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RESEARCH ARTICLE

Determination of the macroinvertebrates benthic ecological index for river health assessment

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ABSTRACT

Conventional river assessments often rely on physico-chemical parameters, which cannot fully capture ecological integrity or long-term impacts of human activities. Benthic macroinvertebrates, however, provide reliable bioindicators as they integrate responses to both short-term and cumulative stressors. This study investigated three rivers in Johor, Malaysia of Sungai Mengkibol, Sungai Dengar and Sungai Madek representing different land-use influences including reference conditions, oil palm plantations and logging activities. Eight sampling stations were established, with benthic macroinvertebrates collected using a Surber net and identified to family or genus level where possible. Four ecological indices were calculated using Shannon-Wiener Diversity Index, Simpson's Dominance Index, Margalef Richness Index, and Hill's Evenness Index that purposely to evaluate river health. Threshold values were developed by comparing reference and impaired stations, leading to the establishment of a Recommended Ecological Index for River Health Assessment. Results showed that healthy rivers consistently displayed high diversity (>1.8), high richness (>2.0), low dominance (<0.2), and strong evenness (>0.8), reflecting balanced and resilient communities. In contrast, impaired rivers exposed to anthropogenic pressures recorded low diversity and richness, high dominance, and poor evenness. The proposed framework sets out clear ecological thresholds to help categorize rivers as healthy, slightly unhealthy, or polluted. This is a significant step, as it's the first time we're developing reference values for Malaysian rivers using macroinvertebrate indices. The findings emphasize how innovative and practical benthic macroinvertebrate-based biomonitoring can be cost-effective and meaningful from an ecological standpoint. By using these indices, we can strengthen our national river management strategies and promote evidence-based approaches to preserving our tropical freshwater ecosystems.

1. INTRODUCTION

Our environment, consisting of dynamic and sensitive components, can disrupt ecological balance and significantly affect the decline of environmental quality. Our ecosystems offer essential services to us, including drinking water supply, fisheries, recreation, and even supporting manufacturing sectors, which make biodiversity conservation and protection a top priority in rapidly developing regions (Schlesinger & Bernhardt, 2020). In Malaysia, rivers face increasing threats from development, forest product harvesting and agriculture, which introduce pollutants and alter habitat conditions. In this country, river monitoring approaches have primarily focused on physico-chemical parameters, such as nutrient levels, heavy metals, dissolved oxygen, pH, and the presence of industrial effluents (Najjah Mohamad Shamsul et al., 2017; Sakke et al., 2023). These parameters are indispensable for understanding pollutant loads and chemical dynamics. However, this method often only provides an overview of river health during sampling, failing to address cumulative or long-term ecological changes that influence ecosystem life (Samsudin et al., 2023).

Recently, there has been a growing consideration of the need to include biological indicators in an ecosystem monitoring approach to consolidate the data acquired. As part of the monitoring approach, benthic macroinvertebrates have emerged as a reliable bioindicator due to being relatively sedentary, sensitive to habitat alterations and pollution, and having long cycles to reflect cumulative environmental changes (Chowdhury et al., 2024). Benthos macroinvertebrate assemblage structure, as shown through diversity, richness, dominance, and evenness measures, offers an integrated dataset of ecological conditions that integrates with physico-chemical assessments. In Malaysia, research on benthic macroinvertebrates has been growing recently and has developed multi-metric indices for river health assessment (Arman et al., 2019), explored their application in recreational water monitoring (Abas Kutty et al., 2024), and examined how the biodiversity and distribution respond to land use change, sedimentation, substrate composition, riparian cover, and channel (Chen et al., 2014; Zhang et al., 2020). These investigations have shown that macroinvertebrates are valuable indicators of ecological integrity and practical tools for sustainable watershed management (Msk et al., 2021).

Despite this progress, a significant gap remains in monitoring Malaysian rivers. There are no nationally recommended threshold values for key ecological indices that effectively distinguish between healthy and impaired river systems. Assessment of biological indicators lacks unified thresholds, hindering effective decision-making and policy implementation (Arman et al., 2019). Establishing these recommended references is essential for standardising biological monitoring to enable comparisons across regions and guide authorities in managing aquatic ecosystems. This study addresses a significant gap by introducing a Recommended Ecological Index for Malaysian rivers. This index is based on data from benthic macroinvertebrate communities and includes relevant threshold values for diversity, richness, dominance, and evenness. This work enhanced ecological research by providing a scientific approach and a cost-effective framework for integration into national biomonitoring efforts. Linking biological data and physicochemical data also offers practical insights for managing river health, planning conservation efforts, and formulating sustainable water policies in Malaysia.

The study area within the Sungai Sembrong catchment in Johor, Peninsular Malaysia, represents a region of diverse land-use patterns and rapid socio-economic transformation. These areas consist of urban settlements, agricultural plantations, and logging concessions, interspersed with patches of secondary forest and riparian vegetation. Sungai Mengkibol flows through the urbanised zone of Kluang town, where residential expansion, commercial activities, and industrial development exert significant pressure on the river ecosystem (Halim, 2009). In contrast, Sungai Dengar is heavily influenced by oil palm plantations that dominate this area, reflecting one of Malaysia's most extensive land uses and its associated environmental trade-offs, including pesticide and fertiliser runoff (Werner & Laattoe, 2016; Ye et al., 2025). Sungai Madek, meanwhile, is situated in an area of ongoing logging activities, where forest clearance and soil erosion have a direct impact on water quality and the structure of aquatic habitats. These rivers are ecologically important and socially relevant, as local communities rely on them for domestic water supply, small-scale fisheries, and recreational uses. However, increasing land-use pressures have led to mounting concerns over river degradation, biodiversity loss, and the long-term sustainability of freshwater resources. The selection of these rivers was intentional, representing a model of how various land-use types, urbanisation, plantation agriculture, and logging impact ecological conditions in Malaysian rivers. Studying them allows for the development of environmental thresholds that are directly applicable to national river management, offering insights that are both scientifically robust and socially meaningful (Heng et al., 2017).

2. MATERIALS AND METHODS

This study was conducted on three rivers in Johor, Peninsular Malaysia: Sungai Mengkibol (2° 0' 2.291" N, 103° 19' 40.468"E), Sungai Dengar (2° 0' 2.291" N, 103° 29' 32.373" E), and Sungai Madek (2° 0' 2.291" N, 103° 19' 40.468" E). Each river was chosen to represent a distinct land-use activity, providing contrasting ecological conditions for comparison (Figure 1). Sampling stations were established to include reference and impaired sites, selected based on physicochemical parameters, in-stream features, and riparian habitat quality. All rivers are tributaries of the Sungai Sembrong catchment, and the study sites were limited to second and third-order streams, which are considered ecologically suitable for benthic macroinvertebrate biomonitoring. Eight stations were established, comprising six impacted and two reference sites.

Benthic macroinvertebrates were collected using a Surber net (30 × 30 cm frame, 500 µm mesh size) in accordance with Karr's Aquatic Insect Stream Sampling Protocol (Alsaleem et al., 2024), with minor modifications for tropical river conditions. At each station, three replicate samples were taken from riffle habitats, as these areas typically support high benthic diversity and provide consistent sampling conditions. Replication also accounted for small-scale spatial variability. Sampling was conducted in May 2024, during the dry season, when river discharge is relatively stable, thereby reducing seasonal bias and ensuring comparability across sites. All specimens were carefully washed, transferred into labelled containers, and preserved in 70% ethanol before being transported to the laboratory for further analysis.

In the laboratory, macroinvertebrates were sorted and identified under a stereomicroscope using regional taxonomic keys. Identification was primarily conducted at the family level, which is widely recognised as a reliable and practical taxonomic resolution in tropical biomonitoring studies. When possible, specimens were further identified to the genus level to enhance ecological interpretation. The decision to use family-level resolution strikes a balance between taxonomic accuracy, practicality, and time efficiency, while maintaining robustness for calculating ecological indices.

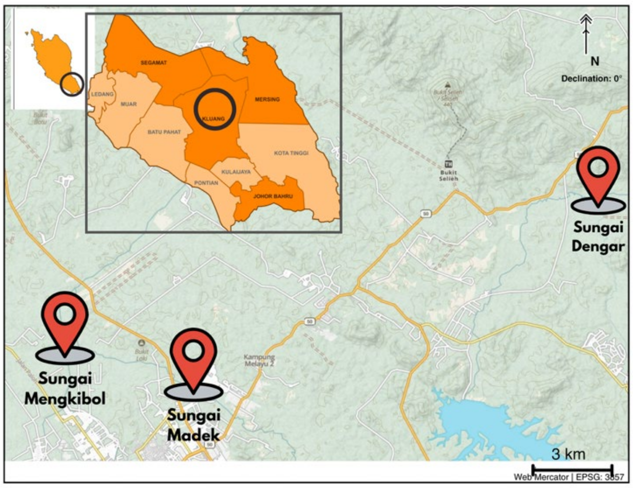

Figure 1. Location of study site (Sungai Mengkibol, Sungai Madek and Sungai Dengar)

Ecological indices were used to evaluate river health based on the structure of the macroinvertebrate community. The Shannon-Wiener Diversity Index (Shen, 2025), Margalef Richness Index and Simpson's Dominance Index were computed using the Species Diversity and Richness software (Leng et al., 2025). Evenness was calculated in Microsoft Excel using Hill's Index (Roswell et al., 2021). Finally, threshold values for ecological indices were proposed by comparing results between reference and impaired sites, enabling the identification of practical benchmarks to distinguish between healthy and degraded river conditions.

3. RESULT AND DISCUSSION

The Hulu Dengar station (reference site), located downstream of Gunung Berlumut, consistently recorded the most stable and balanced ecological indices among all stations studied. This site demonstrated high Density, Richness, and Evenness values while maintaining the lowest Dominance Index, reflecting a healthy and well-balanced benthic macroinvertebrate community. Specifically, the Diversity Index at Hulu Dengar ranged between 1.82 and 2.11, suggesting moderate to high species diversity. At the same time, the Richness Index values (1.86–3.28) further indicated the presence of a wide variety of taxa. Evenness Index values between 0.79 and 0.92 revealed that individuals were evenly distributed across species, without any single taxon disproportionately dominating the assemblage. Correspondingly, the Dominance Index remained very low (0.12–0.21), confirming the absence of stress-tolerant species monopolising the habitat. These findings are consistent with expectations for a reference site that has experienced minimal human disturbance and retains its natural ecological integrity.

In contrast, the Sungai Dengar station, which is directly influenced by surrounding oil palm plantation activities, exhibited more variable results, reflecting the ecological pressures associated with agricultural land use. The Diversity Index fluctuated widely, ranging from 0 to 2.5, while the Richness Index recorded values between 0 and 4.41, the highest observed among all sites. However, this apparent richness was not consistently accompanied by balanced community structure, as shown by the highly variable Evenness Index (0–1) and the elevated Dominance Index (0–0.64). These patterns suggest that while specific taxa may proliferate due to altered habitat and nutrient inputs from oil palm cultivation, the community is unstable and more vulnerable to dominance by a few tolerant species, particularly under stressed conditions (Su Yin & Yee Kwang, 2016)

Meanwhile, Sungai Madek station, situated in an area impacted by logging activities, also reflected signs of ecological stress, although in a slightly different pattern than the oil palm site. Diversity values ranged from 0 to 1.8, indicating lower community diversity than the reference site, while Richness Index values (0–2.5) revealed a decrease in the number of taxa present. Evenness values (0–0.97) showed moderate variation, suggesting that individuals were well distributed in some samples. Still, in others, the community was uneven, potentially due to dominance by a few opportunistic species. The Dominance Index (0–0.33) was moderately low overall, yet still higher than that of the reference site, indicating a shift in community structure caused by habitat alteration. These results reflect how logging activities, through sedimentation, canopy removal, and physical disturbance of the river channel, can disrupt benthic habitats and reduce macroinvertebrate diversity (Roque et al., 2015).

The patterns observed across the three stations reveal apparent differences in ecological integrity shaped by surrounding land-use activities. At Hulu Dengar (reference site), the macroinvertebrate community remained stable, with high Diversity (1.82–2.11), Richness (1.86–3.28), and Evenness (0.79–0.92), alongside low Dominance (0.12–0.21). These values reflect a balanced, resilient community typical of minimally disturbed rivers with intact riparian conditions. By contrast, Sungai Dengar, located within oil palm plantations, showed wider fluctuations in indices, with Diversity ranging from 0 to 2.5 and Richness up to 4.41, but accompanied by higher Dominance values (up to 0.64). This instability suggests ecological imbalance, likely driven by nutrient enrichment, sedimentation, and possible agrochemical runoff, which favour tolerant taxa while reducing the persistence of sensitive species (Ring et al., 2023).

Sungai Madek, impacted by logging activities, exhibited even lower ecological integrity, with Diversity between 0 and 1.8 and Richness not exceeding 2.5. The reduced diversity and higher turbidity are consistent with physical habitat disturbance caused by logging, such as sediment deposition and riparian vegetation loss. These conditions reduce habitat quality and limit sensitive taxa, leaving a community dominated by disturbance and its tolerant groups (Kafle et al., 2022).

Table 1: Ecological Index Ranges by Study Site

River / Station (Land Use)	Diversity Index	Dominan-ce Index	Richness Index	Evenness Index
Reference Sites (Healthy)	1.82 - 2.11	0.12 - 0.21	1.86 - 3.28	0.79 - 0.92
Sungai Dengar (Oil Palm Plantation)	0 - 2.50	0 - 0.64	0 - 4.41	0 - 1.00
Sungai Madek (Logging Area)	0 - 1.80	0 - 0.33	0 - 2.50	0 - 0.97
Sungai Mengkibol (Urban Area)	0 - 1.30	0 - 0.92	0 - 1.56	0 - 0.87

This study's data demonstrated variations in macroinvertebrate community structure across rivers with different land use pressures. At the urban-impacted Sungai Mengkibol, the Diversity Index ranged from 0 to 1.30, the Richness Index from 0 to 1.56, the Evenness Index from 0 to 0.87, and the Dominance Index from 0 to 0.92. These values represent the lowest Diversity and Richness among all sampling stations, indicating severe ecological stress. Such findings are consistent with a previous study by Azrina et al. (2006), who reported similarly low Shannon–Wiener (0.35–0.51) and Margalef Richness (0.05–0.09) values in the polluted downstream stretches of the Langat River. This consistency reinforces the sensitivity of these indices to pollution and habitat degradation.

Sungai Madek (logging area) exhibited relatively higher Evenness Index values compared to the reference site at Hulu Dengar. This was unexpected since undisturbed reference stations are generally assumed to exhibit more stable and evenly distributed macroinvertebrate communities. The low Evenness observed at Hulu Dengar may suggest localised natural disturbances or microhabitat dominance by a few sensitive taxa. In contrast, Sungai Madek's relatively higher values may reflect a transitional state in which tolerant and sensitive taxa coexist (Feng et al., 2025). In comparison, Sungai Mengkibol displayed the lowest Evenness Index, a pattern typical of polluted rivers where a few highly pollution-tolerant species dominate benthic macroinvertebrate communities. This pattern was mirrored in the Dominance Index, which was highest at Mengkibol and lowest at the Hulu Dengar reference site.

Physicochemical parameters further substantiated the biological patterns observed in this study, reinforcing the link between water quality and benthic macroinvertebrate assemblages. Conductivity and total suspended solids (TSS) were notably highest at Sungai Mengkibol, a site heavily influenced by urban development and associated runoff. Elevated conductivity often reflects increased ion concentrations from domestic and industrial discharges, while high TSS values are commonly associated with sediment erosion, poor land management, and stormwater inflows (Samsudin et al., 2023). These factors reduce light penetration, alter substrate composition, and degrade habitat quality, limiting colonisation by sensitive taxa and favouring tolerant groups. Similar associations have been reported by Azrina et al. (2006), who demonstrated that suspended solids and conductivity strongly shape Diversity and Richness indices, as both parameters directly constrain habitat suitability and food availability for aquatic organisms.

When comparing ecological indices across all sites, the highest Diversity, Richness, and Evenness were recorded at Hulu Dengar, the designated reference site, indicating minimal anthropogenic disturbance and the presence of a more balanced community structure (Hao et al., 2022). This was followed, in descending order, by Madek downstream, Dengar upstream, Madek upstream, Dengar downstream, and finally Mengkibol downstream. The Dominance Index demonstrated a notable inverse trend, highlighting the Mengkibol downstream site as the area with the highest dominance of specific tolerant taxa, most prominently the pollution-resistant Chironomidae. This observation is significant as it reflects the ecological impact of land use changes over time (dos Reis Oliveira et al., 2020). As land use intensity increases, a clear environmental gradient transitions from natural forested catchments, characterised by rich biodiversity and more complex ecological interactions, to areas logged or converted into plantations. Ultimately, this gradient leads to urbanised landscapes, where natural habitats have been significantly altered.

As a result of these changes, macroinvertebrate communities undergo a marked shift. In more pristine environments, these communities are often diverse and resilient, featuring a variety of species that contribute to ecological balance (McLaverty et al., 2020). However, the assemblages become increasingly simplified in environments that have a significant impact on human activities. This simplification is characterised by a predominance of tolerant species, which can withstand adverse conditions, such as pollution and habitat degradation, while sensitive species decline or vanish. This shift not only indicates a loss of biodiversity but also suggests a reduction in the overall health and resilience of the ecosystem (Schmid et al., 2019). This gradient powerfully illustrates the cumulative impact of anthropogenic activities on riverine ecosystems. Logging operations and plantation expansion contribute to sedimentation and nutrient enrichment, while urbanisation introduces multiple stressors, including chemical pollutants, organic waste, and altered hydrology (Roque et al., 2015). Such pressures collectively degrade ecological integrity, confirming the sensitivity of macroinvertebrate indices as indicators of river health. Notably, the consistency between biological indices and physicochemical parameters underscores the reliability of an integrated biomonitoring approach, where macroinvertebrate-based metrics can serve as early warning tools to complement traditional water quality assessments.

The ecological interpretation of these results highlights the role of land use change as a driver of biological degradation. River ecosystems adjacent to urban, plantation, or logging areas are exposed to runoff, increased suspended solids, and habitat alteration due to the loss of riparian vegetation. Removing canopy cover and riparian buffers increases sediment loads, alters instream microhabitats, reduces shading, and raises water temperature (McCredie et al., 2025). As Maddock (1999) mentioned, such habitat changes inevitably alter the biotic community composition and structure. The results of this study reaffirm the recommendation by Gillian White and Tim Storer (2012), which emphasises that aquatic biota should serve as a key indicator of river health. Since biota represent the endpoint of cumulative environmental pressures, shifts in benthic macroinvertebrate assemblages provide a reliable measure of ecosystem degradation.

Ultimately, the observed trends across the Johor rivers underscore the practicality of using benthic macroinvertebrates as the basis for a Recommended Ecological Index. This study makes a significant contribution to the scientific understanding and practical application of river health monitoring in Malaysia by linking community-level changes to land-use impacts. Such an approach is vital for ecological assessment, informing community awareness, and guiding sustainable development planning, thereby ensuring that anthropogenic activities do not irreversibly compromise the integrity of aquatic ecosystems.

Together, these findings highlight the strong responsiveness of benthic macroinvertebrate assemblages to land use pressures and physicochemical changes across different river systems. By demonstrating consistent patterns of reduced Diversity and Richness in urban-impacted rivers, contrasted with higher indices at reference sites, this study provides strong empirical support for developing a Recommended Ecological Index for River Health Assessment. Unlike conventional water quality parameters that provide only a snapshot of conditions, the proposed index integrates biological responses, making it a more holistic and reliable tool for monitoring. Implementing this application will enable environmental managers and policymakers in Malaysia to more effectively identify early indicators of ecological degradation, facilitate restoration initiatives, and balance development and conservation efforts.

Biological indices for benthic macroinvertebrate communities, such as the Shannon–Wiener Diversity Index, Simpson's Dominance Index, Margalef Richness Index, and Hill's Evenness Index, are valuable tools for assessing river health. Each of these indices reflects a distinct ecological attribute. The Shannon–Wiener Index measures species diversity, Simpson's Index highlights the extent to which a few tolerant taxa dominate a community, Margalef's Index reflects the richness or number of taxa present, and Hill's Evenness Index indicates the balance in distribution of individuals across taxa. When used together, these indices provide a comprehensive picture of river ecosystem condition, far more robust than relying on a single measure alone.

Based on the data collected in this study, a Recommended Ecological Index for River Health Assessment has been established, as summarised in Figure 2 and Table 2. This index provides a scientifically grounded classification framework distinguishing between healthy, slightly impaired and severely degraded river systems. The framework defines ecological thresholds across four principal biotic indices—Shannon–Wiener Diversity (H'), Simpson's Dominance (D), Margalef Richness (d), and Hill's Evenness (E)—each representing a specific dimension of community structure and ecosystem stability.

The results reveal clear and consistent patterns across these indices characterising the three health categories. In unhealthy and polluted rivers, diversity and richness values were persistently low (Shannon < 1.0; Margalef < 1.0), while dominance was very high (Simpson > 0.5) and evenness was poor (Hill < 0.6). Such conditions indicate biologically stressed environments where environmental pressures, such as organic pollution, sedimentation, or chemical runoff, have eliminated most sensitive taxa. The remaining assemblage is often dominated by a few tolerant and opportunistic species, resulting in a highly unbalanced community with reduced ecosystem resilience (Mustafa Dawood & Zaiha Arman, 2016).

In contrast, moderately polluted or slightly impaired rivers displayed intermediate index values, with Shannon–Wiener between 1.0 and 1.8, Simpson's Dominance between 0.2 and 0.5, Margalef Richness between 1.0 and 2.0, and Hill's

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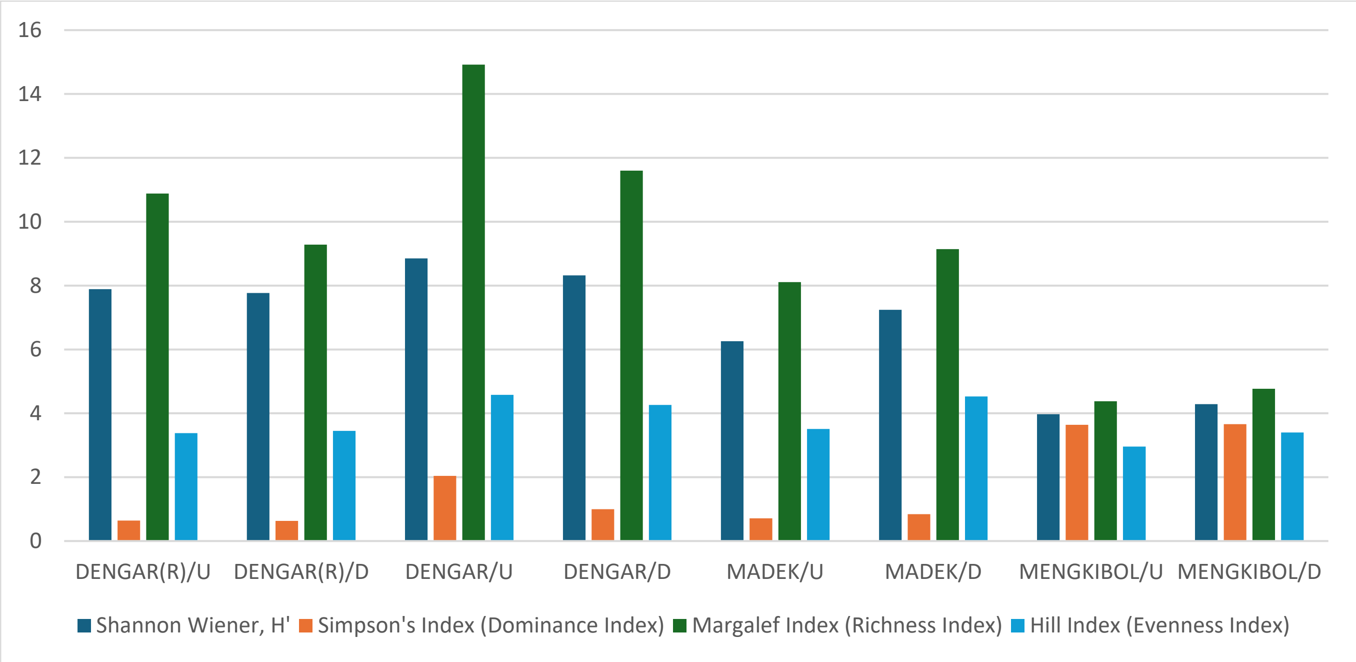
Evenness ranging from 0.6 to 0.8. These conditions typically represent ecosystems under transitional stress, where some pollution-sensitive species have declined, but ecological interactions and community balance are not entirely disrupted. The persistence of moderately tolerant taxa in these systems indicates that partial ecological integrity remains, and recovery is possible if stressors are effectively managed (Jenderedjian et al., 2007)

Figure 2: Ecological Index at all the sampling stations



Conversely, healthy and clean rivers demonstrated high diversity (Shannon > 1.8), high richness (Margalef > 2.0), low dominance (Simpson < 0.2), and strong evenness (Hill > 0.8). These attributes reflect stable, self-regulating ecosystems characterised by a wide range of taxa distributed relatively evenly across the community. Such balanced community structures are hallmarks of resilient and ecologically intact river systems, capable of sustaining natural processes such as nutrient cycling, decomposition, and habitat provisioning (Bunn & Arthington, 2002).

The strength of this classification framework lies in its ability to translate complex biological data into clear, actionable thresholds that can be directly applied in river health assessments. Unlike conventional approaches that depend solely on physico-chemical indicators (e.g., pH, dissolved oxygen, or nutrient concentration), this index integrates biological responses that represent the cumulative impact of environmental changes over time. As such, it provides a more holistic and long-term view of river ecosystem integrity (Msk et al., 2021).

Because this system is developed using empirical field data from tropical rivers in Johor, it is particularly tailored to Malaysian freshwater ecosystems, which are influenced by diverse land use pressures such as oil palm plantations, logging, agriculture, and urbanisation. These human activities create unique ecological gradients that shape the composition of macroinvertebrate communities and river health (Kuehne et al., 2025). Nevertheless, the framework remains flexible and adaptable, allowing future refinement or regional calibration as additional data are collected from other watersheds across Malaysia and Southeast Asia.

By implementing this biological indicator-based classification, researchers, policymakers, and environmental managers can enhance the precision of river monitoring programs, moving beyond traditional short-term chemical analyses toward integrated biomonitoring strategies. Such approaches enable the detection of subtle ecological shifts that may precede visible degradation, facilitating early intervention and adaptive management.

Ultimately, adopting these ecological thresholds and indices represents a crucial step toward evidence-based river conservation. It supports long-term ecosystem monitoring, strengthens environmental policy frameworks, and contributes to the sustainable management of freshwater resources in tropical regions. By aligning biological assessment with practical conservation objectives, this framework provides a scientifically robust tool for protecting and restoring river ecosystems, ensuring their health and functionality for future generations.

Table 2: Recommended Ecological Index for River Health Assessment

Classifications	Shannon-Wiener Diversity Index	Simpson's Dominance Index	Margalef Richness Index	Hill Evenness Index
Unhealthy and Polluted River	< 1.0	> 0.5	< 1.0	< 0.6
A Slightly Unhealthy and Slightly Polluted River	> 1.0, < 1.8	> 0.2, < 0.5	> 1.0, <2.0	> 0.6, > 0.8
Healthy and Clean River	> 1.8	<0.2	> 2.0	> 0.8

4. CONCLUSION

This study demonstrates that the proposed Recommended Ecological Index provides a more reliable tool for assessing river health in Malaysia, as it incorporates key measures of diversity, richness, evenness, and dominance derived from benthic macroinvertebrate communities. Results clearly showed that Sungai Mengkibol (urban) recorded the lowest values for Diversity and Richness, reflecting severe ecological stress. At the same time, the reference site at Hulu Dengar exhibited the highest indices, indicating good environmental health. These findings highlight the strong influence of land use activities, such as urbanisation, oil palm cultivation, and logging, on river ecosystems, where increased pollutants, suspended solids, and habitat alterations drive declines in macroinvertebrate assemblages. The Recommended Ecological Index, therefore, represents a practical and sensitive tool for river health monitoring and management in Malaysia.

However, this study is not without limitations. The research was conducted across several sites in Johor, with sampling restricted to one period and macroinvertebrate identification carried out only to the family level. These factors may limit the generalizability and resolution of the findings. Future research should expand the scope to different regions and seasons, incorporate higher taxonomic resolution, and integrate biological indices with physicochemical and land use data. Such efforts would refine the index further and support the establishment of a nationally recognised ecological monitoring framework. Ultimately, this study provides a scientific basis for improving river health assessments in Malaysia and a valuable contribution to sustainable water resource management and policy development.

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