Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 4, December 2026 issue

Review

Macroinvertebrate-Based Ecological Health Assessment of Main River and Canal Systems in the Mekong Delta: Challenges and Future Directions

Anh Duc Pham[1]†, My Thanh Dang[1], Duc Canh Vu[1], Thanh Luu Pham[1] and Thanh Son Dao[2,3]

[1]Faculty of Environment and Labour Safety, Ton Duc Thang University, 19 Nguyen Huu Tho Street, Tan Hung Ward, Ho Chi Minh City, Vietnam

[2]Faculty of Environment and Natural Resources, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, Dien Hong Ward, Ho Chi Minh City, Vietnam

[3]CARE, Ho Chi Minh City University of Technology (HCMUT), Vietnam National University Ho Chi Minh City, 268 Ly Thuong Kiet Street, Dien Hong Ward, Ho Chi Minh City, Vietnam

†Corresponding author: Anh Duc Pham; phamanhduc@tdtu.edu.vn

ORCID ID: Anh Duc Pham https://orcid.org/0000-0001-7714-6364

ORCID ID: My Thanh Dang https://orcid.org/0009-0007-9682-1530

ORCID ID: Duc Canh Vu https://orcid.org/0000-0002-6612-276X

ORCID ID: Thanh Luu Pham https://orcid.org/0000-0003-3276-1114

ORCID ID: Thanh Son Dao https://orcid.org/0000-0002-2993-2683

Key Words	Macroinvertebrates, Ecological health assessment, River–canal systems, Mekong Delta, Bioassessment methods
DOI	https://doi.org/10.46488/NEPT.2026.v25i04.D1931 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Pham, A.D., Dang, M.T., Vu, D.C., Pham, T.L. and Dao, T.S., 2026. Macroinvertebrate-based ecological health assessment of Main River and canal systems in the Mekong Delta: Challenges and future directions, *Nature Environment and Pollution Technology*, 25(4), D1931. https://doi.org/10.46488/NEPT.2026.v25i04.D1931

ABSTRACT

Macroinvertebrate-based ecological health assessment (EHA) complements physicochemical monitoring in tropical deltas by integrating cumulative ecological responses to interacting stressors. The Mekong Delta is characterized by monsoonal discharge, tidal mixing, fine-sediment dominance, salinity gradients, and a heavily modified ~ 100,000 km canal network that pose significant bioassessment challenges unaddressed by generic, temperate-river frameworks. This review synthesizes approximately 83 peer-reviewed and grey-literature sources (1991–2026) to evaluate the application of macroinvertebrate-based EHA, contrasting evidence from main rivers and artificial canal systems. We identify a fundamental ecological dichotomy: main river assemblages exhibit strong monsoon–tide seasonal turnover, whereas canal networks reflect chronic degradation marked by biotic homogenization and a dominance of pollution-tolerant taxa. However, regional frameworks are constrained by critical systemic biases: a geographic blind spot (<30% of studies focus on canals), an 80% dry-season bias neglecting the Flood Pulse Concept, and operational deficits from family-level identification, fragmented keys, and a lack of standardized quality control (QC). Consequently, uncalibrated temperate indices fail to account for tropical dynamics, masking canal degradation and episodic geochemical thresholds such as acid sulfate soils liberating toxic aluminum ions (Al^{3+}) at pH < 4.5, which traditional metrics (BMWP-VIET) and national standards (QCVN 08-MT:2023) fail to capture. Conversely, locally calibrated multimetric indices (MMIs) demonstrate high diagnostic specificity the confounding effects of chronic siltation and organic enrichment. To bridge the science–policy gap, future frameworks must adopt a strategic roadmap prioritizing typology-based monitoring that explicitly separates rivers from canals, alongside functional trait-based analyses to decouple natural estuarine variability from anthropogenic stress. Finally, high-throughput DNA metabarcoding must be integrated into automated GIS platforms within the Mekong River Commission (MRC) and national networks for unified, transboundary water resource management.

1. INTRODUCTION

The ecological health of river–canal systems is central to environmental sustainability, water security, and human well-being in low-lying deltas. Globally, river deltas are highly productive yet exceptionally vulnerable landscapes that support dense populations, intensive agriculture and aquaculture, and complex socio-ecological interactions (Syvitski et al., 2009; Best, 2019; Hua et al., 2024). Increasingly, deltas are shaped by coupled human–river dynamics that accelerate subsidence, drive sediment deficits, degrade habitats, and simplify ecological structure. Ecological health assessment (EHA) provides a critical framework for evaluating ecosystem condition and informing adaptive water and land management under compounding pressures from hydrological modification, water contamination, urbanization, and climate change (Norris & Thoms, 1999; Yu et al., 2013; Anthony et al., 2015). However, translating EHA into effective management remains challenging in highly engineered tropical deltas.

Similar patterns of channel modification, sediment alteration, and water quality degradation characterize the Mekong Delta. This is particularly evident in extensive artificial canal networks, which have been heavily engineered to support intensive agricultural and urban development (Kondolf et al., 2014; Nguyen & Le, 2014; Doan et al., 2025). These deltaic river–canal systems function as integrated networks that regulate flow, transport sediment, cycle nutrients, and maintain habitat connectivity. However, they remain highly sensitive to disturbances, including flow regulation, salinity intrusion, pollution, and land-use change (Nguyen et al., 2011; Best, 2019; Eslami et al., 2021; Cruz et al., 2026). Recent assessments report frequent exceedances of water quality standards in smaller canals linked to wastewater inputs, aquaculture effluents, and agrochemical use, whereas main rivers generally maintain better conditions, albeit with increasing signs of decline (Tran et al., 2016; Wehrheim et al., 2023; Mekong River Commission [MRC], 2024). This contrast underscores the need for assessment frameworks that distinguish clearly between river and canal systems.

To evaluate these conditions, EHA approaches increasingly integrate physicochemical monitoring with macroinvertebrate-based biological indicators. While physicochemical indicators often miss sudden pollution events, benthic macroinvertebrates integrate cumulative ecological responses to multiple stressors over time (Rosenberg & Resh, 1993; Hering et al., 2006; Friberg et al., 2011; Buss et al., 2015). Due to their limited mobility and diverse functional roles, shifts in their community composition and traits (e.g., feeding guilds) effectively reflect impacts from water quality, habitat structure, and hydrological regimes (Statzner et al., 2001; Bonada et al., 2006; Bendary et al., 2023; Chen et al., 2025). However, EHA implementation in the Mekong Delta is constrained by a key ecological dichotomy: river assemblages are driven by monsoonal–tidal dynamics, whereas canal systems show chronic degradation, biotic homogenization, and dominance of pollution-tolerant taxa (Chessman et al., 2007; Pham, 2014). This dichotomy complicates the transferability of standard bioassessment approaches.

Beyond these ecological differences, the application of EHA in the Mekong is hindered by technical and regulatory hurdles (Bonada et al. 2006; Birk et al 2012; Pham et al 2014). Most current frameworks are calibrated for temperate upland rivers and fail to account for the semi-lentic flow and acid sulfate soils characteristic of tropical canals (Morse et al 2007; Dudgeon 2010; Birk et al 2012; Dang et al 2018). Consequently, relying on uncalibrated indices like the Biological Monitoring Working Party (BMWP) or Average Score Per Taxon (ASPT) often results in misinterpretation of ecological status. In the Mekong Delta, the canal ecosystems, characterized by semi-lentic flow, fine-sediment accumulation, recurrent maintenance dredging, acid sulfate soils, and salinity intrusion, render traditional indices ineffective (Pham et al 2014; Mureithi et al 2025). Research consistently shows that agricultural and urban canals undergo taxonomic shifts, becoming dominated by pollution-tolerant taxa like oligochaetes and chironomids (Ngo et al 2013a; Vo et al 2019a; Le et al 2023a). In contrast, main rivers and floodplain wetlands support higher richness and functional diversity where hydrological connectivity is maintained (Pham, 2014; Ly et al 2025). Without indices incorporating local taxonomic traits and addressing limitations such as dry-season sampling bias and reliance on higher-taxon identification, EHA assessments remain inaccurate (Birk et al 2012; Pham et al 2014). This review examines multi-decadal trends to align bioassessment tools with the ecological realities of river–canal systems for sustainable water management (MRC, 2024; Doan et al 2025).

This review synthesizes macroinvertebrate-based EHA in the Mekong Delta, focusing on contrasts between main rivers and canal systems. Specifically, it aims to: (i) examine methodological approaches used in macroinvertebrate-based EHA; (ii) identify key ecological patterns and stressors shaping communities in rivers versus canals; and (iii) highlight challenges related to sampling design, index development, and interpretation in heavily modified deltaic environments. The review supports the development of locally calibrated, typology-sensitive bioassessment frameworks for sustainable environmental management. To operationalize this objective, a tiered framework is proposed (Fig. 1) that distinguishes main river channels from artificial canal networks and integrates system typology, hydrological regime, and dominant stressors to guide sampling design, taxonomic resolution, and analytical approach.

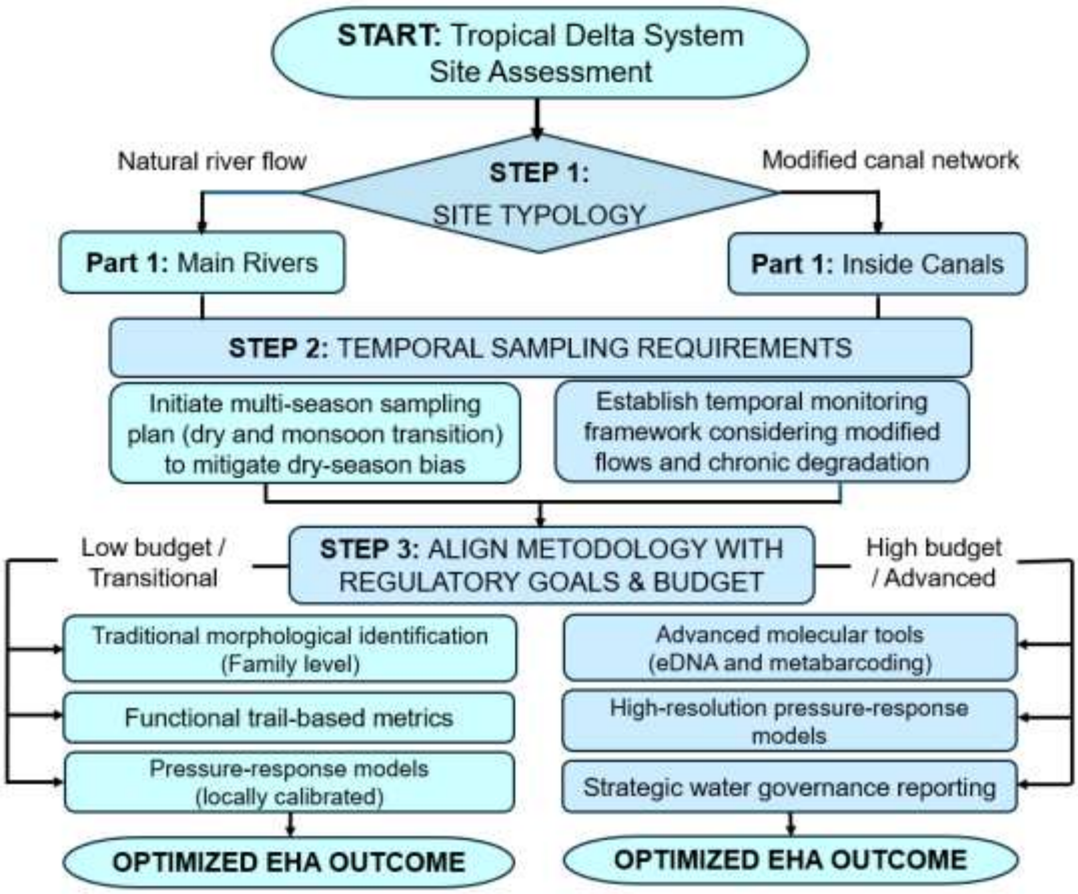

Fig. 1: Strategic decision-tree for selecting bioassessment protocols in tropical delta systems

2. METHODS

2.1. Study System and Regional Context

The Mekong Delta is a low-lying coastal system in southern Vietnam formed by the downstream reaches of the Mekong River. It comprises a heterogeneous network of main river channels, regulated canals, seasonally inundated floodplains, and estuarine zones, generating spatial gradients in hydrology and water quality (Dang et al 2018; Nguyen et al 2020). Main channels are characterized by high seasonal discharge variability, active sediment transport, and tidal influence, whereas canal systems exhibit low flow velocities, fine sediment accumulation, and frequent dredging (Allan, 2004). These conditions, combined with anthropogenic pressures from agriculture, aquaculture, and urbanization, create variable physicochemical environments that structure aquatic communities and influence the performance of biomonitoring indicators (Smith et al., 1999; Dodds & Smith, 2016; Gugliotta et al., 2017).

The Mekong Delta's aquatic network connects main river channels and artificial canals across socio-economic gradients, highlighting the environmental gradients that distinguish riverine from canal ecosystems. Intensive rice production dominates the upper floodplain provinces of An Giang and Dong Thap (Kontgis et al., 2015), while Tien Giang and Ben Tre support perennial horticulture (Le et al., 2017). The Ca Mau Peninsula is characterized by brackish and saline aquaculture, reflecting salinity gradients driven by shrimp farming (Bosma et al., 2014). Urban–industrial development is concentrated in Long An, a key corridor linked to Ho Chi Minh City; in Can Tho and Kien Giang (Dang et al., 2018). The Tien and Hau rivers, along with an extensive canal network, provide hydrological connectivity for irrigation, transport, and regional trade, while mediating the distribution of pollutants and ecological stressors (Kuenzer & Renaud, 2012; Gugliotta, 2017).

2.2. Literature Search and Selection Strategy

This review's methodological framework was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). Following systematic review principles, a comprehensive search was conducted across Web of Science, Scopus, and Google Scholar to identify peer-reviewed and grey literature (1991–2026). This was complemented by regional journals and governmental reports (e.g., MRC) to capture locally relevant data. The specific Boolean logic employed was: *(("macroinvertebrate" OR "zoobenthos" OR "aquatic insect") AND ("ecological health" OR "biomonitoring" OR "bioassessment" OR "index of biotic integrity" OR "DNA metabarcoding") AND ("Mekong Delta" OR "Vietnam") AND ("main river" OR "canal")).* The search was designed to capture both conventional and emerging bioassessment approaches. Foundational and recent methodological studies were prioritized (Rosenberg & Resh 1993; Bonada et al., 2006; MRC, 2008; MRC, 2010; Birk et al., 2012; Buss et al., 2015), alongside regional datasets (e.g., MRC reports or research in Vam Co River) and lowland river–canal case studies from southern Vietnam (Pham et al., 2026b).

2.3. Screening and Eligibility Criteria

Publications were screened using a stepwise process involving title and abstract screening, followed by full-text assessment. To minimize selection bias and ensure the reproducibility of the screening process, two independent reviewers performed the screening; any discrepancies regarding study inclusion were resolved through discussion until consensus was reached. Inclusion criteria: (i) use of macroinvertebrates as EHA indicators; (ii) study location within the Mekong Delta's aquatic network; and (iii) provision of sufficient methodological or ecological data. Exclusion criteria targeted laboratory-based toxicity studies, non-aquatic investigations, and reports lacking methodological detail. During screening, study attributes, including system type (river vs. canal), sampling seasonality (dry vs. wet season), taxonomic resolution, and metric selection were extracted to evaluate methodological biases and cross-system comparability.

2.4. Data Synthesis and Gap Analysis

Extracted data were synthesized qualitatively using a comparative framework that contrasts the hydrological and anthropogenic regimes of rivers versus canals. Studies were evaluated for their ability to detect consistent biological responses to dominant regional stressors, such as organic enrichment, pesticide runoff, and salinity intrusion (Wehrheim et al., 2023; Le et al., 2023b; Pham et al., 2026a). A key component was a performance audit of common indices, assessing the use and reliability of uncalibrated temperature metrics (e.g., BMWP, ASPT) under Mekong Delta tropical conditions (Duong et al., 2011). This evaluation informs the optimization of bioassessment frameworks. To identify critical research gaps, the literature corpus was analyzed for geographic bias, methodological constraints (e.g., single-season sampling, coarse taxonomic identification), and the application of modern bioassessment tools.

2.5. Strengths and Limitations of the Review

This review's primary strength is its comparative framework, which distinguishes between the ecological health of main rivers and artificial canals, a distinction overlooked in deltaic studies. The integration of global and regional sources enhances contextual relevance. Conversely, three limitations persist: (1) spatial bias, with research clustered in accessible river reaches rather than remote canal networks; (2) taxonomic heterogeneity (family vs. species level), which precludes a formal meta-analysis and necessitates a qualitative synthesis; and (3) reliance on long-term datasets, hindering the decoupling of anthropogenic stressors from natural climatic variability. These limitations inform priority areas for future methodological development.

3. RESULTS AND DISCUSSION

3.1. Literature Search Results and Methodological Biases

The final literature corpus comprised 83 publications, with a notable increase in research output after 2005. This reflects a paradigm shift from instantaneous physicochemical monitoring toward integrative biological approaches (MRC, 2010; Pham, 2014; MONRE, 2015), recognizing that biological assemblages, particularly macroinvertebrates, act as "living recorders" of cumulative environmental stress (Karr, 1991; Buss et al., 2015). However, this "record" contains a significant geographical blind spot. While 70% of studies focused on the main distributary channels (Tien and Hau rivers), the ~100,000 km artificial canal network with the primary conduit for agricultural runoff, is underrepresented (<30% of studies). This geographic bias suggests that ecological degradation in canals, where anthropogenic pressures are acute, is underestimated in regional reporting.

Methodologically, studies predominantly rely on quantitative grab sampling in soft sediments. Combined with family-level identification, this limits scalability and timely application in management contexts (Table 1), which synthesizes approaches reported across the reviewed literature rather than repeating methodological details.

Table 1. Key macroinvertebrate sampling approaches reported for river and canal systems in the Mekong Delta.

Sampling method	Target habitat	Sample equipment	Typical application	Key references
Littoral sweep / kick	Shallow margins	D-frame net (450–500 µm)	Rapid bioassessment; multi-habitat rivers	MRC, 2010; Ngo et al., 2013a; Pham, 2014
Hand-net	Confined waters	Standard net (450–500 µm)	Aquatic insects in small in ponds/canals	Bonada et al., 2006; Pham, 2014
Petersen grab	Benthic substrates	Grab (0.025 m²)	Quantitative riverine sampling	MRC, 2010; Vo et al., 2019; Pham et al., 2026b
Ekman grab	Fine sediments	Ekman grab (0.025 m²)	Deeper, low-energy environments	Ngo et al., 2013b; Ngo & Ngo, 2014
Multi-habitat	Mixed habitat	Nets and grabs	Holistic assessment; heterogeneous sites	Pham, 2014; Mamun et al., 2022; Pham et al., 2026b

Figure 2 presents the conceptual stressor–response framework for macroinvertebrate-based EHA in the Mekong Delta. The model links primary regional stressors (Stage 1) to localized habitat alterations (Stage 2) and cascading biological responses (Stage 3), including shifts in taxonomic composition, reduced diversity, and functional reorganization, providing the basis for selecting diagnostic metrics and computing ecosystem health scores (Stage 4). Sections 3.2–3.6 further explore how these stages operate within the Delta's semi-lentic, seasonally pulsed systems.

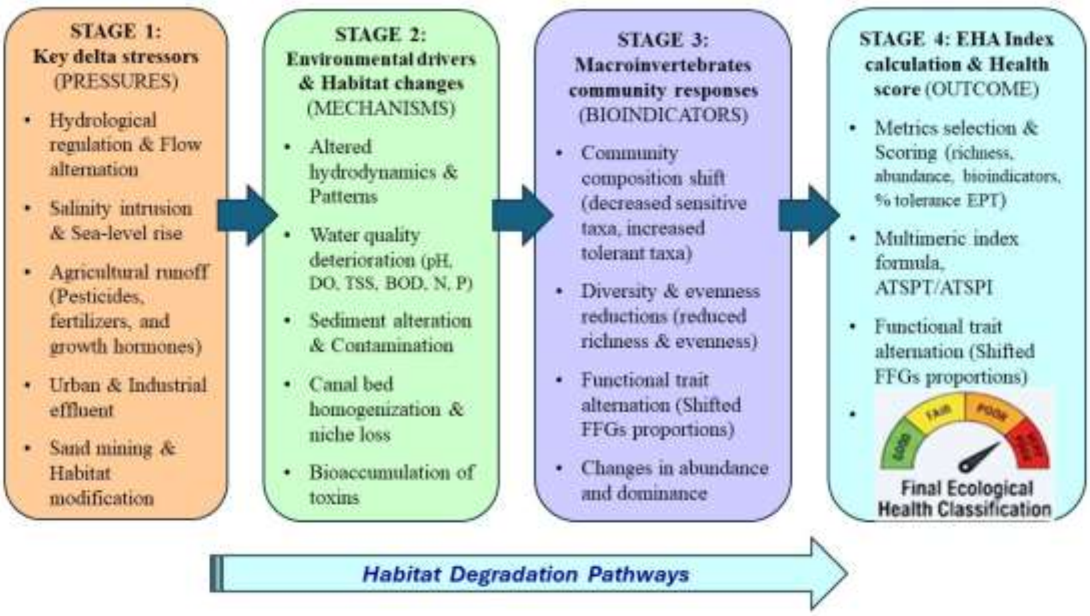

Fig. 2. Conceptual stressor-response framework for macroinvertebrate-based EHA in the Mekong Delta.

3.2. Ecological Divergence: Rivers vs. Canals

Reported macroinvertebrate diversity in the Mekong Delta shows pronounced spatial and temporal variability driven by habitat heterogeneity, hydrology, and methodological differences. The highest richness values were reported by the MRC (2008), which documented 361 littoral and 177 benthic taxa, while Sor et al. (2017) recorded 299 benthic taxa in the Lower Mekong Basin. Mollusks consistently dominate assemblages, accounting for approximately 44–45% of taxa across habitats, including estuarine–coastal transitional waters (Ngo et al., 2013b; Ngo & Ngo, 2014; Pham et al., 2019; Nguyen et al., 2020; Pham et al., 2026a). While abundance and density vary widely across sites and seasons, reflecting strong hydrological control. Densities range from 1–1,251 individuals m^{-2} in littoral habitats and 202–7,340 individuals m^{-2} in benthic habitats (Duong et al., 2008; Le et al., 2011; Ngo et al., 2013b; Ngo & Ngo, 2014). Benthic densities are lower in tributaries influenced by acid sulfate soils, particularly during early rainy-season discharge from rice fields (Pham et al., 2019; Pham et al., 2026a).

Analyses of diversity indices provide further quantitative evidence of ecological heterogeneity. Shannon–Wiener diversity ranged from <0.5 at heavily disturbed sites to >3.0 in structurally complex habitats, while dominance indices often indicated numerical dominance by tolerant taxa (MRC, 2008; MRC, 2009; Pham, 2014; Pham et al., 2019). Tolerance-based metrics such as ATSPT (23–63) and ATSPI (30–60) showed broad ranges and sensitivity to disturbance gradients, supporting their utility when calibrated to regional conditions (MRC 2008, MRC, 2009; Pham, 2014; Pham et al. 2026a).

Consequently, the delta's biotic integrity defies a singular ecological profile. Main river channels function as lotic, high-energy corridors where habitat complexity and lateral floodplain recruitment sustain taxonomic richness (Junk et al., 1989). These corridors exhibit high alpha diversity but low evenness, often dominated by Palaemonid decapods and Thiarid gastropods due to their tolerance of tidal fluctuations and natural turbidity. Conversely, sensitive, oxygen-dependent taxa (e.g., Ephemeroptera, Odonata) remain restricted to shallow littoral zones or floodplain-connected refugia where high flows maintain adequate dissolved oxygen and critical microhabitats (Fig. 3).

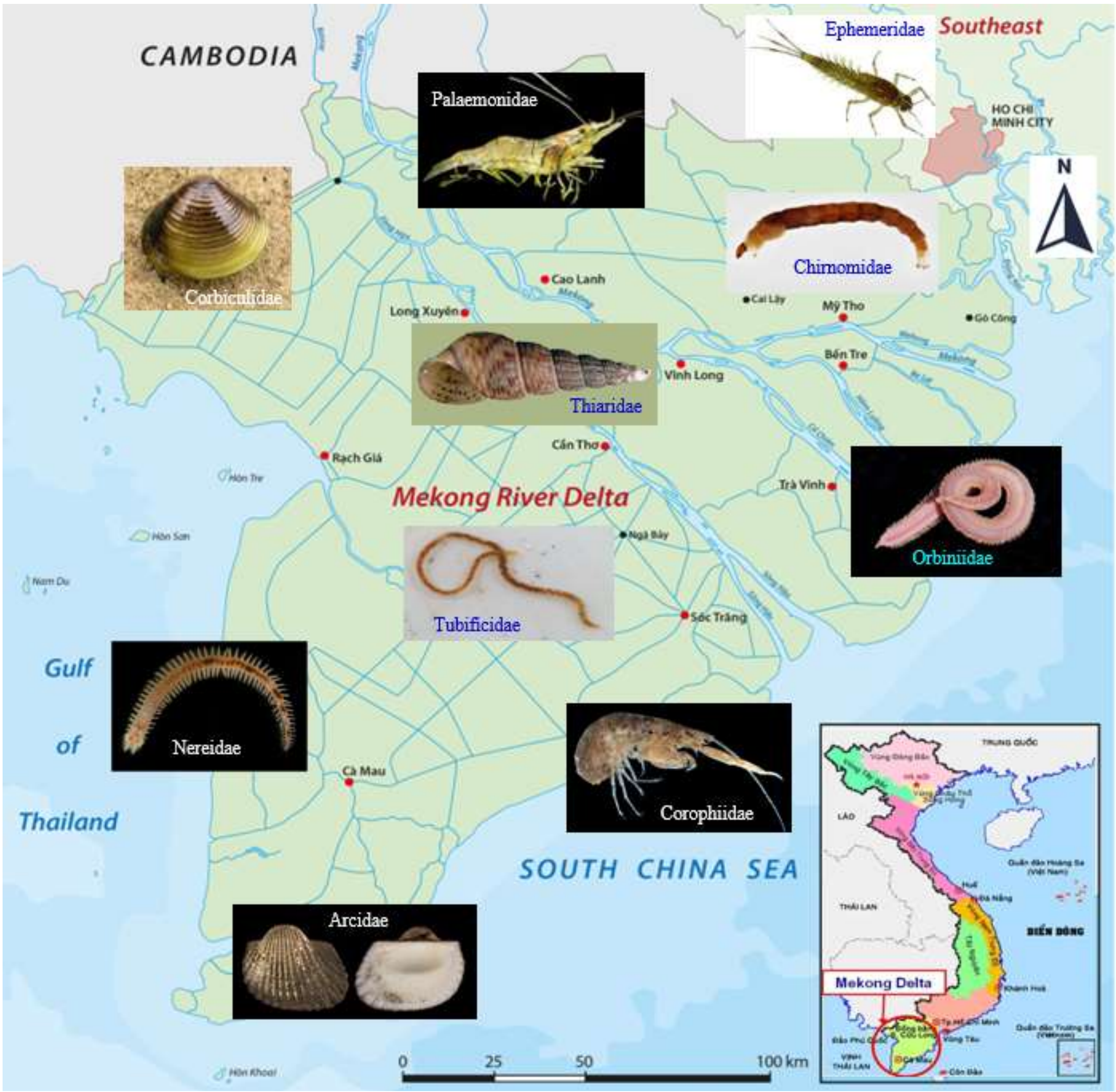

Fig. 3. Geographic distribution of key macroinvertebrate functional groups across the Mekong Delta

Conversely, artificial canals act as semi-lentic conduits harboring depauperate assemblages dominated by Tubificid oligochaetes, Chironomid dipterans, and *Corbicula* spp. (Fig. 3). Driven by low flow velocities and heavy organic enrichment, these modified channels undergo "functional homogenization," where specialized shredders are replaced by generalist collector-filterers adapted to high seston and hypoxic organic sludge (Statzner et al., 2001; Menezes et al., 2010). This stable, tolerance-mediated state acts as a potent environmental filter that conventional biotic indices often fail to detect (Sor et al., 2017; Le et al., 2023b). Finally, estuarine and coastal ecotones transition to euryhaline and marine taxa (polychaetes, bivalves, and crustaceans) physiologically adapted to dynamic salinity gradients (Pham, 2014; Pham et al., 2026b).

3.3. Stressor Dynamics

The ecological divergence detailed in Section 3.2 is underpinned by the Mekong Delta's stressor regimes. In main river channels, high dilution capacities and seasonal flushing pulses partially buffer anthropogenic inputs. Conversely, the canal network is characterized by stagnant flow and prolonged water residence times that exacerbate nutrient loading from agricultural and domestic effluents. As shown in Fig. 2 (Stage 2), these pressures operate synergistically; low flow velocities facilitate the development of anaerobic sediment microenvironments, triggering the loading of phosphorus and initiating a feedback loop of oxygen depletion (Anthony et al., 2015; Vo et al., 2024).

Sedimentation impacts vary by system as rivers undergo periodic resuspension, while canals experience chronic fine-sediment accumulation. The Vam Co River serves as a case study for "context-dependent" responses. While organic enrichment correlates with increased macroinvertebrate density, the presence of acid sulfate soils introduces a geochemical threshold. At pH < 4.5, the toxicity of liberated aluminum ions (Al^{3+}) results in ecological collapse zones despite high biochemical oxygen demand (BOD) (Pham et al 2026b). Current Vietnamese water quality standards (e.g., QCVN 08-MT:2023) and indices like BMWP-VIET fail to account for this acidity–toxicity synergy. Consequently, nutrient-reduction efforts yield no biological improvement because the system remains chemically "locked" by acidity. In these modified deltaic settings, interacting hydrological, sedimentary, and geochemical stressors produce non-linear biological responses that traditional metrics cannot capture.

3.4. Performance and Pragmatism

The performance and applicability of existing macroinvertebrate-based indices and metrics are summarized in Table 2, highlighting indicator types, taxonomic resolution, and limitations under Mekong Delta conditions. Due to the costs of specialized expertise and a deficit of regional species keys, over 75% of existing studies rely on family-level identification. While pragmatic, this "higher-taxon" approach frequently masks the nuanced biological signals required to detect specific stressors, as diverse species with varying sensitivities are aggregated into single, broad categorie (Buss et al., 2015).

Furthermore, Temperate-derived indices, such as the standard BMWP, perform inconsistently in canal networks because they do not account for the low-flow and low-oxygen conditions inherent to tropical deltas. Locally calibrated Multi-Metric Indices (MMIs) (e.g., Pham, 2014; Pham et al., 2026a) have demonstrated sensitivity. Specifically, the integration of metrics such as "Relative Abundance of Oligochaeta" and "Scraper-to-Filterer Ratios" has proven more robust in distinguishing between chronic siltation and organic enrichment (Pham, 2014; Mamun et al., 2022). However, these MMIs still require broader validation across the Delta’s complex salinity and acidity gradients to ensure regional reliability.

Table 2. Summary of macroinvertebrate-based indices and metrics reported for EHA in the Mekong Delta.

Index / Metric	Indicator type	Taxonomic level	Typical application	Notes / Limitations	Key references
Taxonomic richness	Structural	Family / Genus	Overall condition	Sensitive to habitat coverage	MRC, 2008; MRC, 2019; Nguyen et al., 2023;
Shannon–Wiener (H′)	Diversity	Family / Genus / Species	Community diversity	Low stressor specificity	Magurran, 2004; Zilli et al., 2011; Pham, 2014
BMWP-VIET / ASPT	Tolerance-based	Family	Ecological status	Limited canal calibration	Ngo et al., 2013a; Ngo et al., 2013b; Ngo & Ngo, 2014
% Oligochaeta	Tolerance proxy	Higher taxon	Organic enrichment	Confounded by fine sediments	Pham, 2014; Vo et al., 2021
Chironomidae abundance	Tolerance proxy	Family	Nutrient / Oxygen stress	Ubiquitous; moderate tolerance	Bonada et al., 2006; Le et al., 2023a
Functional feeding	Functional	Family	Stressor diagnosis	Requires regional trait data	Statzner et al., 2001; Bonada et al., 2020
Multimetric (MMIs)	Integrated	Family	Holistic status	Limited validation across gradients	Birk et al., 2012; Mamun et al., 2022

3.5. Systemic Challenges

Current bioassessments in the Mekong Delta are constrained by three systemic weaknesses. First, a dry season bias exists, with approximately 80% of reviewed studies neglecting the Flood Pulse Concept (Junk et al., 1989); omitting monsoonal restructuring of habitats, these assessments capture only partial annual dynamics. Second, the region faces a reference condition void; in a delta strongly modified by dikes and canals, the search for "pristine" benchmarks is an exercise in futility (Stoddard et al., 2006; Birk et al., 2012). Future indices must therefore transition toward gradient-based or multivariate models that evaluate ecological status along a spectrum of human impact rather than against "natural" states (Davies & Jackson 2006; Chessman, 2006; Feio et al., 2014).

Finally, persistent taxonomic bottlenecks and a reliance on family-level identification mask the presence of cryptic species and rare taxa (Jones, 2008; Sweeney et al., 2011). This resolution deficit is severely compounded by fragmented regional identification keys and a widespread lack of standardized quality control (QC) protocols across historical datasets. Consequently, these operational deficiencies act as major systemic bottlenecks that hinder coordinated, transboundary ecological health assessments, especially since these sensitive indicators are the first to respond to climate-driven shifts in salinity and hydrological regimes (Macher et al., 2016; Eriksen et al., 2025).

3.6. Future Horizons

The trajectory of EHA in the Mekong Delta is shifting toward predictive, diagnostic frameworks. To bridge the science–policy gap, we propose a strategic roadmap (Fig. 1): first, adopt typology-based monitoring that differentiates major rivers from irrigation canals; second, integrate molecular tools such as DNA metabarcoding to overcome taxonomic constraints and enable cost-effective large-scale monitoring; and third, align bioindicator data with GIS platforms within Mekong River Commission and national systems to support coordinated, transboundary water quality management.

Methodological challenges and recommended pathways for advancing macroinvertebrate-based EHA are synthesized in Table 3, linking limitations such as taxonomic gaps, hydrological seasonality, and canal-specific disturbances to solutions and their benefits for EHA. These molecular tools enable the detection of cryptic biodiversity and community shifts before irreversible ecological collapse occurs (Nguyen et al., 2025; Eriksen et al., 2025). Moving beyond taxonomic presence to functional roles allows separation of natural variability from anthropogenic impacts. Trait-based approaches (e.g., respiration mode, dispersal strategy) provide diagnostic insight into stressors such as hypoxia, pesticide exposure, and sedimentation (Statzner et al., 2001). Embedding this typology-sensitive, molecularly informed roadmap (Fig. 1) and GIS-based spatiotemporal analysis into MRC policy empowers managers to balance intensifying irrigation demands with the ecological integrity of the delta's river–canal network.

Table 3. Methodological challenges and recommended pathways for advancing macroinvertebrate-based EHA in the Mekong Delta.

Evidence-based limitation	Recommended methodological pathway	Primary benefit for EHA
Taxonomic expertise gap	eDNA / Metabarcoding or using trait-based metrics	Rapid, large-scale screening or reducing dependence on species-level identification
Strong hydrological seasonality	Seasonal stratification and mixed-effects	Separates natural variability from anthropogenic stress
Canal-specific disturbances	Canal-adapted indices; habitat and sediment metrics	Improves sensitivity and diagnostic power in artificial waterways
Fine sediment and organic enrichment	Target tolerant benthic taxa and feeding groups	Clarifies status in naturally turbid, low-energy waters
Acid sulfate soils and acidification	Integrate of sediment chemistry with bioindicators	Detects episodic geochemical toxicity (Al^{3+}, pH)
Policy fragmentation	MRC/GIS integration	Facilitates basin-scale trend analysis and transboundary management

Resolving the complexities in macroinvertebrate-based assessments within the Mekong Delta necessitates a strategic departure from temperate-derived indices. Instead, the focus must shift toward ecological frameworks that calibrate for the region's unique hydrological dynamics and multi-stressor landscape. By synthesizing delta-specific typologies with advanced diagnostic tools, specifically functional trait-based analysis and high-throughput DNA metabarcoding (Baird & Hajibabaei, 2012; Taberlet et al., 2012; Elbrecht et al., 2017; Pawlowski et al., 2018; Fueyo et al., 2024; Eriksen et al., 2025), researchers can effectively decouple natural estuarine variability from human-induced degradation. Translating these high-resolution ecological baselines into evidence-based policy instruments is imperative for the long-term conservation and transboundary management of the Mekong's biological integrity.

4. CONCLUSIONS AND FUTURE DIRECTIONS

Macroinvertebrate-based EHA in the Mekong Delta is highly context-dependent, varying sharply between dynamic, tidally mixed main rivers and the ~ 100,000 km artificial canal network, which undergoes chronic stress (pesticide runoff, siltation) and functional homogenization. Current frameworks are constrained by critical systemic biases: a geographic blind spot (< 30% of studies focus on canals), an 80% dry-season bias neglecting the Flood Pulse Concept, and operational deficits driven by family-level identification, fragmented keys, and a lack of standardized QC protocols. Consequently, uncalibrated temperate indices fail to account for tropical deltaic dynamics, masking degradation in canals and estuarine zones. Recent advances demonstrate that deltaic assemblages are strongly conditioned by hydrological extremes, salinity gradients, and episodic geochemical thresholds such as acid sulfate soils releasing toxic aluminum ions (Al^{3+}) at pH < 4.5 which traditional indices (BMWP-VIET) and national standards (QCVN 08-MT:2023) fail to capture. Conversely, locally calibrated multimetric indices (MMIs) utilizing target metrics (e.g., relative abundance of Oligochaeta, scraper-to-filterer ratios) have proven robust in isolating chronic siltation from organic enrichment.

Future work must prioritize the proposed strategic roadmap to bridge the science–policy gap. This requires topology-based monitoring that explicitly separates main rivers from artificial waterways, alongside the systematic implementation of functional trait-based analysis (e.g., respiration modes and dispersal strategies) to decouple natural estuarine variability from anthropogenic degradation. Finally, high-throughput DNA metabarcoding must be systematically scaled to bypass taxonomic constraints and embedded into automated GIS platforms within the MRC and national frameworks to achieve unified, transboundary water resource management.

Author Contributions: Conceptualization, Anh Duc Pham and Thanh Luu Pham; methodology, Anh Duc Pham, Thanh Luu Pham and Thanh Son Dao; software, My Thanh Dang and Duc Canh Vu; validation, Anh Duc Pham and Thanh Luu Pham; formal analysis, Thanh Luu Pham and Anh Duc Pham; investigation, Anh Duc Pham, My Thanh Dang and Duc Canh Vu; resources, Anh Duc Pham and Thanh Son Dao; writing—original draft preparation, Anh Duc Pham; writing—review and editing, Thanh Luu Pham, Thanh Son Dao and Anh Duc Pham; visualization, Anh Duc Pham and Pham Thanh Luu; supervision, Anh Duc Pham. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to express their thanks to Ton Duc Thang University, Vietnam, their invaluable technical support in the execution of this project.

Conflicts of Interest: The authors declare no conflicts of interest.

REFERENCES

1. Allan, J. D., 2004. Landscapes and Riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics,* 35, 257–284. https://doi.org/10.1146/ annurev.ecolsys.35.120202.110122
2. Anthony, E., Brunier, G., Basset, M.T., Goichot, M., Dussouillez, P., & Nguyen, V.L., 2015. Linking rapid erosion of the Mekong River delta to human activities. *Scientific Reports,* 5(1), 14745. https://www.researchgate.net/publication/283116676
3. Baird, D.J., & Hajibabaei, M., 2012. Biomonitoring 2.0: a new paradigm in ecosystem assessment made possible by next-generation DNA sequencing. *PLoS ONE* 7, e32706. https://doi.org/10.1371/journal.pone.0032706
4. Bendary, R.E., Goher, M.E., & El-Shamy, A.S., 2023. Taxonomic and functional diversity of macroinvertebrates in sediment and macrophyte habitats: A case study, the Ibrahimia Canal, Nile River, Egypt. *Egyptian Journal of Aquatic Research*, 49(2), 129–135. https://doi.org/10.1016/j.ejar.2023.05.001
5. Best, J., 2019. Anthropogenic stresses on the world's big rivers. *Nature Geoscience,* 12, 7–21. https://doi.org/10.1038/s41561-018-0262-x
6. Birk, S., Bonne, W., Borja, Á., Brucet, S., Courrat, A., Poikane, S., Solimini, A., Van De Bund, W., Zampoukas, N., & Hering, D., 2012. Three hundred ways to assess Europe's surface waters: an almost complete overview of biological methods to implement the Water Framework Directive. *Ecological Indicators,* 18, 31–41. https://doi.org/10.1016/j.ecolind.2011.10.009
7. Bonada, N., Prat, N., Resh, V.H., & Statzner, B., 2006. Developments in aquatic insect biomonitoring: a comparative analysis of recent approaches. *Annual Review of Entomology*, 51, 495–523. https://doi.org/10.1146/annurev.ento.51.110104.151124
8. Bosma, R. H., Nguyen, T.H., Siahainenia, A.J., Tran, H.T.P., & Tran, H.N., 2014. Shrimp-based livelihoods in mangrove silvo-aquaculture farming systems. *Reviews in Aquaculture*, 16, 1–18. https://doi.org/10.1111/RAQ.12072
9. Buss, D.F., Carlisle, D.M., Chon, T.S., Culp, J., Harding, J.S., Keizer-Vlek, H.E., Robinson, W.A., Strachan, S., Thirion, C., & Hughes, R.M., 2015. Stream biomonitoring using macroinvertebrates around the globe: a comparison of large-scale programs. *Hydrobiologia*, 757, 1–21. https://doi.org/10.1007/s10750-015-2191-8
10. Chen, S., Guo, C., Wang, X., Wu, Y., Wang, Y., Wang, Y, Wang, Y, & Guo, H., 2025. Channelization and flow depletion shift benthic macroinvertebrate and fish communities in urban rivers. *PLoS One*, 20(7), e0328843. https://doi.org/10.1371/journal.pone.0328843
11. Chessman, B.C., Williams, S.A., & Besley, C., 2007. Bioassessment of streams with macroinvertebrates: effect of sampled habitat and taxonomic resolution. *Journal of the North American Benthological Society,* 26, 546–565. https://doi.org/10.1899/06-100.1

12. Cruz, M., Rosman, P.C.C., Marisa, C.R.A., & Iglesias, I.I., 2026. Modelling estuarine wetlands and their role as nature-based solutions: a review. *Science of The Total Environment*, 1014, 181325. https://doi.org/10.1016/j.scitotenv.2025.181325
13. Dang, T.D., Cochrane T., Arias, M.E., & Pham, D.T.V., 2018. Future hydrological alterations in the Mekong Delta under the impact of water resources development, land subsidence and sea level rise. *Journal of Hydrology Regional Studies*, 15(C), 119–133. https://doi.org/10.1016/j.ejrh.2017.12.002
14. Davies, S. P., & Jackson, S. K. (2006). The biological condition gradient: a descriptive model for interpreting change in aquatic ecosystems. *Ecological Applications*, 16(4), 1251–1266. https://doi.org/10.1890/1051-0761(2006)016[1251:tbcgad]2.0.co;2
15. Doan, V.T., Le, C.C., Le, H.V.T., Trieu, N.A., Vo, L.P., Tran, D.A., Nguyen, H.V., Tabata, T., & Vu, T.T.H., 2025. Comprehensive statistical analysis for characterizing water quality assessment in the Mekong Delta: Trends, Variability, and key influencing factors. *Sustainability*, 17(12). https://doi.org/10.3390/su17125375\
16. Dodds, W.K. & Smith, V.H. 2016. *Nitrogen, phosphorus, and eutrophication*. Inland Waters. Nitrogen, phosphorus, and eutrophication in streams, Inland Waters, 6:2, 155–164. http://dx.doi.org/10.5268/IW-6.2.909
17. Dudgeon, D., 1999. *Tropical Asian Streams: Zoobenthos, Ecology and Conservation*. Hong Kong University Press, Hong Kong. https://doi.org/10.1515/9789882202962
18. Dudgeon, D., 2010. *Prospects for sustaining freshwater biodiversity in Asia*. Freshwater Biology.Elbrecht, V., Vamos, E.E., Steinke, D., & Leese, F., 2017. Estimating intraspecific genetic diversity from community DNA metabarcoding data. *Molecular Ecology,* 26, 2315–2329. https://doi.org/10.1111/mec.14034
19. Duong, C.D., Nguyen, C.T., & Nguyen, T.C.T., 2008. Research on water body zoning based on benthic macroinvertebrate communities. *Can Tho University Journal of Science*, 21, 61–66. (In Vietnamese)
20. Duong, C.D., Nguyen, V.C., & Le, C.Q., 2011. Application of benthic macroinvertebrate indices for assessing water pollution in Tam Bot Canal, Long Xuyen, An Giang Province. *Can Tho University Journal of Science*, 20A, 18–27. (In Vietnamese)
21. Elbrecht, V., Vamos, E.E., Steinke, D., Leese, F., 2017. Estimating intraspecific genetic diversity from community DNA metabarcoding data. *Molecular Ecology,* 26, 2315–2329. https://doi.org/10.1111/mec.14034
22. Eriksen, T.E., Brittain, J.E., Sandin, L. & Friberg, N., 2025. Unveiling cryptic macroinvertebrate sentinels to enhance biomonitoring in tropical rivers: Bridging traditional approaches with DNA barcoding in the Indo-Burma biodiversity hotspot. *Science of the Total Environment*, 958, 178064. https://doi.org/10.1016/j.scitotenv.2024.178064
23. Eslami, S. et al., 2021. Dynamics of salt intrusion in the Mekong Delta: results of field observations and integrated coastal–inland modelling, Earth Surf. Dynam., 9, 953–976, https://doi.org/10.5194/esurf-9-953-2021, 2021.
24. Feio, M. J., Davies, C. E., Hirsch, F., Pusch, M. T., Murphy, J. F., & Hughes, R. M., 2014. The biological assessment and rehabilitation of the world's rivers: an overview. *Water*, 6(3), 671-689.
25. Friberg, N., et al., 2011. *Biological indicators in freshwater ecosystems*. Ecological Indicators.
26. Fueyo, Á., Sánchez, O., Carleos, C., Escudero, A., Cordón, J., Granero-Castro, J. & Borrell, Y.J. (2024). Unlocking rivers' hidden diversity and ecological status using DNA metabarcoding in Northwest Spain. *Ecology and Evolution*, 14(8), e70110. https://doi.org/10.1002/ece3.70110
27. Gugliotta et al., 2017. Process regime, salinity, morphological, and sedimentary trends along the fluvial to marine transition zone of the mixed-energy Mekong River delta, Vietnam. *Continetial Shelf Research*, 147(7), 7–26. https://doi.org/10.1016/j.csr.2017.03.001

28. Gugliotta, M., Saito, Y., Ta, T.K.O., Tamura, T., & Nguyen, V.L., 2018. Sediment distribution and depositional processes along the fluvial to marine transition zone of the Mekong River delta. *Sedimentology*, 64(1), 165–187. https://doi.org/10.1111/sed.12489
29. Hering, D., et al., 2018. Implementation options for DNA-based identification into ecological status assessment under the European Water Framework Directive. *Water Research,* 138, 192–205. https://doi.org/10.1016/j.watres.2018.03.003
30. Hua, H.H., Cremin, E., Huynh, V.D., Long, G., & Renaud, F.G., 2024. Impacts of aquaculture practices on the sustainability of social-ecological systems in coastal zones of the Mekong Delta. *Ocean and Coastal Management*, 258, 107392. https://doi.org/10.1016/j.ocecoaman.2024.107392
31. Jones, F. C. (2008). Taxonomic sufficiency: The influence of taxonomic resolution on freshwater bioassessments using benthic macroinvertebrates. *Environmental Reviews*, 16(1), 45-69.
32. Junk, W.J., Bayley, P.B., & Sparks, R.E., 1989. The flood pulse concept in river–floodplain systems. *In* D.P. Dodge (Ed.), *Proceedings of the International Large River Symposium (LARS)*. Canadian Special Publication of Fisheries and Aquatic Sciences, 106, 110–127.
33. Karr, J.R., 1991. Biological integrity: a long-neglected aspect of water resource management. *Ecological Applications,* 1, 66–84. https://doi.org/10.2307/1941848
34. Kondolf, G.M. et al., 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future*, 2, . https://doi.org/10.1002/2013EF000184
35. Kontgis, C. Schneider ,A., & Ozdogan, M., 2015. *Mapping rice paddy extent and intensification in the Mekong Delta*. Remote Sensing, 7, 15802–15827. https://doi.org/10.1016/j.rse.2015.08.004
36. Kuenzer, C., & Renaud, F.G., 2012. *Climate and environmental change in the Mekong Delta.* Regional Environmental Change, 12(Suppl 1), S1–S6. 10.1007/978-94-007-3962-8_2
37. Le, C.Q., Trinh, T.L., & Vu, N.U., 2011. Distribution of zoobenthos in Cai Sao Canal, An Giang Province. Can Tho University Journal of Science. (In Vietnamese)
38. Le, H.A., Nguyen, T., Gratiot, N., Deleersnijder, E., & Soares-Frazão, S., 2023a. The multi-channel system of the Vietnamese Mekong Delta: impacts on the flow dynamics under relative sea-level rise scenarios. *Water*, 15, 3597. https://doi.org/10.3390/w15203597
39. Le, T.P.Q., Billen, G., Garnier, J., Théry, S., Chau, V.M., 2017. Nutrient (N, P) budgets for the Red River basin (Vietnam and China). *Global Biogeochemical Cycles, 19(2), 1–16.* https://doi.org/10.1029/2004GB002405\
40. Le, T.T., Pham, V. H., & Nguyen, N. T., 2023b. Ecological impacts of dredging and canal maintenance on benthic communities in the Mekong Delta. *Vietnam Journal of Water Resources*, 79, 41–52. (In Vietnamese)
41. Luong, V.T., 2001. *Research on estuarine aquatic organisms in the western coastal area of the Ca Mau Peninsula to support aquaculture development*. Scientific Research Project, Southern Institute of Water Resources Science, Ho Chi Minh City, Vietnam. (In Vietnamese)
42. Ly, V.V., Dinh, M.Q., Nguyen, T.K.L., Vo, T.T.L., Tran, N.A., Tran, T.T., Luu, T.L., Nguyen, L., & Ngo, M.H., 2025. Benthic macroinvertebrates diversity in the Tra Su Melaleuca Forest Landscape Protection Area, Mekong Delta, Vietnam. *Applied Ecology and Environmental Research*, 23(6), 10431–10442. http://dx.doi.org/10.15666/aeer/2306_1043110442

43. Macher, J. N., Salis, R. K., Blakemore, K. S., Tollrian, R., Matthaei, C. D., & Leese, F. (2016). Multiple-stressor effects on stream invertebrates: DNA barcoding reveals contrasting responses of cryptic mayfly species. *Ecological Indicators*, 61, 159-169.
44. Mamun, M., Jargal, N., Atique, U., & An, K.G., 2022. Ecological River Health Assessment Using Multi-Metric Models in an Asian Temperate Region with Land Use/Land Cover as the Primary Factor Regulating Nutrients, Organic Matter, and Fish Composition. *Int J Environ Res Public Health*, 19(15), 9305. https://doi.org/10.3390/ijerph19159305
45. Mekong River Commission (MRC), 2008. *Biomonitoring of the lower Mekong River and selected tributaries,* 2004 – 2007, MRC Technical Paper No. 20, Mekong River Commission, Vientiane. 77 pp. https://doi.org/10.52107/mrc.ajhz8m
46. Mekong River Commission (MRC), 2009. *Report on the 2006 biomonitoring survey of the Lower Mekong River and selected tributaries*. MRC Technical Paper No. 22, Mekong River Commission, Vientiane. 124 pp. https://doi.org/10.52107/mrc.ajhz6k
47. Mekong River Commission (MRC), 2010. *Biomonitoring Methods for the Lower Mekong Basin*. Mekong River Commission, Vientiane. 65 pp. https://doi.org/10.52107/mrc.ajhypg
48. Mekong River Commission (MRC), 2019. *Report on the 2017 Biomonitoring Survey of the Lower Mekong River and Selected Tributaries*. Mekong River Commission, Vientiane. 94 pp. https://doi.org/10.52107/mrc.ajg4wd
49. Mekong River Commission (MRC), 2024. *2022 Lower Mekong Water Quality Monitoring Report*. Mekong River Commission, Vientiane. 75 pp. https://www.mrcmekong.org/wp-content/uploads/2024/11/2022
50. Menezes, S., Baird, D.J., & Soares, A.M.V.M., 2010. Beyond taxonomy: a review of macroinvertebrate trait-based community descriptors as tools for freshwater biomonitoring. *Journal of Applied Ecology,* 47, 711–719. https://doi.org/10.1111/j.1365-2664.2010.01819.x
51. Ministry of Natural Resources and Environment (MONRE), 2015**.** *Guideline on Surface Water Environmental Monitoring*. MONRE, Hanoi. (In Vietnamese)
52. Morse, J.C., et al., 2007. Freshwater biomonitoring with macroinvertebrates in East Asia. *Frontiers in Ecology and the Environment,* 5(1), 33–42. https://doi.org/10.1111/j.1365-2664.2010.01819.x
53. Mureithi, P.W., Aine, A., Basooma, R. Namumbya, J., Nansumbi., F., Yegon, M.J., Meimberg, H., & Graf, W., 2025. Advancements in macroinvertebrate-based river bioassessment research in the Afrotropical region: review and steps towards a regional framework. *Environ Monit Assess,* 197(935)**.** https://doi.org/10.1007/s10661-025-14272-3
54. Ngo, X.Q., & Ngo, T.L., 2014. Composition and biodiversity of benthic macroinvertebrates communities in the Mekong River. *HCMUE J. Sci*., 58, 38–49. https://doi.org/10.54607/hcmue.js.0.58.788(2014)
55. Ngo, X. Q., Nguyen, T. D., & Pham, H. T., 2013a. Composition and distribution of benthic macroinvertebrates in the Mekong River, Vietnam. *Journal of Biology*, 35(4), 459–470.
56. Ngo, X.Q., Nguyen, V.S., Nguyen, D.T., Pham, V.L. & Ngo, T.L., 2013b. Biodiversity of littoral macroinvertebrates in the Mekong River. *HCMUE J. Sci*., 51, 16–28. https://doi.org/10.54607/hcmue.js.0.51.247(2013)
57. Norris, R.H., Thoms, M.C., 1999. What is river health? *Freshwater Biology* 41, 197–209. https://doi.org/10.1046/j.1365-2427.1999.00425.x
58. Nguyen, V.C.N., Nguyen, C.T., Le, N.Y., & Lavane, K., 2023. Using the distribution index of zoobenthos for assessing the level of pollution in E Canal, Vinh Thanh District, Can Tho City, Can Tho City. *Journal of Science, Can Tho University*, 59, 80–88, DOI:10.22144/ctu.jvn.2023.109 (In Vietnamese)

59. Nguyen, V. T., & Le, T. H., 2014. Impacts of canalization and water control structures on water quality in the Mekong Delta. *Journal of Science, Can Tho University*, 32, 45–54. (In Vietnamese)
60. Nguyen, N.H., Delgado, J.M., Vo, K.T., Le, M.H., Merz, B., Bardossy, A., & Apel H., 2011. Floodplain hydrology of the Mekong Delta, Vietnam. *Hydrol. Process*., John Wiley & Sons, Ltd. https://doi.org/10.1002/hyp.8183
61. Nguyen, M.N, Le, D.T., Pham, V.H., Vu, T.D.H., Ouillon, S., & Nguyen, C.T. 2025. Suspended sediment pattern along the Mekong Delta's west coast induced by strong southwest monsoon activities and extreme events. *Marine Geology*, 485, 107563. https://doi.org/10.1016/j.margeo.2025.107563
62. Nguyen, T.L.C., Dinh, T.T.H., Dang, T.C.T., Pham, A.D., Nguyen, T.T., Huynh, T.T.Q., & Tran, N.P., 2020. Diversity of zooplankton and benthic macroinvertebrates of estuarine coastal waters in Tien Giang province, southern Vietnam. *Vietnam Journal Science, Technology and Engineering*, 62 (4), 3. https://doi.org/10.31276/VJSTE.62(4).03-07
63. Norris, R.H., & Thoms, M.C., 1999. What is River Health. Freshwater Biology 41(2):197 – 209. https://doi.org/10.1046/j.1365-2427.1999.00425.x
64. Page, M. J., et al., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews *BMJ* 2021; 372 :n71. https://doi.org/10.1136/bmj.n71
65. Pawlowski, J. et al., 2018. The future of biotic indices in the ecogenomic era: Integrating (e)DNA metabarcoding in biological assessment of aquatic ecosystems. Science of The Total Environment, 637–638, 1295–1310. https://doi.org/10.1016/j.scitotenv.2018.05.002
66. Pham, A.D., 2014. *Study on the Water Quality Assessment using Benthic Macroinvertebrates for the Lower Dongnai River Biomonitoring, Vietnam*. PhD Dissertation, Institute for Environment and Resources, Vietnam National University in HCMC, Vietnam. (In Vietnamese)
67. Pham, A.D. et al., 2019. *Aquatic organism monitoring program for water bodies in Long An province, Vietnam*. PhD Dissertation, Long An Department of Environment and Resources (DONRE), Vietnam. (In Vietnamese)
68. Pham, A.D., Nguyen, T.D., Dao, T.S., Nguyen, V.T., Nguyen, X.D., Phan, D.D. & Pham, T.L., 2026a. Ecological health assessment of the Mekong River and its tributaries: Challenges and future perspective – A review. *Nature Environment and Pollution Technology*, 25(2), D1853. https://doi.org/10.46488/NEPT.2026.v25i02.D1853
69. Pham, A.D., Dang, M.T., Pham, T.L., Bui, T.H. and Dao, T.S., 2026b. Ecological health assessment of the Vam Co River System, Vietnam: Insights from benthic macroinvertebrates and environmental changes. *Nature Environment and Pollution Technology*, 25(2), D1853. https://doi.org/10.46488/NEPT.2026.v25i02.D1853
70. Poff, N.L., Olden, J.D., Vieira, N.K.M., Finn, D.S., Simmons, M.P., Kondratieff, B.C., 2006. Functional trait niches of North American lotic insects: trait-based ecological applications in light of phylogenetic relationships. *Journal of the North American Benthological Society* 25, 730–755. https://doi.org/10.1899/0887-3593(2006)025[0730:FTNONA]2.0.CO;2
71. Rosenberg, D.M., & Resh, V.H., 1993. *Freshwater Biomonitoring and Benthic Macroinvertebrates*. Chapman & Hall, New York.
72. Smith, V.H., et al. 1999. *Eutrophication of freshwater ecosystems*. Environmental Science & Pollution Research.
73. Sor, R., Boets, P., Chea, R., Goethals P., & Lek, S., 2017. Spatial organization of macroinvertebrate assemblages in the Lower Mekong Basin. *Limnologica*, 64, 20–30. https://doi.org/10.1016/j.limno.2017.04.001

74. Statzner, B., Bis, B., Dolédec, S., Usseglio-Polatera, P., 2001. Perspectives for biomonitoring at large spatial scales: a unified measure for the functional composition of invertebrate communities in European running waters. *Basic and Applied Ecology*, 2, 73–85. https://doi.org/10.1078/1439-1791-00039
75. Stoddard, J. L., Larsen, D. P., Hawkins, C. P., Johnson, R. K., & Norris, R. H., 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications*, 16(4), 1267–1276. https://doi.org/10.1890/1051-0761(2006)016[1267:SEFTEC]2.0.CO;2
76. Sweeney, B. W., Battle, J. M., Jackson, J. K., & Dapkey, T. (2011). Can DNA barcodes of stream macroinvertebrates improve descriptions of community structure and water quality? *Journal of the North American Benthological Society*, 30(1), 195-216.
77. Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. *Nature Geoscience*, 2, 681–686. https://doi.org/10.1038/ngeo629
78. Taberlet, P., et al. 2012. *Environmental DNA*. *Molecular Ecology*, 21(8), 1789–1793. https://doi.org/10.1111/j.1365-294X.2012.05542.x
79. Tran, N. T., Pham, H. Q., & Dang, T. M., 2016. Surface water pollution in agricultural canals of the Mekong Delta. *Vietnam Journal of Science and Technology*, 54(3), 356–365. (In Vietnamese)
80. Vo, Q.B., Pham, V.T., Nguyen, V.T., Hoang, M.H., Le, V.D., Downes, N.K., & Pham, V.D.T., 2024. Correction to: Understanding watershed sources of pollution in Vinh Long Province, Vietnamese Mekong Delta. Discover Applied Sciences, 6(407). https://doi.org/10.1007/s42452-024-06063-1
81. Vo, T. D., Nguyen, V. H., & Le, Q. T. 2019. Seasonal dynamics of benthic macroinvertebrates in Mekong Delta canals. *Can Tho University Journal of Science*, 55, 88–98. (In Vietnamese)
82. Wehrheim, C., Manfred, L., Harro, S., & Marc, W., 2023. Identifying key influences on surface water quality in freshwater areas of the Vietnamese Mekong Delta from 2018 to 2020. *Water,* 15(7), 1295. https://doi.org/10.3390/w15071295
83. Yu, G. et al., 2013. Ecosystem health assessment based on analysis of a land use database. *Applied Geography*, 44, 154–164. https://doi.org/10.1016/j.apgeog.2013.07.010