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Original Research

Ecological Health Assessment of the Vam Co River System, Vietnam: Insights from Benthic Macroinvertebrates and Environmental Changes

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ABSTRACT

This research examines the relationships between benthic macroinvertebrates and environmental variables in the Vam Co River system, located in Southern Vietnam. Field surveys conducted four times between May and November 2023 were designed to assess seasonal changes in macroinvertebrate diversity and water quality. The river system, characterized by low to moderate pollution levels, elevated nutrient concentrations, and substrates dominated by fine and coarse sands, plays a significant role in shaping the distribution and abundance of benthic macroinvertebrates. A total of 32 species were recorded, with bivalves and crustaceans being the most dominant groups during monitoring periods. Benthic macroinvertebrate densities fluctuated from 28 to 167 individuals/m^2, reflecting habitat suitability associated with substrate composition. Biodiversity, measured by the Shannon–Wiener index (H'), ranged from 1.51 to 2.94, while the Average Tolerance Score Per Individual (ATSPI) varied between 37 and 51, suggesting ecological health conditions ranging from moderate to good levels. Species richness showed positive correlations with pH, total suspended solids (TSS), and dissolved oxygen (DO), indicating these variables support diverse communities. In contrast, ATSPI scores reflecting pollution tolerance, were positively correlated with biochemical oxygen demand (BOD$_5$), total nitrogen (T_N) and total phosphorus (T_P), and negatively correlated with pH, TSS, and DO. These findings highlight the role of benthic macroinvertebrates as key indicators assessing the ecological health of river systems. They also emphasize the importance of implementing long-term, integrated monitoring and adaptive management strategies to ensure the sustainable protection of the Vam Co River system.

INTRODUCTION

Rivers and streams provide essential ecosystem services, including water supply for agriculture, industry, and residential needs, as well as habitat for aquatic and riparian species, nutrients for aquatic organisms and support for fisheries and recreational activities (Costanza et al., 2014). However, rapid urbanization, industrialization, and agricultural intensification have severely affected the structure and function of aquatic ecosystems, resulting in significant water quality degradation and loss of ecosystem integrity (Hakeem et al., 2020). As such, evaluating the health of river and stream ecosystems has garnered increasing global attention and has become a critical environmental management issue worldwide, particularly in regions such as the Americas (Bashir et al., 2020), Australia (Davies et al., 2010), China (Wu et al., 2010), Europe (Hering et al., 2010), Peru (Paredes-Agurto et al., 2024), and Thailand (Rattanachan et al., 2015). Although early studies focused primarily on environmental factors, recent research focuses on the integration of biomonitoring indicators with water quality parameters to more comprehensively assess the health status of rivers and streams (Wang, 2023).

Biomonitoring using bioindicator groups such as microorganisms, microalgae, aquatic macrophytes, zooplankton, macroinvertebrates, and fish have provided an integrated assessment of the ecological health of river systems, with each biological group offering distinct its own advantages (De Pauw et al., 1996; Hellawell 1986). Among these, macroinvertebrates are most widely used to evaluate environmental stresses such as organic pollution, metal contamination, nutrient enrichment, acidification, sedimentation, toxicants, and other general stressors (Hellawell, 1986). Indeed, the macroinvertebrate assemblages constituted the basis of most biomonitoring programs currently in Europe and North America. A variety of indicators and biological methods are being applied to assess the water quality of river ecosystems worldwide. Many countries (or states or water authorities) even have developed their own biotic indices based on macroinvertebrates, including single bioindicators or integrated biotic indices (Hellawell, 1986; Li & Zheng, 2010). Two key approaches included diversity indices (Shannon & Weaver, 1963), which described community structure through richness and evenness, and saprobic indices (Sládecek, 1973), which developed for assessing organic pollution based on species' oxygen tolerance. The US Environmental Protection Agency (EPA) has also used the Rapid Biological Assessment Protocol (RBP) to diagnose the health of aquatic ecosystems (Barbour et al., 1999). Subsequently, comprehensive tools such as the Index of Biological Integrity (IBI), Trophic State Index (TSI), Chemical Pollution Index (CPI), and Watershed Sustainability Index (WSI) have been developed to assess broader ecological conditions (Hara et al., 2019). Most assessment methodologies were originally developed in temperate and subtropical regions, creating uncertainties about their effectiveness in tropical ecosystems, which face distinct environmental challenges (Bonada et al., 2006).

In Vietnam, water quality assessment of river systems has progressed through the applications of biomonitoring methods based on macroinvertebrates. (Nguyen, 2001; Pham & Le, 2004; Hoang, 2009; Nguyen, 2013; Pham, 2014). These organisms serve as bioindicators due to their sensitivity to changes in environmental conditions, making them reliable measures of water quality and ecosystem health. The use of bioindicators for water quality assessment in regions such as the Hong River basin, Dong Nai River basin, and Mekong Delta illustrates ongoing national efforts toward improved water resource monitoring and management. Since the late 1980s and throughout the 1990s, benthic macroinvertebrates have been employed as bioindicators to assess the water quality of Vietnam's major river systems (Pham & Le, 2004; Pham, 2014). In 2002, Vietnam made a significant stride toward improving the management and protection of its aquatic ecosystems by issuing comprehensive guidelines for biological water quality assessment (TCVN 7220-2: 2002). It was not until the late 2010s that full surveys on benthic macroinvertebrates were conducted to assess the ecological health of the Vam Co Dong and Vam Co Tay rivers using integrated approaches that combined water quality and bioindicator factors (Pham et al., 2020). However, most previous studies assessing water quality using benthic macroinvertebrates have focused on single physical, chemical, or biological variables. Only a few studies have combined these variables or explored the correlations between them. This study aims to assess the relationships between benthic macroinvertebrate assemblages and key environmental variables in the Vam Co River system by analyzing species composition and abundance, assessing water quality indicators, and evaluating physical habitat conditions to better understand their influence on ecological health.

2. MATERIALS AND METHODS

2.1. Study Area

The Vam Co River system is located mostly in Tay Ninh Province, Southern Vietnam (Fig. 1), with coordinates ranging from 10°05′00″ to 10°25′00″N and from 105°50′00″ to 106°40′00″E. The system consists of two main tributaries: Vam Co Tay (235 km) and Vam Co Dong (196 km). These tributaries originate in Prey Veng Province (Cambodia), confluence at Ban Quy junction and flow through the eastern region of the Mekong Delta of Vietnam. From here the river flows about 50 Km into Nha Be River before entering the sea at Soai Rap River Mouth (Dao and Bui, 2016). The watershed is characterized by diverse land-use patterns, including wetlands, agricultural areas, industrial parks, and urban zones. In this study, eight sampling sites were selected to collect both abiotic and macroinvertebrate samples. These sites are located near human activities, such as agriculture, aquaculture, villages and industry, which are potential sources of anthropogenic pressure on water quality (Table 1).

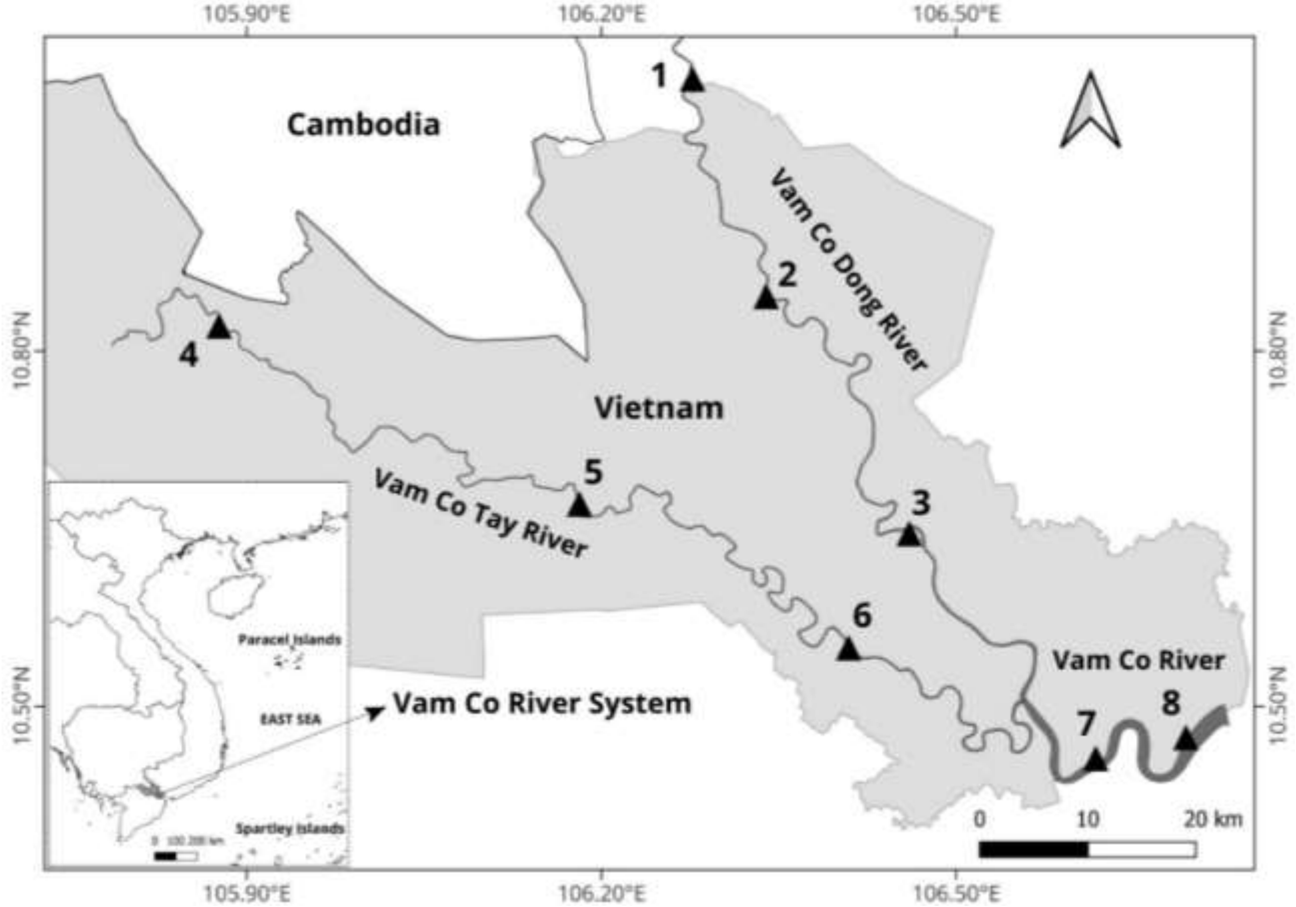

Fig. 1: Map of the study area showing the location of the sampling sites of Vam Co River system. Vam Co Dong River (numbers 1, 2, and 3); Vam Co Tay River (4, 5, and 6); Vam Co River (7 and 8)

Table 1: Coordinates and locations of the sampling sites

Sampling sites	Local names	Longitude (N)	Latitude (E)	Major human activities
1	Vam Co Dong River	11° 1'43.22"	106°16'40.03"	Agricultural area, village, raw water intake location
2	Vam Co Dong River	10°50'40.49"	106°20'25.35"	Agricultural area and village
3	Vam Co Dong River	10°38'41.31"	106°28'22.31"	Industrial parks and residential area
4	Vam Co Tay River	10°49'7.26"	105°52'36.60"	Agricultural area, village, raw water intake location
5	Vam Co Tay River	10°40'10.20"	106°10'55.28"	Agricultural area and village
6	Vam Co Tay River	10°32'52.69"	106°24'33.67"	Tan An City, field irrigation
7	Vam Co River	10°27'18.69"	106°37'52.63"	Agricultural area and village

8	Vam Co River mouth	10°28'19.77"	106°42'27.87"	Aquaculture and village

2.2. Environmental Variables

Samples were collected in March (middle of the dry season), May (transition from dry to rainy season), August (middle of the rainy season) and November (transition from rainy to dry season) in 2023. At each sampling event, water samples for environmental quality analysis were collected in accordance with the water monitoring guidelines (APHA, 2017). Surface water samples were taken from the middle of the river using 2-liter polyethylene bottles, and stored on ice at approximately 4°C until laboratory analysis.

On-site measurements of water environmental parameters, including pH and dissolved oxygen (DO, mg/L), were made using a Portable Multi-Meter (HACH HQ2200). Salinity (Sal, ‰) was also measured using the EXTECH RF20 Salinity Refractometer, equipped with automatic temperature compensation (ATC). The total suspended solids (TSS, mg/L), biochemical oxygen demand (BOD_5, mg/L), total nitrogen (T_N, mg/L), and total phosphorus (T_P, mg/L) were measured in the laboratory conditions. To determine TSS, a well-mixed sample was filtered through a pre-weighed standard glass fiber filter, and the residue retained on the filter was dried to constant weight at 103–105°C (APHA, 2017). BOD_5 was measured using the sample dilution method with the addition of a nitrification inhibitor (APHA, 2017). T_N was determined acidimetrically after reduction with Devarda's alloy (APHA, 2017). T_P is determined by digesting the sample to convert phosphorus compounds to orthophosphate, which is then quantified spectrophotometrically (APHA, 2017).

To assess the habitat conditions of benthic macroinvertebrates in the Vam Co River system, the following variables were recorded at each sampling site, within the main flow area: flow velocity (FV, m/s), water depth (WL, m), and bottom sediment composition (BS, %). Flow velocities were measured using a JDC Flowatch hydrometric propeller at three locations within each site: the right, left, and middle of the river. Water depth and bottom substrate were recorded simultaneously with benthic macroinvertebrate sampling. Depth was measured using a sounding rope weighted with 8 kg, lowered from a boat until it reached the riverbed (Dear & Kemp, 2007). Bottom sediments were classified into five mineral grain size categories based on their proportional composition: clay (≤ 0.002 mm), silt (0.002 – 0.063 mm), fine sand (0.063 – 0.63 mm), coarse sand (0.63 – 2.0 mm), and gravel (2.0 – 63 mm) (Folk and Ward, 1957; Blott and Pye, 2012).

2.3. Benthic Macroinvertebrates Sample Collection and Analysis

Standardized sampling and preservation procedures were followed to ensure reliable collection of benthic macroinvertebrate data, in accordance with the protocols outlined by the MRC (2010) and Pham (2014). These procedures were essential to maintaining data integrity and ensuring accurate analysis of benthic macroinvertebrate populations. At each sampling site, sediment samples were collected from five locations along both the right and left sides of the river, totaling ten locations per site. At each location, four sediment grabs were taken using a Petersen sampler, with each grab covering approximately 0.025 m^2. This resulted in a total of forty grabs per site, representing a combined sampling area of 1 m² at each site. The pooled samples were gently washed with water in situ using a sieve (0.3 mm mesh size), preserved with the formalin solution at a final concentration of 5% (MRC, 2010; Pham, 2014). The benthic macroinvertebrate identification was implemented using a compound microscope (Olympus CX41) at 40–100× magnification based on morphological characteristics according to the taxonomic books (Brandt, 1974; Dang et al., 1980; McCafferty, 1983; Grintsov & Sezgin, 2011). The abundance of benthic macroinvertebrates was expressed as individuals per square meter (individuals/m²).

2.4. Data Analysis

Benthic macroinvertebrate data were presented as minimum (Min), maximum (Max), mean, and standard deviation (SD) values for each sampling site. One-way analysis of variance (ANOVA) was conducted to test for significant differences in species density, species richness, and biotic indices among sites. Prior to ANOVA, assumptions of normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests. All faunal population data were recorded in Microsoft Excel and analyzed using R statistical software. Pearson correlation analysis was applied to test the relationships between benthic macroinvertebrate metrics (species richness, abundance, Shannon–Wiener diversity index, and Average Tolerance Score Per Individual [ATSPI]) and environmental variables. The Shannon-Wiener Diversity Index (H') was calculated based on macroinvertebrate community data to assess biodiversity levels, which can reflect habitat conditions and potential water quality status (Stiling, 2002). The ATSPI, developed by the Mekong River Commission (MRC, 2010) and refined by Pham (2014), was used to evaluate ecological health by quantifying the average pollution tolerance of individuals in the community. This index is calculated as the abundance-weighted average of species-specific tolerance scores. Water quality and ecological condition classifications were based on threshold values for H′ and ATSPI as defined in Pham (2014) (see Table 2). To further explore the relationships between environmental factors and macroinvertebrate assemblages, Canonical Correspondence Analysis (CCA) was employed. This multivariate technique was used to identify how physicochemical variables influenced community structure, dominant species distribution, and bio-index patterns across sampling sites. All multivariate statistical analyses were conducted using CANOCO software, version 4.56 (ter Braak & Šmilauer, 2009).

H' was calculated using the following formula (Shannon & Weaver, 1949):

$$H' = -\sum_{i=1}^{s}(p_i log_2 p_i) \qquad (1)$$

where p_i is the ratio of the number of species i over the total number of all benthic macroinvertebrates.

ATPSI was calculated using the following formula (MRC, 2010):

$$ATSPI = \frac{\Sigma(n_i \times t_i)}{\Sigma n_i} \qquad (2)$$

where n_i: number of individuals of species i; t_i: tolerance score of species i; $\Sigma(n_i \times t_i)$: sum of the product of the number of individuals and their respective tolerance scores; Σn_i: total number of individuals across all species.

Table 2: Classification of water quality and ecological conditions based on ATSPI and H' values (Pham, 2014)

ATSPI	H'	Ecological health ranking
≤ 35	> 3.25	Very good
36 – 45	2.21 – 3.25	Good
46 – 50	1.41 – 2.20	Moderate
51 – 55	0.50 – 1.40	Moderate to Poor
> 55	< 0.50	Poor
Complete loss of benthic macroinvertebrates		Very poor

3. RESULTS AND DISCUSSIONS

3.1. Environmental Variables

The Vam Co River system exhibited significant spatial variation in its physicochemical parameters, transitioning from inland areas to the river mouth. pH values ranged from 4.72 to 7.05, decreasing in regions influenced by acid sulfate soils and increasing toward the river mouth. While salinity (0.1 – 16.3‰) followed a typical estuarine gradient, rising downstream due to tidal influence (Table 3). In both the Vam Co Dong and Vam Co Tay Rivers, pH values tended to decrease as the rivers flowed through areas with acid sulfate soils, where sulfide oxidation produces sulfuric acid (Tran et al., 2017), and increased as they approached the estuary. Similarly, salinity increased from upstream locations toward the river mouth. In general, pH values in the Vam Co River were lower than those in the Dong Nai and Sai Gon Rivers (pH: 6.5 – 8.5), likely due to its flow through areas with acid sulfate soils (Pham, 2014; Vu, 2019). TSS concentrations were relatively stable among the sampling sites, ranging from 18 to 84 mg/L in the Vam Co Dong River, 20 to 84 mg/L in the Vam Co Tay River, and 38 to 82 mg/L in the Vam Co River (Table 3).

DO and BOD_5 concentrations in the Vam Co Dong River ranged from 2.7 to 4.9 mg/L and 7.4 to 16.1 mg/L, respectively (Table 3). In the Vam Co Tay River, DO concentrations fluctuated between 3.5 and 5.1 mg/L, while BOD_5 ranged from 7.1 to 12.8 mg/L. In the Vam Co River, DO concentrations varied between 3.8 and 5.3 mg/L, and BOD_5 ranged from 7.3 to 9.4 mg/L. DO concentrations were lowest in the Vam Co Dong River, while BOD_5 levels were highest there, indicating poorer water quality relative to the Vam Co Tay River and the Vam Co confluence. The T_N and T_P concentrations in the Vam Co Dong River ranged from 1.38 to 2.84 mg/L and 0.190 to 0.340 mg/L, respectively (Table 3). In the Vam Co Tay River, T_N ranged from 1.38 to 2.07

mg/L, and T_P ranged from 0.190 to 0.290 mg/L. In Vam Co River, T_N values ranged from 1.29 to 1.69 mg/L and T_P from 0.150 to 0.220 mg/L. DO levels generally increased downstream, while BOD_5, T_N, and T_P tended to decrease due to dilution and sedimentation within the Vam Co River system. The physiochemical parameters also indicated that water quality generally improved during the rainy season (DO: 2.9 – 5.3 mg/L; BOD_5: 7.1 – 14.2 mg/L; T_N: 1.29 – 2.69 mg/L) compared to the dry season (DO: 2.7 – 4.3 mg/L; BOD_5: 7.1 – 16.1 mg/L; T_N: 1.39 – 2.84 mg/L), although this trend was not clearly demonstrated. Downstream improvements in DO and reductions in BOD_5, T_N, and T_P suggest dilution and sedimentation processes play a role in mitigating pollution. This suggests the influence of dilution, sedimentation, re-aeration, and possibly nutrient assimilation by aquatic vegetation. Although seasonal differences were observed such as slightly higher DO and lower BOD_5 and nutrient concentrations during the rainy season, these trends were not consistent across all parameters or sites.

Table 3: Water quality parameters from Vam Co River System the study period. Data were presented as minimum to maximum and mean values (in parentheses)

Sampling sites	pH	Sal (‰)	TSS (mg/L)	DO (mg/L)	BOD_5 (mg/L)	T_N (mg/L)	T_P (mg/L)
1	6.14 – 6.58	0.1	27 – 84	3.8 – 4.9	7.4 – 8.4	1.38 – 1.52	0.220 – 0.270
	(6.32)	(0.1)	(53)	(4.2)	(8.1)	(1.45)	(0.240)
2	4.72 – 6.15	0.6 – 0.7	18 – 71	3.2 – 4.2	8.1 – 9.4	1.43 – 1.63	0.190 – 0.260
	(5.27)	(0.7)	(40)	(3.4)	(8.8)	(1.53)	(0.235)
3	5.61 – 6.27	0.4 – 3.1	25 – 80	2.7 – 3.8	11.8 – 16.1	1.92 – 2.84	0.310 – 0.340
	(5.88)	(1.9)	(48)	(3.1)	(14.5)	(2.55)	(0.320)
4	6.23 – 6.59	0.1	26 – 83	4.1 – 5.1	7.1 – 7.5	1.38 – 1.44	0.190 – 0.260
	(6.38)	(0.1)	(52)	(4.4)	(7.3)	(1.40)	(0.220)
5	5.08 – 6.24	0.2 – 0.6	20 – 75	3.5 – 4.8	7.6 – 8.3	1.46 – 1.58	0.220 – 0.260
	(5.52)	(0.5)	(43)	(3.9)	(8.1)	(1.51)	(0.240)
6	5.74 – 6.38	0.4 – 2.9	29 – 84	3.3 – 4.3	9.2 – 12.8	1.73 – 2.07	0.260 – 0.290
	(6.00)	(1.8)	(51)	(3.8)	(11.5)	(1.91)	(0.268)
7	6.38 – 6.81	0.7 – 11.1	38 – 82	3.8 – 4.8	8.5 – 9.4	1.44 – 1.69	0.160 – 0.220
	(6.62)	(6.2)	(55)	(4.2)	(9.1)	(1.53)	(0.183)
8	6.58 – 7.05	2.2 – 5.8	49 – 74	4.2 – 5.3	7.3 – 8.5	1.29 – 1.42	0.150 – 0.210
	(6.81)	(10.1)	(58)	(4.6)	(7.9)	(1.37)	(0.185)

The flow velocity and water depth in the Vam Co River system ranged from 0.34 to 1.37 m/s and 3.0 to 9.0 m, respectively. River bottom sediments were classified into five particle size categories: coarse sand (24 – 39%) and fine sand (37 – 53%) were dominant in the Vam Co Dong River and Vam Co Tay River, while fine sand (41 – 56%) and silt (21 – 29%) dominated in the Vam Co River. Flow velocity and water depth measurements were crucial for understanding the hydrodynamic conditions of the river system. These factors influence the dispersion and dilution of pollutants in the river, and contribute to the adaptation of the habitat to aquatic species by affecting oxygen levels, sediment dynamics, and overall habitat stability. Higher flow velocities promote oxygenation through increased turbulence and aeration, supporting larger aquatic populations. Consistent with general hydrological models (Allan & Castillo, 2007), water flows in the Vam Co River system are generally higher in the wet season than in the dry season.

3.2. Assemblages of Benthic Macroinvertebrates

During the four monitoring times, a total of 32 species from 6 major taxonomic groups were identified in the studied area. Among these groups, bivalves and crustaceans were dominant, comprising a total of 17 species, which accounts for approximately 53.1% of the total species identified (Fig. 2). There were 5 species of polychaetas (accounting for 15.6% of the total), 5 species of gastropods (15.6%), 3 species of oligochaetes (9.4%), and 2 species of insects (6.3%) among the benthic macroinvertebrates identified. The Vam Co River flows through a flat terrain and is therefore strongly affected by tidal dynamics and saltwater intrusion, which is reflected in the low number of insect species observed in the system. Seasonal patterns were evident, with higher numbers of benthic macroinvertebrate species in the wet season and lower numbers in the dry season, possibly due to improved habitat connectivity and water quality during the wet season. The number of species ranged from 16 in May (transitional period) to 23 in November, reflecting seasonal variations in ecological conditions.

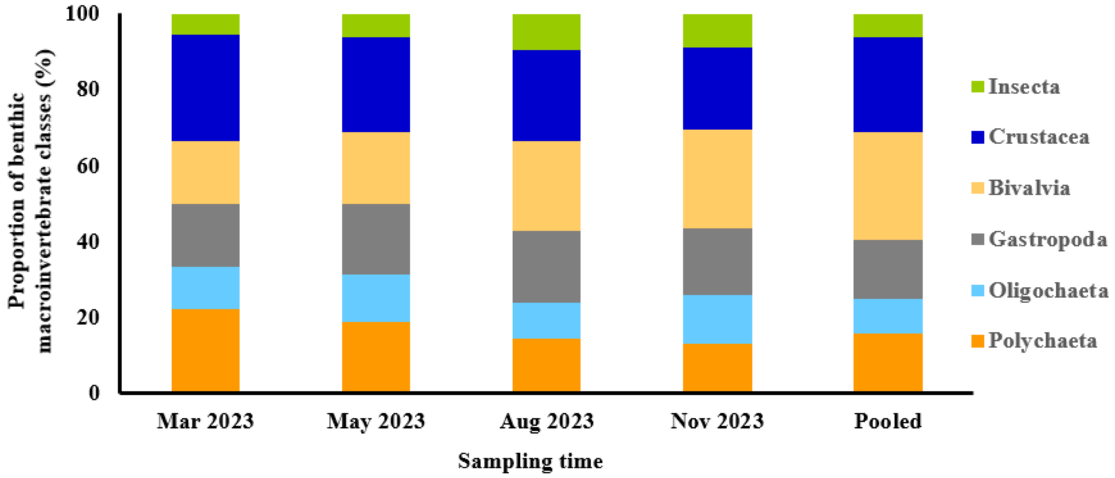

Fig. 2: The proportion of benthic macroinvertebrate classes at Vam Co River system during the study period. Pooled, pooled data of all four monitoring times

Species number of benthic macroinvertebrate in the Vam Co River system ranged from 6 to 13 species/m², with the lowest richness at Site 2 and the highest at Site 4 (Fig. 3a). Although overall species numbers varied only slightly among sampling sites, the composition of benthic macroinvertebrate communities differed substantially, especially between freshwater and estuarine zones. This difference may be due to variety in salinity, substrate type, and nutrient availability, which influence the presence or absence of certain species adapted to particular environmental conditions. The Vam Co Dong River and Vam Co Tay River were primarily inhabited by freshwater taxa, reflecting the dominance of inland freshwater inputs despite tidal influence which is consistent with the low salinity levels (0.1 – 2.0‰) observed in these river stretches. Common species included *Limnodrilus hoffmeisteri, Branchiura sowerbyi* (Oligochaeta); *Sermyla tornatella, Melanoides tuberculatus* (Gastropoda*); Corbicula, Ensidens ingallsianus* (Bivalvia); and, *Ablabesmyia, Chironomus* (Insecta). In contrast, estuarine and coastal species were more prevalent at the confluence sites (Sites 7 and 8), indicating increasing salinity and a shift from freshwater to brackish macroinvertebrate communities. This distribution pattern emphasizes the influence of salinity, hydrological connectivity, and environmental heterogeneity on benthic macroinvertebrate community structure.

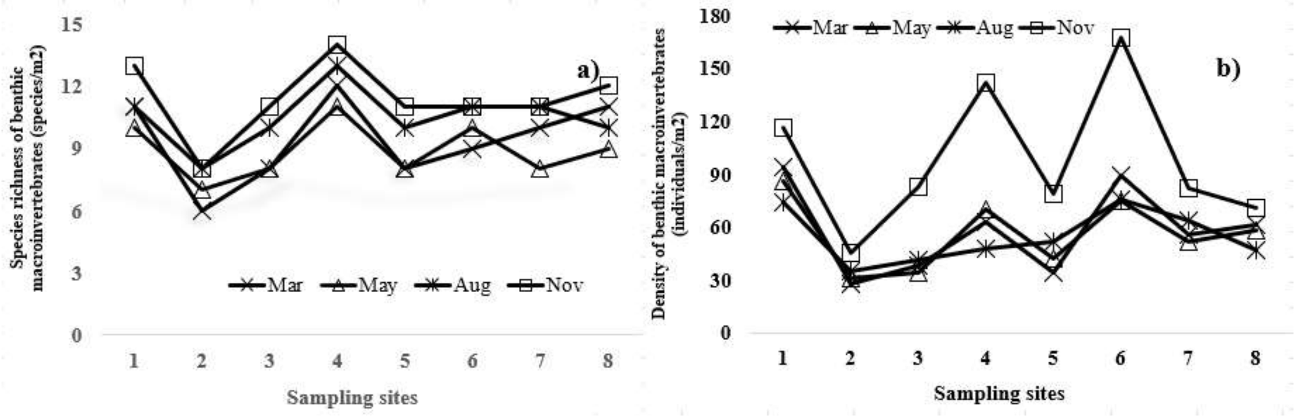

Fig. 3: Species richness (a) and density (b) of benthic macroinvertebrates in Vam Co River system during the study period

Benthic macroinvertebrate density fluctuated from 28 to 167 individuals/m², with the lowest density at Site 2 and the highest at Site 6 (Fig. 3b). The lowest macroinvertebrate density at Site 2 may be attributed to acidic conditions and/or habitat degradation, whereas the highest density observed at Site 6 was likely associated with elevated nutrient availability, which can enhance the abundance of individual organisms. In the Vam Co Dong River and the Vam Co Tay River, communities were dominated by freshwater taxa such as *Limnodrilus hoffmeisteri*, *Melanoides tuberculatus, Corbicula leviuscula, Ablabesmyia* sp. (Fig. 4a & Fig. 4b). In contrast, estuarine species including *Nephtys polybranchia* and *Grandidierella lignorum*, dominated the confluence sites (Fig. 4c), reflecting the influence of increasing salinity and estuarine mixing at downstream sites.

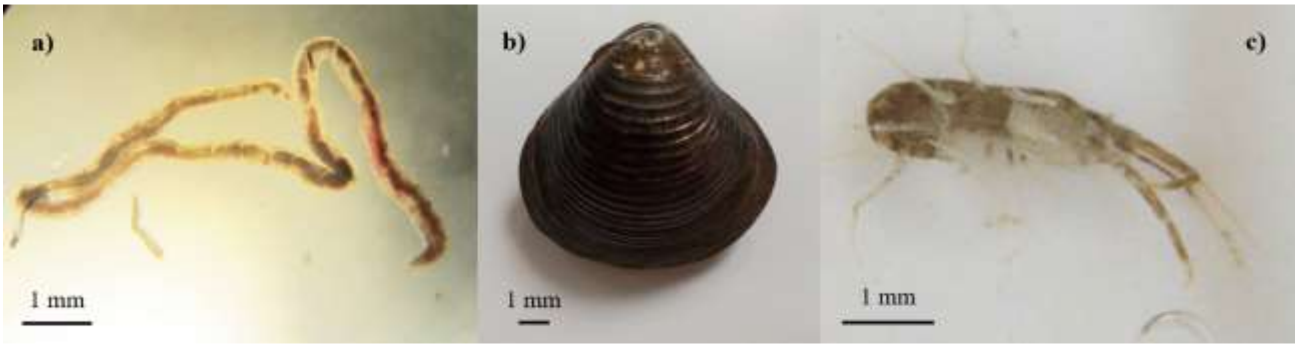

Fig. 4: Some dominant species of benthic macroinvertebrates in Vam Co River system during the study period: *Limnodrilus hoffmeisteri* (a), *Corbicula leviuscula* (b), and *Grandidierella lignorum* (c)

The ecological characteristics of the Vam Co Dong River and Vam Co Tay River were strongly influenced by acid sulfate soils (Vo et al., 2024) and tidal influences from the East Sea. These conditions created an environment characterized by low pH and periodic salinity variation, supporting macroinvertebrate species adapted to such conditions (Sites 1, 2, 4, and 5), such as *Filopaludina sumatrensis, Melanoides tuberculatus, Sermyla tornatella, Chirrama* sp., and *Polypedium* sp.. The presence of estuarine or marine benthic macroinvertebrates like *Namalycastis abiuma, Nephtys polybranchia* (Polychaeta); *Melita* sp. (Crustacea) further underscored the dynamic nature of these inland waters (eg. Sites 3 and 6), where ecological habitats are influenced by both freshwater and marine influences (Putro et al., 2025).

Compared to the Red River (Duong et al., 2014), the Vam Co exhibited lower TSS levels, reflecting differences in sediment input possibly driven by variations in catchment geology and land use. The DO concentrations were also lower than those reported for the Lower Dong Nai River (3.4 – 6.2 mg/L, Le T.P., 2015) and the tidal-influenced parts of the Mekong River (3.9 – 7.6 mg/L; MRC, 2008) reflecting that Site 2 (Vam Co Dong River – Acid sulfate soil site), Site 3 (Vam Co Dong River – Industrial concentration site) and Site 6 (Vam Co Tay – Tan An City) could experience periodic hypoxic conditions, affecting sensitive species (Ephemeroptera, Plecoptera, Odonata). Moderate increases in BOD_5 levels are associated with a reduction in sensitive species but support a community of tolerant species involved in the decomposition of organic matter.

The dominance of organic pollution-tolerant macroinvertebrates such as *Nephtys polybranchia, Bispira polymorpha,* and *Chironomus* spp. indicated declining ecological conditions. Thus, the presence of rich-organic tolerant macroinvertebrate indicated the worsening ecological health. Additionally, the elevated concentrations of T_N and T_P in the Vam Co River system indicated a nutrient-rich, eutrophic environment (Reynolds, 2007), exceeding the typical global range for riverine systems (4 – 800 µg/L; Lukhabi et al., 2024). These eutrophic conditions favor the growth of benthic macroinvertebrates that are tolerant of high nutrient levels and moderate organic pollution, as described by Horne and Goldman (1994).

According to Le et al. (2012), macroinvertebrate abundance may be higher in upland streams due to lower pollution levels and more stable substrates. However, in the Vam Co River, site-specific factors such as substrate and water quality likely had a stronger influence. Benthic macroinvertebrate species exhibited specific preferences for different substrate types for specific substrate types, ranging from mud and sand to gravel and rocks (Dudgeon, 1999; Allan & Castillo, 2007). The study by Kostanda et al . (2025) demonstrated that various substrate types, such as loamy sand, clay, and coarse sand, created distinct habitats that could affect benthic macroinvertebrate communities in different ways. Muddy or sandy sediments were preferred habitats for benthic macroinvertebrates that are obligate benthic dwellers, such as certain polychaetes, mollusks, and crustaceans (Gao et al., 2006). The trend of increased silt particles downstream is thought to be due to erosion and sediment transport processes, in which coarser particles such as sand settle out earlier and finer silt particles are carried downstream, resulting in greater silt accumulation downstream. This natural sorting affects water clarity, substrate composition, and habitat structure.

The benthic maceoinvertebrate communities of the Vam Co River system have significant taxonomic similarities with those of other major rivers in Vietnam, including the Lower Dong Nai River and Lower Mekong River and their associated tributaries (MRC, 2008; Le et al., 2012; Pham, 2014; Ngo X.Q. & Ngo T.L., 2014; Pham & Dang, 2016). These ecosystems shared similar macroinvertebrate groups, including oligochaetes, gastropods, bivalves, crustaceans, insects, and estuarine polychaetes in tidal zones. Bivalves and crustaceans contributed highest number of species in the Vam Co River system. Most benthic macroinvertebrates in the Vam Co Dong River and Vam Co Tay River were freshwater species, with higher densities observed under nutrient-enriched conditions. Estuarine or brackish-water species were primarily observed from the Vam Co River confluence downstream toward the coastal zone, reflecting increasing salinity. However, the Vam Co River system displayed lower overall species richness and macroinvertebrate density compared to the Dong Nai River and Mekong River. The lower species and invertebrate densities in the Vam Co River system may be due to acidic conditions from acid sulfate soils and unfavorable substrates such as coarse sand and low organic content that limit habitat suitability.

3.3. Biological Indices

The mean H’ values for benthic macroinvertebrates in the Vam Co River system ranged between 1.65 and 2.80, while the mean ATSPI values fluctuated from 38 to 50 during the four monitoring times in 2023 (Table 4). Spatially, Sites 1, 4, 7, and 8 exhibited good ecological conditions, likely supported by more favorable hydrological regimes, less anthropogenic stress, or likely supported by tidal mixing, which dilutes pollutants and stabilizes physicochemical conditions. In contrast, Sites 2, 3, 5, and 6 showed moderate ecological health, likely influenced by localized stressors—acid sulfate water intrusion at Site 2 (Vam Co Dong River), industrial activity at Site 3, urban runoff at Site 5, and possibly combined impacts at Site 6 (Tan An City).

Table 4: Biodiversity index values (H’) and average tolerance score per individuals (ATSPI) of benthic macroinvertebrates from Vam Co River system during the study period

Sampling sites	H’		ATSPI		Ecological health ranking
	Range	Mean	Range	Mean	
1	2.37 – 2.84	2.61	39 – 41	41	Good
2	1.51 – 1.83	1.65	49 – 51	50	Moderate
3	1.72 – 2.37	1.97	42 – 49	47	Moderate
4	2.68 – 2.94	2.80	37 – 39	38	Good
5	1.72 – 2.08	1.87	47 – 49	48	Moderate
6	1.84 – 2.51	2.15	41 – 48	45	Good
7	1.93 – 2.65	2.28	40 – 49	45	Good
8	2.04 – 2.71	2.35	40 – 47	43	Good

Temporally, both H’ and ATSPI values tended to be higher during the rainy season (August, November) and lower during the dry season (March, May). This seasonal trend is likely due to increased discharge and the dilution of pollutants, as well as expanded habitat availability. However, excessive flows can also mobilize sediments and cause physical disturbance, potentially affecting macroinvertebrate communities. In contrast, dry season conditions may especially in sites affected by acid sulfate soils (e.g., Site 2), where low water levels and reduced buffering capacity can lead to localized acidification. The observed seasonal and spatial variability in ecological health is consistent with other tropical river systems, where pressures such as urban development (e.g., Site 3) and agricultural runoff (e.g., Site 5) have been shown to degrade water quality and biodiversity (Wang et al., 2012; Copatti et al., 2013; Mmako et al., 2021). Integrating H′ and ATSPI metrics provides insights into how environmental pressures and hydrological dynamics interact to shape river health, highlighting the complex interplay between seasonal variability, spatial gradients, and ecological indicators.

3.4. Relationships of Benthic Macroinvertebrates to Environmental Variables

Statistical analysis showed that species richness of benthic macroinvertebrates in the Vam Co River system was moderate positive correlated with pH ($r = 0.62$), TSS ($r = 0.50$) and DO ($r = 0.57$), indicating that more neutral pH, higher oxygen levels and moderate suspended solids are beneficial for biodiversity (Fig. 5). Similarly, the biodiversity of benthic macroinvertebrates (H’) demonstrated moderate positive correlations with pH ($r = 0.66$), DO ($r = 0.56$), TSS ($r = 0.43$), but moderate negative correlations with biochemical oxygen demand (BOD_5; $r = –0.37$) and total nitrogen (T_N; $r = –0.36$). A weak negative correlation was also observed with total phosphorus (T_P; $r = –0.26$). Additionally, the ATSPI values moderate correlated with BOD_5 ($r = 0.34$) and T_N ($r = 0.31$), and negative correlated with pH ($r = -0.58$), TSS ($r = -0.33$), DO ($r = -0.47$). Interestingly, macroinvertebrate densities exhibited moderate correlations with water quality variables, suggesting that other factors such as habitat structure or substrate type may play a more dominant role (Fig. 5).

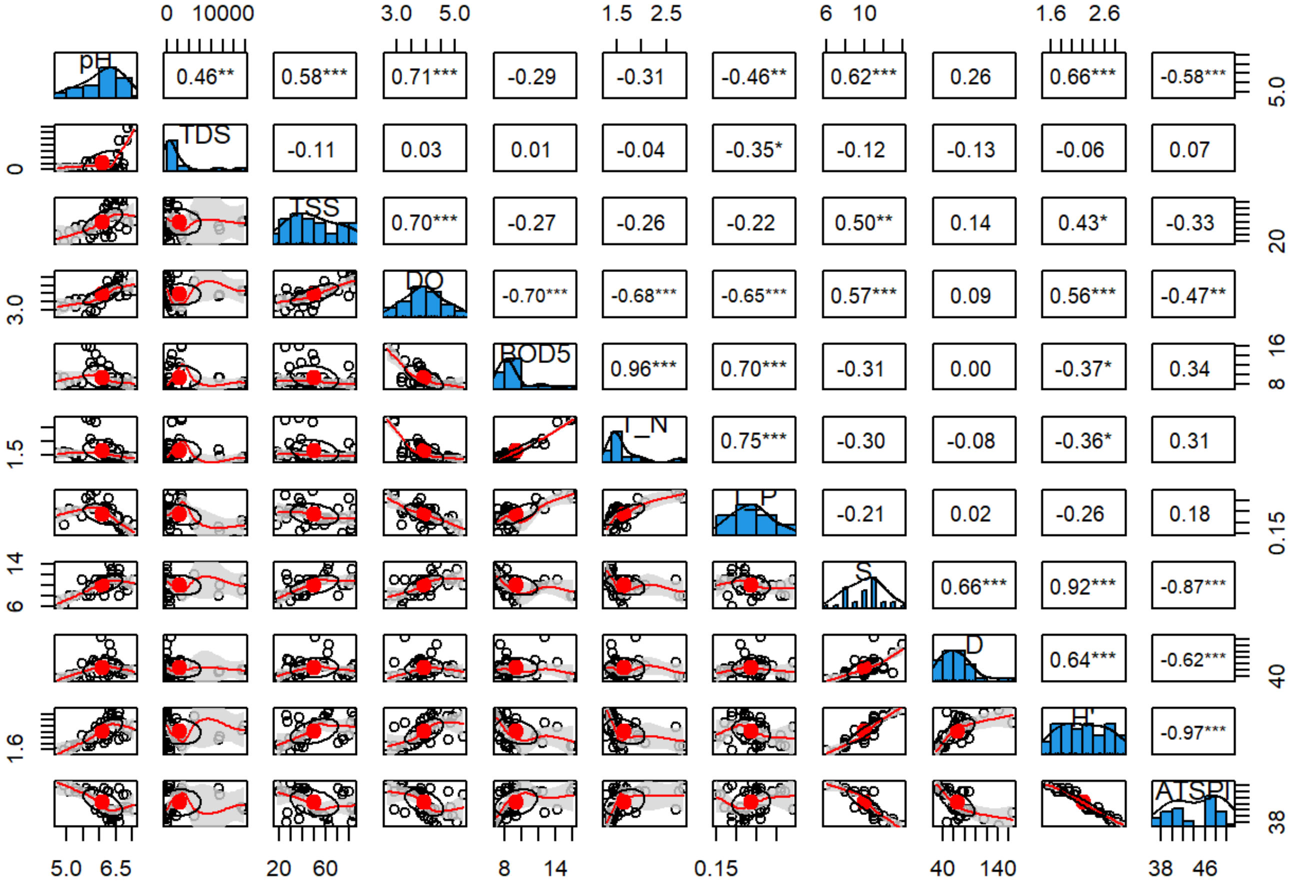

Fig. 5: Correlation between benthic macroinvertebrates and water quality parameters in Vam Co River system based on Pearson correlation test; r, correlation coefficient during the study period ("*": significant levels, the higher the number of "*", the higher the correlation level).

Statistical analysis further showed that species richness of benthic invertebrates exhibited a positive correlation with flow velocity (FV) (r = 0.25) and water depth (WL) (r = 0.20), and negative correlations with silt (BS_Silt) (r = -0.20) and clay (BS_Clay) content (r = -0.25) (Fig. 6). Both abundance and H′ values showed negative correlations with silt content (r = -0.21 and r = -0.35, respectively), suggesting that areas dominated by fine, unstable substrates may support less diverse and less abundant communities due to reduced habitat heterogeneity and oxygenation. In contrast, ATSPI values were positively correlated with BS_Silt (r = 0.20) and BS_Clay (r = 0.33), indicating a greater prevalence of pollution-tolerant species in depositional environments that are typically characterized by low flow and rich in organic matter.

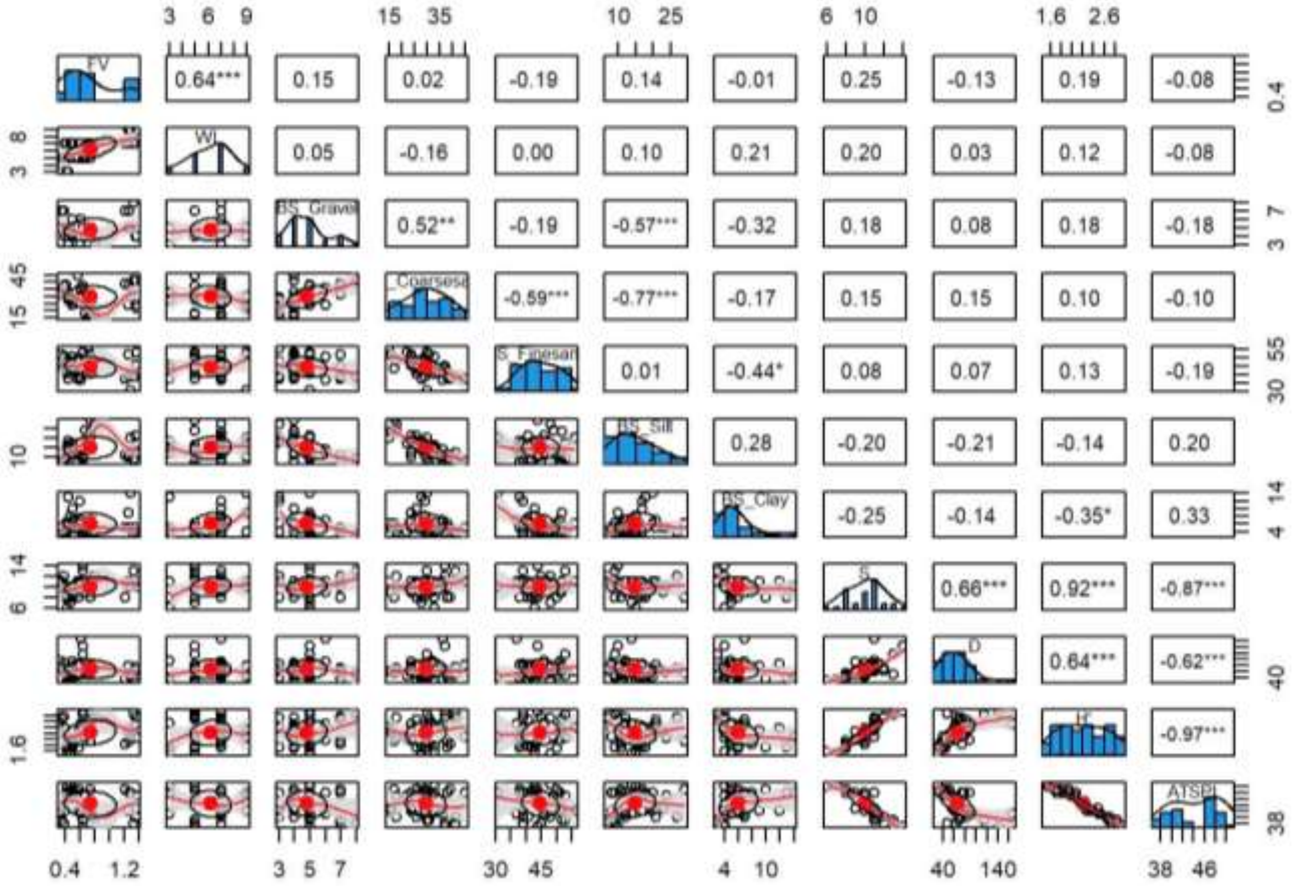

Fig. 6: Correlation between benthic macroinvertebrates and physical habitat variables in Vam Co River system based on Pearson correlation test; r, correlation coefficient during the study period ("*": significant levels, the higher the number of "*", the higher the correlation level).

3.5. Insights from Canonical Correspondence Analysis (CCA)

CCA effectively illustrates the effects of environmental variables on benthic macroinvertebrate diversity and indicator species, showing two main ecological variables (Fig. 7). The first gradient was associated with degraded environmental conditions, including low FV and WL, fine sediment particles (silt and clay), and elevated concentrations of BOD_5, T_N, and T_P. These conditions are indicative of eutrophication, organic enrichment, and reduced habitat heterogeneity, which tend to support pollution-tolerant taxa adapted to low-oxygen environments. Representative organisms included tolerant oligochaetes and chironomids (Fig. 7a). In contrast, the second gradient reflected more favorable physicochemical conditions, such as higher FV and WL, coarser sediment types (e.g., sand or gravel), and increased values of pH, Sal, and DO. These features are characteristic of dynamic, oxygenated habitats with more complex structures, supporting more sensitive and ecologically specialized species (Fig. 7b).

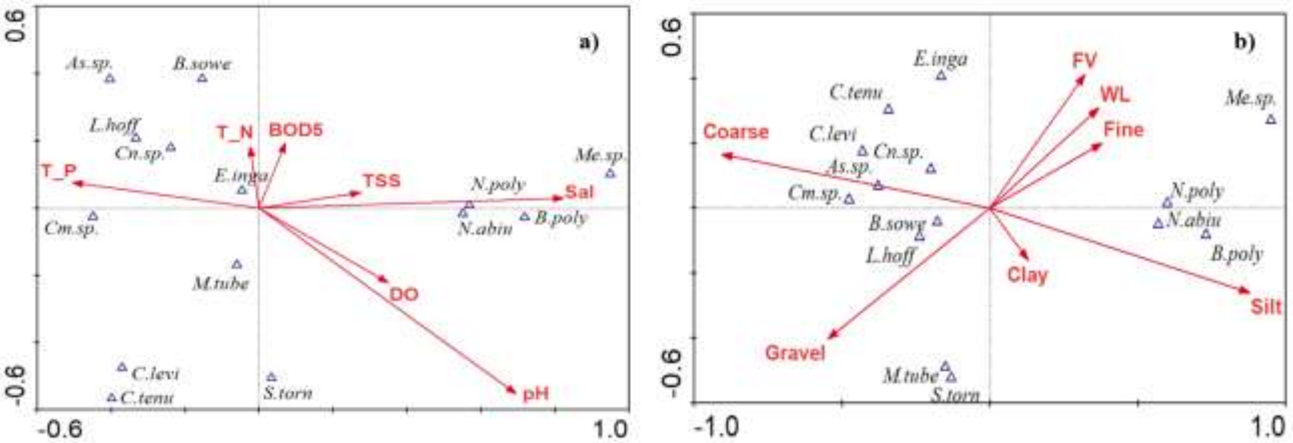

Fig. 7: Canonical correspondence analysis plot relating the dominant species of benthic macroinvertebrates to water quality parameters (a) and physical habitat variables (b) in the sampling sites of Vam Co River system. *Ablasbesmyia* sp.: Ab.sp., *Bispira polymorpha*: B.poly, *Branchiura sowerbyi*: B.sowe, *Chimarra* sp.: Cm.sp., *Chironomus* sp., Ch.sp., *Corbicula leviuscula*: C.levi, *Corbicula tenuis*: C.tenu, *Ensidens ingallsianus*: E.inga, *Limnodrilus hoffmeisteri*: L.hoff, *Melanoides tuberculatus*: M.tube, *Melita* sp.: Me.sp., *Namalycastis abiuma*: N.abiu, *Nephtys polybranchia*: N.poly, *Sermyla tornatella*: S.torn

The positive correlation between species richness and biodiversity of benthic invertebrates with moderate pH, DO, and TSS levels suggests that these parameters promote more favorable ecological conditions. This aligns with findings by Yazdian et al. (2014), who reported that suitable ranges of pH and DO enhance macroinvertebrate diversity and abundance. While moderate TSS may reflect organic content or stable substrates favorable to some taxa, excessive TSS is generally detrimental. In contrast, the negative correlations of biodiversity with BOD_5, T_N, and T_P support the understanding that organic and nutrient pollution reduce community diversity, as noted by Karrouch et al. (2017). The unexpected low correlations between the abundance of benthic macroinvertebrates and water quality parameters could considered several possibilities: benthic macroinvertebrate abundance may respond to seasonal or short-term fluctuations in water quality parameters; substrate type or flow dynamics, could play a significant role in macroinvertebrate abundance beyond the broad-scale water quality parameters measured. Moreover, these findings regarding the biodiversity indices (H' and ATSPI) and their relationship with water quality in the Vam Co River system reflected important patterns that influenced by seasonal variations and geographical factors. Besides, ATSPI positively correlated with physical habitat substrate (BS) that indicated the type of present substrate significantly influences the certain characteristics of benthic macroinvertebrate communities. Further studies should focus on sediment composition and hydrodynamic variability to better understand the effects of habitat on macroinvertebrate populations. Such insights will inform the conservation and management of tropical river systems under increasing human pressure.

Statistical analyses revealed significant spatial variability in flow velocity across the Vam Co River system ($p < 0.05$), highlighting the dynamic hydrological regime of this tropical river. Flow variability is known to influence sediment transport, nutrient availability, and habitat conditions, which in turn influence macroinvertebrate populations (Allan & Castillo, 2007), and such dynamics may also operate in the Vam Co River system. Generally, higher flows enhance oxygenation and are associated with coarser substrates that support more sensitive taxa, whereas lower flows often result in sediment deposition and organic matter accumulation, favoring tolerant species. However, responses may vary depending on the species' ecological traits and microhabitat structure. Additionally, the substrate composition differed markedly between upper and lower reaches, with coarser materials in upstream areas and finer sediments at downstream. These gradients create distinct ecological niches, as macroinvertebrate communities exhibit substrate-specific preferences, for instance, oligochaetes and chironomids often dominate in muddy or fine-sand environments, while taxa like mayflies or certain bivalves prefer gravel or coarse sand substrates (Rosenberg & Resh, 1993; Gao et al., 2006).

River biodiversity was indeeded closely linked to habitat quality, as seen in our study of the Vam Co river system. The CCA indicated that species composition was shaped by both water quality parameters (pH, DO, BOD_5, T_N, T_P) and physical factors like flow velocity and substrate type. These environmental gradients influence habitat suitability, affecting both the abundance and diversity of macroinvertebrates. Supporting studies, such as Bertaso et al. (2015), confirm that fluctuations in water quality and sedimentation can alter aquatic communities, particularly under nutrient and organic pollution. Among the influencing variables, water quality parameters appeared to have the strongest effect, followed by habitat quality indicators such as substrate type and flow velocity. Wilkins et al. (2015) also found that benthic macroinvertebrate diversity responded positively to improved environmental conditions.

5. CONCLUSIONS

This study provided a comprehensive assessment of the ecological health of the Vam Co River system through the integration of benthic macroinvertebrate populations, physicochemical water quality, and habitat characteristics. The river system was characterized by low to moderate pollution levels, elevated nutrient concentrations, with bottom substrates primarily composed of silt, as well as fine and coarse sands. These factors collectively influenced the distribution and structure of benthic macroinvertebrate communities.

A total of 32 species were recorded, with bivalves and crustaceans as the dominant taxa, indicating moderate biodiversity. This is comparable to levels observed in other lowland tropical rivers in southern Vietnam, such as the Lower Dong Nai and Mekong River systems. The H' and ATSPI values indicated water quality ranging from good at upstream and estuarine sites to moderate in midstream sections, where acid sulfate soils, industrial activities, and nutrient enrichment were more pronounced. The correlation and CCA analyses confirmed moderate relationships between macroinvertebrate communities and environmental variables, particularly pH, DO, BOD_5, T_N, substrate composition, and to a lesser extent, TSS and flow dynamics. These findings highlight the sensitivity of benthic macroinvertebrates to both natural and anthropogenic levels, reinforcing their usefulness as bioindicators of ecological health in tropical river systems.

To protect the ecological integrity of the Vam Co River system, priority should be given to reducing nitrogen and phosphorus inputs, which are responsible for eutrophication and biodiversity loss. Addressing acidification from acid sulfate soils and preserving habitat heterogeneity, especially substrate variability and flow, is also essential. Long-term biomonitoring using benthic macroinvertebrates, as reliable bioindicators, is vital for tracking ecological change, informing adaptive management, and supporting science-based policy. These efforts are crucial to maintaining biodiversity and ecosystem services in the face of increasing human pressure.

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REFERENCES

1. Allan, J.D., & Castillo, M.M., 2007. *Stream Ecology: Structure and Function of Running Waters*, 2nd ed. Chapman and Hall, New York. http://doi.org/10.1007/978-1-4020-5583-6
2. American Public Health Association (APHA), 2017. *Standard Methods for the Examination of Water and Wastewater*, 23rd ed. American Water Works Association, Washington, DC.
3. Barbour, M.T., Gerritsen, J., Snyder, B.D., & Stribling, J.B., 1999. *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish*, 2nd ed. Vol. 339, US Environmental Protection Agency, Office of Water, Washington, DC.
4. Bashir, I., Lone, F.A., Bhat, R.A., Mir, S.A., Dar, Z.A., & Dar, S.A., 2020. Concerns and threats of contamination on aquatic ecosystems. In: Hakeem, K., Bhat, R., Qadri, H. (eds) *Bioremediation and Biotechnology*. Springer, Cham. http://doi.org/10.1007/978-3-030-35691-0_1

5. Bertaso, T.R.N., Spies, M.R., Kotzian, C.B., & Flores, M.L.T., 2015. Effects of forest conversion on the assemblages' structure of aquatic insects in subtropical regions. *Revista Brasileira De Entomologia*, 59, pp. 43–49.
6. Blott, S.J., & Pye K., 2012. Particle size scales and classification of sediment types based on particle size distributions: Review and recommended procedures. *Sedimentology*, 59(7), pp. 2071–2096. http://doi.org/10.1111/j.1365-3091.2012.01335.x
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, pp. 495–523. http://doi.org/10.1146/annurev.ento.51.110104.151124
8. Brandt, R.A.M., 1974. *The Non – Marine Aquatic Mollusca of Thailand*. Frankfurt and Main.
9. Copatti, C.E., Ross, M., Copatti, B.R., & Seibel, L.F., 2013. Bioassessment using benthic macroinvertebrates of the water quality in the Tigreiro river, Jacuí Basin. *Acta Scientiarum Biological Sciences*, 35(4), pp. 521–529. http://doi.org/10.4025/actascibiolsci.v35i4.18934
10. Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., & Turner, R.K., 2012. Changes in the global value of ecosystem services. *Global Environmental Change,* 26, pp. 152–158. http://doi.org/10.1016/j.gloenvcha.2014.04.002
11. Dang, N.T., Thai, T.B., & Pham, V.M. (1980). *Identification of Invertebrates in North Vietnam*. Publisher of Science and Technology, Hanoi.
12. Davies, P.E., Harris, J.H., & Hillman, T.J., Walker, K.F., 2010. Catchment-based classification of Australian rivers. *Marine and Freshwater Research*, 61(7), pp. 764–777. http://doi.org/10.107/MF09043
13. De Pauw N., & Hawkes, H.A., 1993. Biological Monitoring of River Water Quality. *Freshwater Biomonitoring and Benthic Macroinvertebrates,* pp. 87–111, Springer, Dordrecht.
14. Dao, T.S., & Bui, T.N.P., 2016. Phytoplankton from Vam Co River in Southern Vietnam. *Environmental Management and Sustainable Development*, 5(1), pp. 113–125. http://doi.org/10.5296/emsd.v5i1.8775
15. Dear, I., & Kemp, P., 2007. *The Oxford Companion to Ships and the Sea*, 2nd edition. Oxford University Press. http://doi.org/10.1093/acref/9780199205684.001.0001
16. Dudgeon, D., 1999. Tropical Asian Streams: Zoobenthos, Ecology and Conservation. Hong Kong University Press.
17. Duong, T.T., Le, T.P.Q., Ho, T.C., Ho, T.N., Hoang, T.T.H., Dang, D.K., & Lu, X., 2014. Phytoplankton community structure and water quality of Red River, Vietnam. *J. Viet. Environ.*, 6(1), pp. 27–33. http://doi.org/10.13141/jve.vol6.no1.pp27-33
18. Edmondson, W.T., 1976. *Freshwater Biology*, 2nd edition. John Wiley and Sons, New York.
19. Folk, R.L., & Ward, W.C., 1957. Brazos River bar: a study in the significance of grain-size parameters. *Journal of Sedimentary Petrology*, 27 (1), pp. 3–26. http://doi.org/10.1306/74d70646-2b21-11d7-8648000102c1865d
20. Gao, A., Chen, Q., & Zeng, J., 2006. Ecological characteristics of the marine benthic organisms in the muddy intertidal zone of Cangnan. *Marine Sciences-Qingdao-Chinese Edition,* 30(5), pp. 92–96.

21. Grintsov, V., & Sezgin V., 2011. Manual for Identification of Amphipoda from the Black Seas. Sevastopol, Ukraine. ISBN 978-966-02-5743-6
22. Hakeem, K.R., Bhat, R.A., & Qadri, H., 2020. Concerns and threats of contamination on aquatic ecosystems. *Bioremediation and biotechnology*, pp. 1–26. http://doi.org/10.1017/978-030-35691-0_1
23. Hellawell, J.M., 1986. Biological Indicators of Freshwater Pollution and Environmental Management. Springer US. http://doi.org/10.1007/978-94-009-4315-5
24. Hering, D., Borja, A., Carstensen, J., Carvalho, L., Elliott, M., & Feld, C.K., 2010. The European water framework directive at the age of 10: A critical review of the achievements with recommendations for the future. *Sci. Total Environ*., 408 (19), pp. 4007–4019. http://doi.org/10.1016/j.scitotenv.2010.05.031
25. Hoang, T.T.H., 2009. *Monitoring and Assessment of Macroinvertebrate Communities in Support of River Management in Northern Vietnam*. PhD Dissertation, Ghent University, Gent, Belgium.
26. Horne, A.J., & Goldman, C.R., 1994. *Limnology*. McGraw-Hill Inc. http://doi.org/10.4319/lo.1984.29.2.0447b
27. Karrouch, L., Chahlaoui, A., & Essahale, A., 2017. Anthropogenic impacts on the distribution and biodiversity of benthic macroinvertebrates and water quality of the Boufekrane River, Meknes, Morocco. *Journal of Geoscience and Environment Protection*, 5(7), pp. 1–23. http://doi.org/10.4236/gep.2017.57014
28. Kostanda, M., Spriņģe, G., Ozoliņš, D., Skuja, A., & Purmalis, O., 2025. Longitudinal Distribution of Benthic Macroinvertebrates Related to River Ecological Quality. *Limnological Review*, *25*(1), 8. https://doi.org/10.3390/limnolrev25010008
29. Le, P.N., Le, P.Q., & Pham, A.D., 2012. Study on ranking of bio-indices using benthic macroinvertebrate for Lower Dongnai River system, Vietnam. *J Environ Sci Eng*, 54(2), pp. 196–205, PMID: 24749371.
30. Le, T.P., 2015. Water quality assessment using water quality index: a case of the Dong Nai river – sections flow through Bien Hoa city. *Thu Dau Mot University Journal of Science*, 5(2), pp. 135–144.
31. Li, L.B., & Zheng, L.L., 2010. Biomonitoring and bioindicators used for river ecosystems: Definitions, approaches and trends. *Procedia Environmental Science*, pp. 1510–1524. http://doi.org/10.1016/j.proenv.2010.10.164
32. Lukhabi, D.K., Mensah, P.K., Asare, N.K., Akwetey, M.F.A., & Faseyi, C.A., 2024. Benthic macroinvertebrates as indicators of water quality: A case study of estuarine ecosystems along the coast of Ghana. *Heliyon*, 10(7). http://doi.org/10.1016/j.heliyon.2024.e28018
33. McCafferty, W.P., 1983. *Aquatic Entomology: The Fishermen's and Ecologists' Guide to Insects and Their Relatives*. Jones & Barlett Publishing, Massachusetts.
34. Mmko, T.V., Abraham, A.B., Wilminem, J.L.P., & Kekana, M., 2021. Assessment of river health using benthic macroinvertebrates in the Dwars River, olifants water management area, Limpopo Province, South Africa. *African Journal of Aquatic Science*, 46(4), pp. 1–11. http://doi.org/10.2989/16085914.2021.1922348
35. Mekong River Commission (MRC), 2008. *Biomonitoring of the Lower Mekong River and Selected Tributaries, 2004–2007*. MRC Technical Paper, 20, Mekong River Commission, Vientiane. ISSN: 1683-1489.

36. Mekong River Commission (MRC), 2010. *Biomonitoring methods for the Lower Mekong Basin*. Mekong River Commission, Vientiane. ISBN: 978-9932-08-060-1.
37. Ngo, X.Q., & Ngo, T.L., 2014. Composition and biodiversity of benthic macroinvertebrates communities in the Mekong River. *Journal of Science HCMC University of Education*, 58, pp. 38–49.
38. Nguyen, H.H., Everaert, G., Gabriels, W., Hoang, T.T.H., & Goethals, P.A., 2013. Multimetric macroinvertebrate index for assessing the water quality of the Cau river basin in Vietnam. *Limnologica*, 45. http://doi.org/10.1016/j.limno.2013.10.001
39. Nguyen, X.Q., 2001. Developing on freshwater quality assessment based on macroinvertebrates in Vietnam. *Journal of Biology*, 23(3a), pp. 82–88.
40. Paredes-Agurto, M.S.M., Cherre, A.F.U., Dioses, J.M.M. and Garcia, R.B., 2024. Aquatic Macroinvertebrate Diversity and Water Quality, La Gallega-Morropón Creek, Piura, Peru. *Nature Environment and Pollution Technology*, 23(4), pp. 2397-2402. http://doi.org/10.46488/NEPT.2024.v23i04.043
41. 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.
42. Pham, A.D., & Dang, Q.D., 2016. Water quality assessment using benthic macroinvertebrates in Saigon River and its tributaries, Vietnam. *GeoScience Engineering*, 62(2), pp. 15–20. http://doi.org/10.1515/gse-2016-0013
43. Pham, A.D., Pham, V.M., & Dao, T.S., 2020. *The Studies on Aquatic Fauna and Flora in Sai Gon-Dong Nai River System 2014 – 2019*. Science Report, Ton Duc Thang University, Vietnam.
44. Pham, V.M., & Le T., 2004. Study on Biological Criteria for Water Quality Assessment in Water Bodies at Ho Chi Minh City. Department of Science and Technology in HCMC, Vietnam.
45. Putro, S.P., Sihab, A., Titisari, R.S., Anarizta, L.A., & Hodaifa, G., 2025. Spatial and temporal distribution of macrobenthic polychaetes (Animalia: Annelida) comparing mangrove forest and aquaculture zone at Karimunjawa Island, Jepara District, Indonesia. *Biodiversitas*, 26(1), pp. 178–189. http://doi.org/10.13057/biodiv/d260119.
46. Pure Water Inc., 2024. https://pureaqua.com/tds-converter-calculator/.
47. Rattanachan, N., Boonsoong, B., Getwongsa, P., Uttaruk, Y., & Sangpradub N., 2016. A benthic macroinvertebrate multimetric index for assessment of the ecological integrity of northeast streams, Thailand. *EnvironmentAsia*, 9(2), pp. 186–194. http://doi.org/10.14456/ea.2016.24
48. Reynolds, C.S., 2006. Ecology of Phytoplankton: Ecology, Biodiversity and Conservation. Cambridge University Press, Cambridge. http://doi.org/10.1017/cbo9780511542145
49. Shannon, C.E., & Weaver, W., 1963. *The Mathematical Theory of Communication*. University of Illinois Press, Urbana.
50. Sládecek, V. (1973). *System of Water Quality from the Biological Point of View*. Advances in Limnology, 7, ISBN 978-3-510-47005-1.
51. Stiling, P. (2002). *Ecology: Theories and Applications*, 4th edition. Prentice-Hall of India Private Ltd, New Delhi.

52. ter Braak, C.J.F., & Smilauer, P., 2009. *CANOCO Reference Manual and Canodraw for Windows User's Guide: Software for Canonical Community Ordination* (version 4.56). Microcomputer Power.
53. Tran, V.H., Le, P.T., Ngo, N.H., & Tran, V.D., 2019. Morphological and physico-chemical properties of acid sulfate soils in Dong Thap Muoi. *CTU Journal of Science*, 56(103). http://doi.org/10.22144/ctu.jsi.2020.118
54. Vo, Q.M., Tran, V.H., & Pham, T.V., 2024. Constraints of acid sulfate soils and practical use for the improvement of farming in the Mekong Delta, Vietnam: A review. *Indian Journal of Agricultural Research*, 58(3), pp. 369–379. http://doi.org/10.18805/IJARe.AF-834
55. Vu, T.H., 2019. Water quality assessment of Dong Nai River basin. HNUE Journal of Science, 64(10), pp. 176–182. http://doi.org/10.18173/2354-1059-2019-0086
56. Wang, B., Liu, D., Liu, S., Zhang, Y., Lu, D., & Wang, L., 2012. Impacts of urbanization on stream habitats and macroinvertebrate communities in the tributaries of Qiangtang River, China. *Hydrobiologia*, 680, pp. 39–51. http://doi.org/10.1007/s10750-011-0899-6
57. Wang, H.Z., 2024. Assessments and diagnoses of aquatic ecosystem integrity based on integrity requirements of ecosystem service targets. *Water Biology and Security*, 3(1), pp. 1653–1660. http://doi.org/10.1016/j.watbs.2023.100230
58. Wilkins, P.M., Cao, Y., Heske, E.J., & Levengood, J.M., 2015. Influence of a forest preserve on aquatic macroinvertebrates, habitat quality, and water quality in an urban stream. *Urban Ecosystems*, 18, 989–1006.
59. Wu, W., Xu, Z., Zhan, C., Yin, X., & Yu, S. (2015). A new framework to evaluate ecosystem health: A case study in the Wei River basin, China. *Environ, Monit. Assess*., 187, 460. http://doi.org/10.1007/s10661-015-4596-1
60. Yang, W., & Chen, Y., 1999. Community ecology of intertidal zone of Shengsi islands III. Species is distribution of benthos in rocky intertidal zone. *Donghai Marine Science,* 17(1), pp. 61–65.
61. Yazdian, H., Jaafarzadeh, N., & Zahraie, B., 2014. Relationship between benthic macroinvertebrate bio-indices and physicochemical parameters of water: a tool for water resources managers, *J Environ Health Sci Eng*. 12(1), 30. http://doi.org/10.1186/2052-336X-12-30