesian tropical rivers, moving beyond “as-is” application to provide more reliable ecological diagnosis and an operational basis for restoration and mitigation planning in the Krueng Aceh watershed.

2. Materials and Methods

2.1. Time and Location

This research was conducted over 6 months, from March to August 2024, in the Krueng Aceh Watershed. Geographically, Krueng Aceh Watershed lies between 5°03'41"–5°38'10" North Latitude and 95°11'41"–95°49'46" East Longitude. Sampling was conducted at 10 sites representing six sub-watersheds in the watershed, namely Krueng Inong, Krueng Keumireu, Krueng Jrue, Krueng Seulimuem, Krueng Khea, and Krueng Aceh Hilir, as shown in Figure 1. The determination of the sampling location was conducted purposively; however, it may not represent the overall condition of the

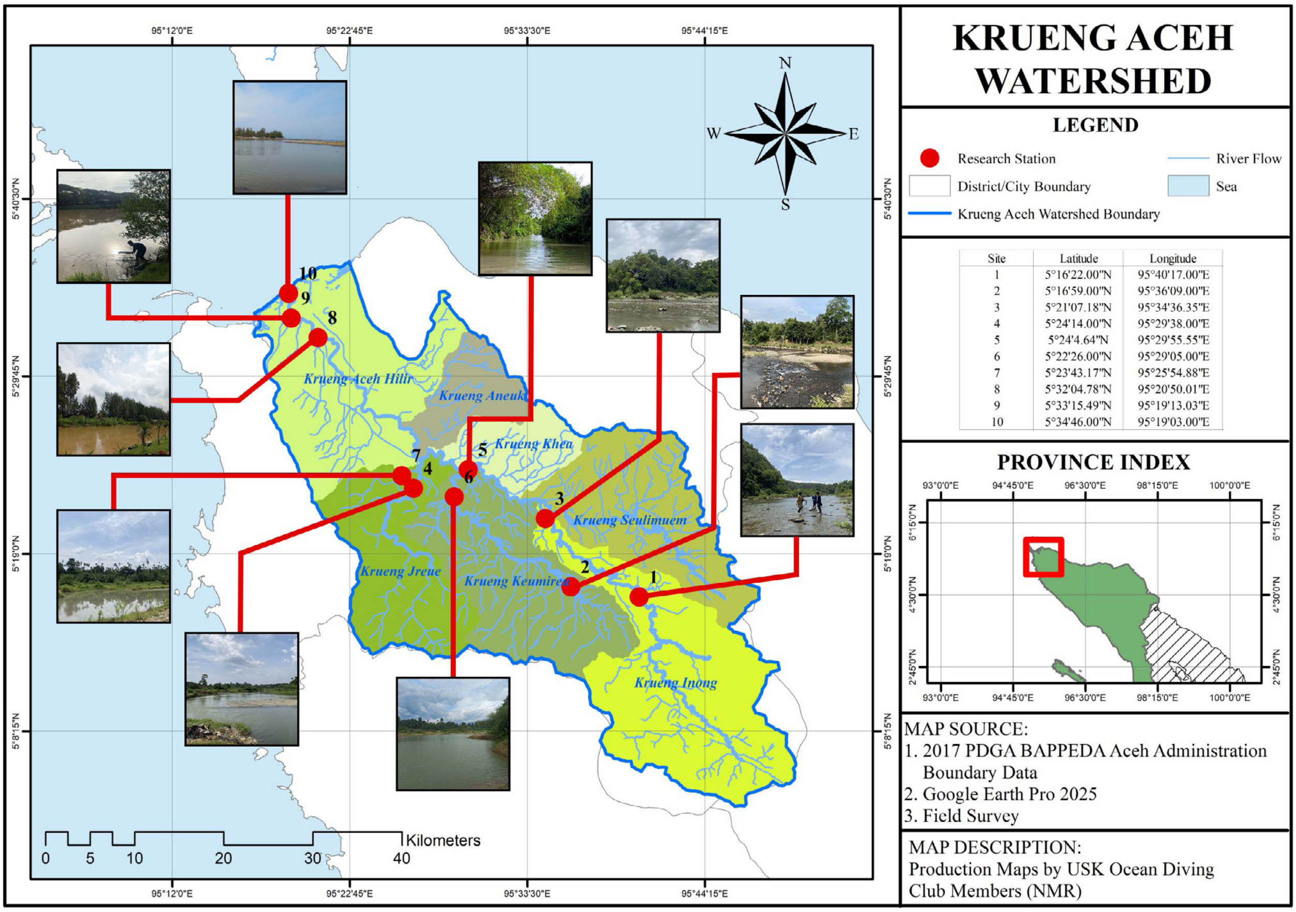

Figure 1. Research location in Krueng Aceh Watershed, Aceh Province

watershed. A detailed description of the research areas was provided in the analysis by Octavina *et al.* (2025).

2.2. Sampling Procedure

Benthic macroinvertebrate samples were collected using a Surber net and PVC pipes adjusted to the riverbed substrate types, namely rock and sandy textures. In the upstream and middle sections, where rock and sand were dominant, a Surber net measuring 300 × 300 mm with a mesh size of 500 µm was used. In the estuary section, which had a silty clay texture, a PVC pipe with a length of 100 cm and a diameter of 8.6 cm was used. Samples were collected at each point on the left, middle, and right banks, with three replicates per point, except in the downstream section, where only the left and right banks were sampled, each with five replicates, due to strong currents and river depth.

In the upstream and midstream sections of the river, surber nets were set against the current and not submerged. Disturbances were then applied to the front of the substrate net, such as moving rocks, gravel, and sand, for 2-10 minutes to dislodge benthic macroinvertebrates that had been hiding. Specimens captured by the Surber net were then removed and sieved through a multi-stage sieve to separate macroinvertebrates from litter, gravel, or soil (Ochieng *et al.* 2021; Muntalif *et al.* 2023). Downstream, samples were collected using PVC pipes, inserted 10 times into the soft substrate. The soil trapped in the PVC pipes was then removed and sieved through a multi-stage sieve to separate the macroinvertebrate samples from soil, rocks, or litter. The captured benthic macroinvertebrates were placed in sample bottles, labeled, preserved with 96% ethanol (Scotti *et al.* 2019), and taken to the Marine Biology Laboratory of the Faculty of Marine and Fisheries, Universitas Syiah Kuala. Benthic macroinvertebrates were identified using a Carl Zeiss Microscopy GmbH Primo Star microscope produced in Germany, using the taxonomic key book and text by McCafferty and Provonsha (1983) with the taxonomic key guide Hauer and Resh (2017) and field identification cards by CT Dept. of Energy & Environmental Protection (2016) in https://portal.ct.gov/DEEP-RBVProgram, as well as the online platform https://www.macroinvertebrates.org/.

Several water quality parameters were measured on-site, including water clarity, current velocity, dissolved oxygen, depth, salinity, surface temperature, and pH. Clarity was assessed using a Secchi disc, current velocity using a flow meter (Flowatch FL-03 JDC), dissolved oxygen using a DO meter (Lutron DO-5510), depth using a manual scale board, salinity using a hand-held refractometer (ATAGO manual), water temperature and Total Dissolved solids using a DO meter (TDS Ez-9909), and pH using a pH meter (Lutron pH-222). Furthermore, 2 kg of sediment was collected from each sampling station and placed in a plastic container. Sediment texture, C-organic, and N-total were analyzed at the Soil Laboratory, Faculty of Agriculture, Universitas Syiah Kuala (see Octavina *et al.* 2025).

2.3. Research Parameters

The research parameters measured were biotic indexes, namely the Biological Monitoring Working Party (BMWP) index and Average Score Per Taxon (ASPT) (Elliott & Hellawell 1978; Hawkes 1979, 1998). The original BMWP table was modified by Hawkes (1998) and Alba-Tercedor & Sánchez-Ortega (1978), who added additional taxa without altering the original score values, as shown in Table 1. Consequently, Alba-Tercedor (1996) updated the taxonomic groups and corresponding scores, as shown in Table 2, and revised the classification and interpretation guidelines in Tables 3 and 4, building on Armitage *et al.* (1983) and Galbrand (2007). BMWP evaluation was obtained from the total score of each taxon (class, order, or family) recorded at

Table 1. Original biological monitoring working party (BMWP) taxa scores (adapted from Alba-Tercedor 1996, and National Water Council 1981)

Taxa (familia)	Score
Siphlonuridae, Heptageniidae, Leptophlebiidae, Ephemerellidae, Potamanthidae, Ephemeridae, Taeniopterygidae, Leuctridae, Capniidae, Perlodidae, Perlidae, Chloroperlidae, Aphelocheiridae, Phryganeidae, Molannidae, Beraeidae, Odontoceridae, Leptoceridae, Goeridae, Lepidostomatidae, Brachycentridae, Sericostomatidae	10
Astacidae, Lestidae, Agriidae, Gomphidae, Cordulegasteridae, Aeshnidae, Corduliidae, Libellulidae, Psychomyiidae, Philopotamidae	8
Caenidae, Nemouridae, Rhyacophilidae, Polycentropodidae, Limnephilidae	7
Neritidae, Viviparidae, Ancylidae, Hydroptilidae, Unionidae, Corophiidae, Gammaridae, Platycnemididae, Coenagriidae	6
Mesovelidae, Hydrometridae, Gerridae, Nepidae, Naucoridae, Notonectidae, Pleidae, Corixidae, Haliplidae, Hygrobiidae, Dytiscidae, Gyrinidae, Hydrophilidae, Clambidae, Helodidae, Dryopidae, Elminthidae, Chrysomelidae, Curculionidae, Hydropsychidae, Tipulidae, Simuliidae, Planariidae, Dendrocoelidae	5
Baetidae, Sialidae, Piscicolidae	4
Valvatidae, Hydrobiidae, Lymnaeidae, Physidae, Planorbidae, Sphaeriidae, Glossiphoniidae, Hirudidae, Erpobdellidae, Asellidae	3
Chironomidae	2
Oligochaeta	1

Table 2. Modified biological monitoring working party (BMWP) taxa scores (adapted from Alba-Tercedor 1996 and National Water Council 1981; boldface family names are recent/modified additions)

Taxa (familia)	Score
Siphlonuridae, Heptageniidae, Leptophlebiidae, Ephemerellidae, Potamanthidae, Ephemeridae, Taeniopterygidae, Leuctridae, Capniidae, Perlodidae, Perlidae, Chloroperlidae, Aphelocheiridae, Phryganeidae, Molannidae, Beraeidae, Odontoceridae, Leptoceridae, Goeridae, Lepidostomatidae, Brachycentridae, Sericostomatidae	10
Astacidae, Lestidae, Agriidae, Gomphidae, Cordulegasteridae, Aeshnidae, Corduliidae, Libellulidae, Psychomyiidae, Philopotamidae	8
Caenidae, Nemouridae, Rhyacophilidae, Polycentropodidae, Limnephilidae	7
Neritidae, Viviparidae, Ancylidae, Hydroptilidae, Unionidae, Corophiidae, Gammaridae, Platycnemididae, Coenagriidae, Ampullariidae, Thiaridae, Pachychilidae, Bulinidae, Bithyniidae, Costellariidae, Cyrenidae,	6
Mesovelidae, Hydrometridae, Gerridae, Nepidae, Naucoridae, Notonectidae, Pleidae, Corixidae, Haliplidae, Hygrobiidae, Dytiscidae, Gyrinidae, Hydrophilidae, Clambidae, Helodidae, Dryopidae, Elminthidae, Chrysomelidae, Curculionidae, Hydropsychidae, Tipulidae, Simuliidae, Planariidae, Dendrocoelidae, Psephenidae, Elmidae,	5
Baetidae, Sialidae, Piscicolidae	4
Valvatidae, Hydrobiidae, Lymnaeidae, Physidae, Planorbidae, Sphaeriidae, Glossiphoniidae, Hirudidae, Erpobdellidae Asellidae	3
Chironomidae, Limoniidae,	2
Oligochaeta, Gecarcinucidae, Penaeidae, Corydalidae, Nereididae	1

the sampling site. According to Alba-Tercedor (1996), the total score categories water quality on a scale ranging from "very good" to "very poor." Each taxon was assessed based on its level of sensitivity to pollution. Taxa that were intolerant (sensitive) to pollution received a high score (10), while tolerant taxa received a low score (1). Since the BMWP system was originally developed using invertebrate taxa from the Iberian Peninsula, it was necessary to adjust the scoring system for application in Aceh. These adjustments were guided by MINAE (2007) and previous publications such as Chazanah *et al.* (2020), Mustow (2002), Ochieng *et al.* (2020), and Uherek & Pinto Gouveia (2014). Research procedures are presented in a flowchart (Figure 2).

BMWP index analysis was conducted to assess the condition of the aquatic environment, following the several stages outlined by Armitage *et al.* (1983).

- Identification of benthic macroinvertebrate families at each site using reference materials such as McCafferty and Provonsha (1983), taxonomic keys by Hauer & Resh (2017), field identification cards by CT Dept. of Energy & Environmental Protection (2016) in https://portal.ct.gov/DEEP-RBVProgram, and the online resource https://www.macroinvertebrates.org/.
- Assignment of sensitivity scores (BMWP scores) to each family, based on established sensitivity tables (Hawkes 1998; Alba-Tercedor & Sánchez-Ortega 1978; Armitage *et al.* 1983; Elliott & McCafferty 1982; Hodkinson *et al.* 1981).
- The process of combining the values of all scores from the taxa (families) found, using the following equation:

$$\text{Skor BMWP} = \sum_{n=1}^{n} a_i \qquad (1)$$

Where a_i represented the sensitivity score of each taxon (family) and n signified the number of taxons (families) found at the sampling areas. The BMWP-ASPT formula was then calculated using the formula described by Armitage *et al.* (1983) and Galbrand *et al.* (2007).

$$\text{BMWP - ASPT} = \frac{\text{Total BMWP index score}}{\text{Total of taxa found and scored}} \qquad (2)$$

2.4. Data Analysis

To relate biological condition to environmental drivers, we used Pearson's correlation coefficient because both the biotic indices (BMWP–ASPT) and the physicochemical variables are continuous. Pearson quantifies both the direction and magnitude of associations, which is essential for interpreting ecological mechanisms. We then applied Tukey's HSD to identify which station pairs differed while controlling the family-wise error rate.

3. Results

A total of 1,240 benthic macroinvertebrate specimens were collected during research in the Krueng Aceh watershed. These specimens belonged to three phyla: Annelida (one family, one species); Arthropoda (19 families, 35 species); and Mollusca (10 families, 14 species). Therefore, the recorded benthic macroinvertebrates comprised five classes, 29 families, 42 genera, and 49 species.

The results of the biotic index analysis showed that of the 29 families identified, 15 contributed to the BMWP assessment based on the original BMWP table of the National Water Council in 1981. These included Hydrophilidae, Dytiscidae, Chironomidae, Baetidae, Caenidae, Ephemerellidae, Heptageniidae, Leptophlebiidae, Potamanthidae, Perlidae, Hydropsychidae, Philopotamidae, Psychomyiidae, Neritidae, and Unionidae. Families not found in the original BMWP table were assigned a default score of 1, as observed in Table 1. At the same time, taxa not listed and belonging to recognized orders or classes were given the lowest score corresponding to the equivalent group in Table 2. In Table 1, there were only seven orders: Coleoptera, Diptera, Ephemeroptera, Plecoptera, Trichoptera, Cycloneritida, and Unionida. Three classes —Insecta, Gastropoda, and Bivalvia —were also identified in this research. However, the analysis recorded nine orders, including taxa from four additional classes not listed in the original table. In the Insecta class, four families were recorded across three orders, namely Psephenidae and Elmidae in Coleoptera, Limoniidae in Diptera, and Corydalidae in Megaloptera. The Gastropoda class was the most represented, with six families from three orders: Ampullariidae (Architaenioglossa), Thiaridae, Pachychilidae, and Bithyniidae (Sorbeoconcha), Bulinidae (Pulmonata), and Costellariidae (Neogastropoda). The Bivalvia class included Cyrenidae, classified under Venerida, while the Polychaeta class was represented solely by Nereididae under Phyllodocida.

Benthic macroinvertebrates found in the Krueng Aceh Watershed ranged from pollution-sensitive to pollution-tolerant taxa, as shown in Appendix 1. The sensitive families included Ephemerellidae,

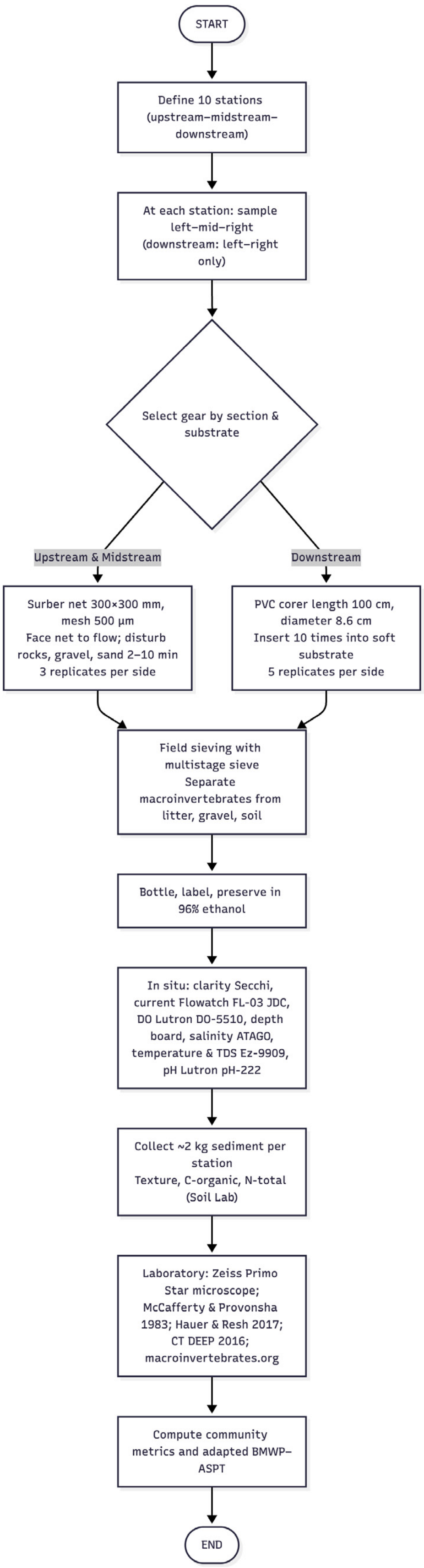

Figure 2. Research flowchart

Heptageniidae, Leptophlebiidae, Potamanthidae, and Perlidae, while tolerant families included Gecarcinucidae, Penaeidae, Nereididae, and Corydalidae. For instance, Nereis sp. was found at Station 10 (Lampulo) and further classified as moderately polluted.

The data showed that the highest BMWP and ASPT values were found at the upstream station, decreased in the middle segment, and reached their lowest at the downstream station. The quality category based on BMWP shifted from good (upstream) to poor–very poor (downstream), while ASPT reinforced this pattern with a decrease in value at the most downstream station (Tables 3, 4, and Figure 3).

Based on BMWP index calculations at 10 research stations, the Krueng Aceh Watershed was categorized as good to very poor (Tables 3 and 4). These results were further supported by ASPT, which also indicated water quality conditions ranging from very good to very poor (Tables 4 and 5). The upstream and middle sections of the watershed were generally classified as good, while poor conditions were recorded in the downstream sections. The results of water quality measurements indicated that the Krueng Aceh Watershed still complied with the quality standards stipulated in the Government Regulation of Indonesia (Appendix 6, PP 22 of 2021), with class II water quality standards.

Based on Figure 4, BMWP and ASPT are highly correlated (strong positive correlation). The biotic index, BMWP, has a negative correlation with TDS, depth, fine sediment fraction, organic carbon, and total nitrogen. This means that any increase in TDS, depth, fine sediment fraction, organic carbon, or total nitrogen will reduce the abundance of benthic macroinvertebrates, thereby lowering the BMWP score.

Table 3. Biological monitoring working party (BMWP) categories and scores (adapted from Armitage *et al.* (1983) and Alba-Tercedor 1996)

Code	Water quality categories	BMWP score
1	Water of very good quality	>150
2	Water of good quality; no obvious contamination or distortion	100–150
3	Water of normal quality; eutrophic, moderate contamination	61–100
4	Water of poor quality; contaminated	36–60
5	Water of poor quality; highly contaminated	16–35
6	Water of very poor quality; highly contaminated	<15
	Reference	(Ochieng *et al.* 2020)

Furthermore, BMWP has a positive correlation with water clarity and sand fraction, meaning that locations with clearer water tend to have higher biotic scores. In contrast, coarser substrates tend to support the presence of sensitive taxa, thereby increasing BMWP.

The results of the Tukey's HSD test revealed that the BMWP and ASPT values from upstream to downstream differ significantly ($p<0.01$) among locations (Table 6). The most pronounced decline occurs in the transition from midstream to downstream, indicating increased ecological pressure in the lower segment of the watershed. This pattern is consistent with field observations (higher turbidity, finer sediment, lower DO) that we documented during sampling. The combination of quality classes in Table 4 and trends in

Table 5. Average score per taxon (ASPT) (Galbrand *et al.* 2007)

ASPT value	Water quality categories
>6.0	Water quality is excellent
5.5–6.0	Water quality is very good
5.0–5.5	Water quality is good
4.5–5.0	Water quality is fair
4.0–4.5	Water quality is slightly poor
<4.0	Water quality is poor

Table 4. Water quality status of Krueng Aceh watershed based on the BMWP-ASPT biotic index (Armitage *et al.* 1983) and Alba-Tercedor 1996; Ochieng *et al.* 2020; Galbrand (2007)

Index[*1)]	Zonation[*2)]									
	Upstream			Middle				Downstream		
	1	2	3	4	5	6	7	8	9	10
BMWP	146	81	68	120	92	92	66	24	18	13
Category[*1)]	B	C	C	B	C	C	C	F	F	G
BMWP-ASPT	7.2	6	5	6	6	6	6	6	6	3.25
Category[*1)]	A	B	C	B	B	B	B	B	B	F

[*1)]1) Biotic index for water quality: A: very good, B: good, C: normal, D: rather bad, E: bad, F: very bad, [*2)]1: River in Jalin Village, 2: River in Bukit Meusara Jantho Village, 3: River in Keunaloi Village, 4: River in Keureuweung Village, 5: River in Riting Indrapuri Village, 6: River in Reukih Dayah Village, 7: River in Lamleupung Village, 8: River around Pango Village, 9: River around Kampung Baru Village, 10: River around Lampulo Village

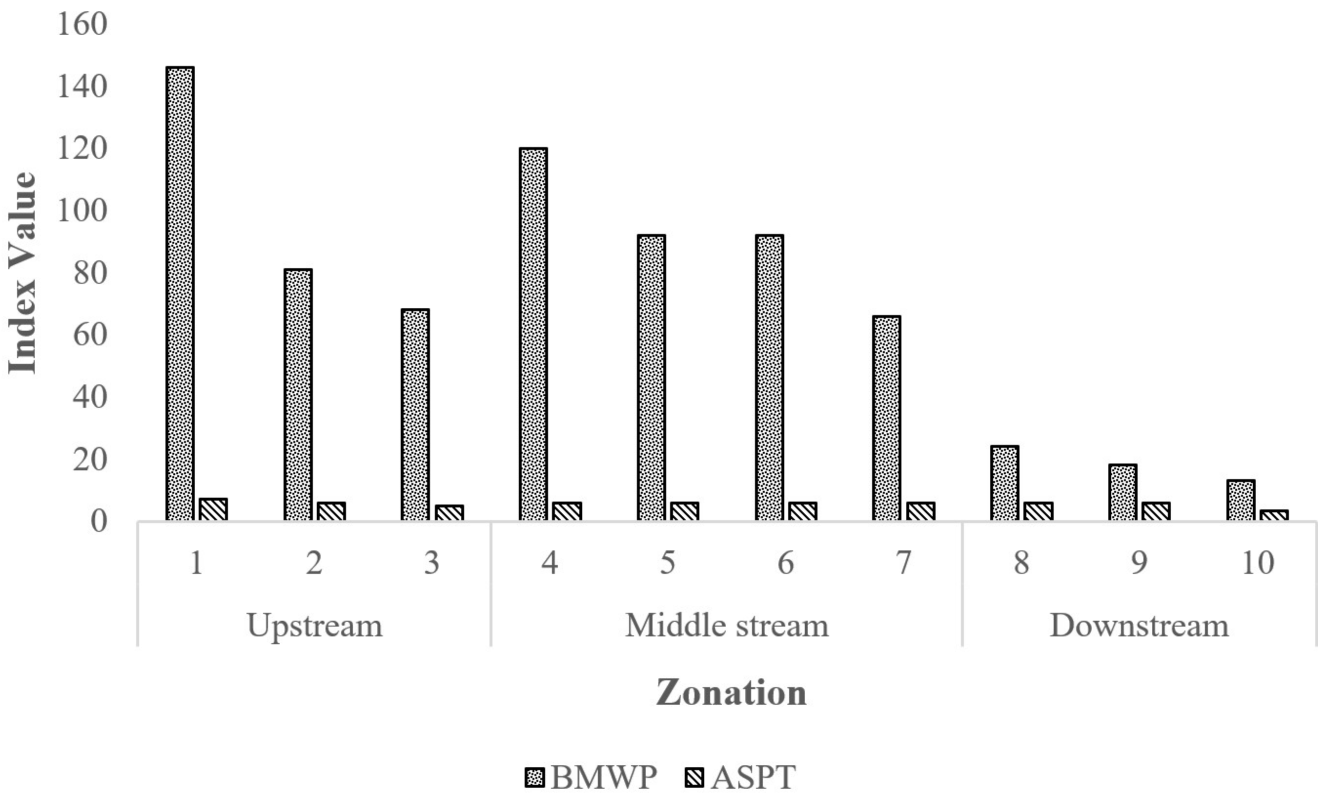

Figure 3. BMWP and ASPT trends from upstream to downstream in the Krueng Aceh watershed

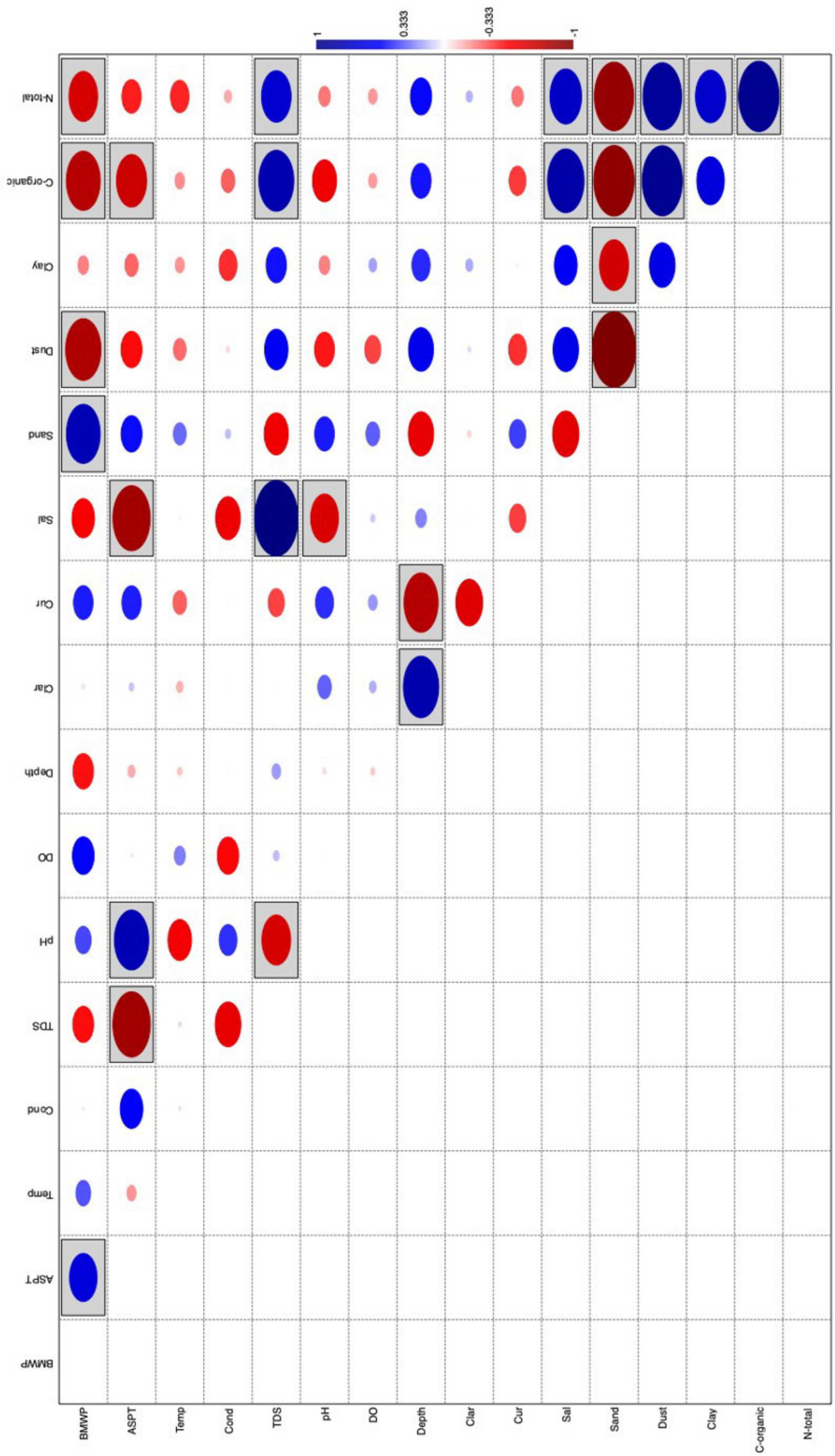

Figure 4. Plot of pearson's correlation coefficient for environmental variables and biotic index scores. Significant correlations (p<0.05) are marked with coloured boxes. Blue: positive correlation, red: negative correlation, ellipse size: strength, grey box: significant sign. Temp: temperature, Cond: conductivity, Clar: clarity, Cur: current, Sal: salinity

Table 6. Tukey's HSD pairwise comparisons of BMWP among river sections

Comparison	Mean diff	SE (tukey)	q-stat	Conclusion
Upstream–middle	53.20	7.17	7.43	Significant ($p<0.01$)
Upstream–downstream	114.67	7.82	14.66	Significant ($p<0.001$)
Middle–downstream	61.47	6.30	9.77	Significant ($p<0.001$)

Figure 3 indicates a shift in composition from sensitive taxa (EPT) upstream to tolerant taxa (Chironomidae, Oligochaeta) downstream.

4. Discussion

Our first important finding concerns taxonomic representativeness: this research identified 14 additional families not previously listed in the BMWP table by the National Water Council (1981). These include Psephenidae, Elmidae, Gecarcinucidae, Penaeidae, Limoniidae, Corydalidae, Ampullariidae, Thiaridae, Pachychilidae, Bulinidae, Bithyniidae, Costellariidae, Cyrenidae, and Nereididae. A full description of each other specimen has been previously reported in a separate report (see Octavina *et al.* 2025). The results indicate that the Krueng Aceh River supports a rich diversity of aquatic life, despite ecological pressures. Similarly, research by Uherek & Pinto Gouveia (2014) in Brazil reported three additional orders outside the original BMWP list, prompting the modification of the index to assess the Maroaga River. The analysis takes a fresh approach by including new taxa, thereby helping ensure the assessment accurately captures the state of tropical rivers in Indonesia. This modification accommodates the fact that the presence of local macroinvertebrates also reflects local environmental conditions. Based on the results of these modifications, a value was obtained.

The benthic macroinvertebrate community in the Krueng Aceh watershed is highly sensitive to pollution but also highly tolerant of it. These sensitive groups include the families Elmidae, Perlidae, Heptagenidae, and Philopotamidae (Jumaat & Hamid 2021), Baetidae (Gattolliat *et al.* 2023), and Hydropsychidae (Gudiño-Sosa *et al.* 2023). These sensitive taxa are concentrated in the headwaters, where the current is faster, the substrate is rougher, and turbidity and fine sedimentation are lower. These groups are known to decline under conditions of high suspended solids and "embedded" substrates; their presence in the headwaters is consistent with habitat heterogeneity and better oxygenation for taxa that are highly intolerant to pollution. While highly tolerant families include Hydrophilidae, Psephenidae (Deb *et al.* 2024; Rodriguez *et al.* 2021), Chironomidae, Thiaridae (Nicacio & Juen 2015; Xu *et al.* 2014), and Oligochaeta (Atanacković *et al.* 2020). Conversely, the abundance of tolerant taxa increases towards the estuarine corridor downstream. This group is commonly found in higher TDS/conductivity, increased organic load, and finer substrates. This pattern is consistent with increased anthropogenic pressure downstream, where domestic waste, small-scale industry, sand mining, and runoff from agriculture and plantations drive increases in turbidity, increased particulate/dissolved load, and intermittent decreases in DO, especially after heavy rains or during low discharge. The presence of brackish-tolerant neritiods in the lower segment also reflects salinity transitions and changes in the hydrological regime near the estuary. The presence of these sensitive and highly tolerant groups varies depending on site conditions. For example, upstream stations are still dominated by sensitive species, while downstream stations (such as Lampulo Station) have found *Nereis* sp. This is consistent with previous reports from several other locations in Aceh (Fastawa *et al.* 2018; Ramadhaniaty *et al.* 2023), reflecting the declining environmental quality in these areas. Furthermore, the presence of Vittina turrita (Krings *et al.* 2021) in the freshwater-brackish water transition zone demonstrates the ability of some species to adapt to environments with wide salinity variations.

The upstream–downstream gradient of the Krueng Aceh River shows a clear ecological transition. The upstream section harbours more sensitive families (EPT), which generally require relatively stable flow, rocky substrate, high brightness, and adequate DO; EPT groups are known to be sensitive to pollution, making them an indicator of relatively clean waters (Jerves-Cobo *et al.* 2017). The middle section shows mixed conditions, resulting in a more balanced community. Towards the downstream, turbidity increases and sediment becomes finer, covering/clogging the pores of benthic habitats, disrupting detritus/periphyton, and shifting the community towards tolerant taxa (e.g., Chironomidae, Oligochaeta) that are able to exploit fine sediment and organic flux (Schäffer *et al.* 2020). Higher organic loads downstream often reduce dissolved oxygen (DO) through microbial respiration, making selection more favourable for stress-tolerant taxa such as Chironomidae/Oligochaeta (Makumbe *et al.* 2022).

In general, the research results indicate that, based on the assessment of the water quality of the Krueng Aceh River using the modified BMWP method, the water quality falls in the good category. This category describes a relatively clean river and has not experienced much ecological change, although it has not yet reached the condition of very clean water. However, the water quality in the downstream is lower than in the upstream, for example, at Lampulo station, as explained above, this is likely influenced by the intensity of anthropogenic activities such as household and industrial activities, sand mining (quarry C), agriculture, tourism, and the flow of domestic and plantation waste that accumulates in this downstream area. Although still in fairly good condition, the upstream section of the Kreung Aceh River has also been affected by sand mining (quarry C) and deforestation. This is indicated by high TDS, conductivity, organic carbon, and total nitrogen values, reflecting high levels of dissolved substances and organic matter in the water. Compared to the Citarum River in West Java (Chazanah *et al.* 2020; Muntalif *et al.* 2023; Pratiwi *et al.* 2023) or the Batanghari River in Jambi (Badariah *et al.* 2023; Wiriani *et al.* 2020), the condition of the Krueng Aceh River is relatively better and able to support the river's sustainable ecological function. However, the declining trend in water quality, especially in downstream areas, remains a significant concern for the river's sustainability and the health of surrounding communities.

Tukey's HSD confirms a clear longitudinal pattern for BMWP (Upstream > Middle > Downstream), consistent with the well-known sensitivity of family-level biotic indices to stress gradients: clearer, well-oxygenated headwaters support sensitive taxa, whereas downstream reaches with higher dissolved and suspended loads favor tolerant assemblages. Mechanistically, fine, organic-rich sediments settle onto coarse substrates, reduce habitat heterogeneity, clog interstitial pores, and limit oxygen diffusion, shifting communities away from EPT taxa toward tolerant deposit feeders —the same pattern we observed at lower sites, where BMWP scores were lowest. Pearson correlations reinforce this interpretation by showing strong concordance between BMWP and ASPT and by indicating that biotic scores decline with increasing TDS/conductivity, depth, and fine fractions (silt, clay) and organic content (C and total N), but rise with greater clarity (and, in some cases, higher DO). Together, these lines of evidence support the validity of our locally adapted BMWP/ASPT for tropical rivers and argue for practical actions focused on reducing sediment and dissolved loads, rehabilitating riparian zones, and lowering organic inputs in downstream segments and contributing sub-watersheds. We note, however, that spatial non-independence, differences in sampling gear among sections, and a single-season sampling window warrant cautious interpretation and motivate multi-season studies with standardized methods to confirm causality (McKenzie *et al.* 2024).

The application of the modified BMWP biotic index has proven effective in reflecting the condition of the Krueng Aceh River. This index also shows that several Arthropod groups, such as Dytiscidae, Chironomidae, Baetidae, Caenidae, Leptophlebiidae, Heptageniidae, and Philopotamidae, have a broad and consistent distribution found in both the original BMWP index system, BMWP-CR (MINAE 2007), and BMWP-Thai (Mustow 2002). Therefore, the BMWP approach remains valid when used across geographic areas, provided adjustments are made to the taxa scores relevant to the local area. The presence of benthic macroinvertebrates in the Krueng Aceh Watershed not only reflects the health status of the river but also the dynamics of interactions between human activities and ecological processes. Therefore, a benthic macroinvertebrate-based biomonitoring approach is an alternative for adaptive, evidence-based water resources management, thereby providing a basis for formulating watershed management policies. However, integrating biological, physicochemical, and spatial data into an integrated water quality monitoring system is highly recommended to improve assessment accuracy and support the sustainability of river ecological functions. The use of benthic macroinvertebrates as bioindicators should be an integral part of an ecosystem-based watershed management framework; hence, pollution mitigation and environmental quality improvement efforts can be carried out effectively, targeted, and sustainably.

Most studies in this region apply BMWP as is. Our research is among the first to (i) compile a comprehensive list of local families for Krueng Aceh, (ii) incorporate these families into BMWP scoring through context-based sensitivity determination, and (iii) demonstrate that the adapted index aligns with measurable physicochemical gradients and pressure hotspots. This presents a transferable blueprint for Indonesian tropical rivers: start with a published BMWP framework, add locally present families, ecologically justify sensitivity placements, and report BMWP/ASPT per section alongside key physicochemical indicators to guide restoration.

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