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

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ABSTRACT

This study investigated the relationships between benthic macroinvertebrates and environmental variables in the Vam Co River system in southern Vietnam. Field surveys were conducted four times from May to November 2023 to evaluate seasonal variations in macroinvertebrate diversity and water quality. The river, characterized by moderate pollution levels, elevated nutrient concentrations, and substrates mainly composed of fine and coarse sand, significantly influences the distribution and abundance of benthic macroinvertebrates. A total of 32 species were identified, with bivalves and crustaceans being the most prevalent groups during the sampling period. Benthic macroinvertebrate densities ranged from 28 to 167 individuals per square meter, reflecting habitat quality linked to the substrate type. Biodiversity, assessed using the Shannon–Wiener index (H'), varied from 1.51 to 2.94, whereas the average tolerance score per individual (ATSPI) ranged from 37 to 51, indicating moderate-to-good ecological health. Species richness was positively associated with pH, total suspended solids (TSS), and dissolved oxygen (DO), suggesting that these factors support diverse communities. Conversely, ATSPI scores, which indicate pollution tolerance, were positively correlated with biochemical oxygen demand (BOD5), total nitrogen (T_N), and total phosphorus (T_P) and negatively correlated with pH, total suspended solids (TSS), and DO. These findings demonstrate the importance of benthic macroinvertebrates as bioindicators of river health and underscore the need for ongoing integrated monitoring and adaptive management to promote the sustainable conservation of the Vam Co River system.

INTRODUCTION

Rivers and streams provide essential ecosystem services, including water supply for agriculture, industry, and residential needs, 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 degradation of water quality and loss of ecosystem integrity (Hakeem et al. 2020). 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 has focused on integrating biomonitoring indicators with water quality parameters to 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, has provided an integrated assessment of the ecological health of river systems, with each biological group offering distinct advantages (De Pauw & Hawkes 1996, Hellawell 1986). Among these, macroinvertebrates are the most widely used to evaluate environmental stressors, such as organic pollution, metal contamination, nutrient enrichment, acidification, sedimentation, toxicants, and other general stressors (Hellawell 1986). Macroinvertebrate assemblages are the basis of most biomonitoring programs in Europe and North America. Various indicators and biological methods have been used to assess water quality in river ecosystems worldwide. Many countries (or states or water authorities) have developed their own biotic indices based on macroinvertebrates, including single bioindicators or integrated biotic indices (Hellawell 1986, Li & Zheng 2010). Two key approaches include diversity indices (Shannon & Weaver 1963), which describe community structure through richness and evenness, and saprobic indices (Sládecek 1973), which were developed to assess organic pollution based on species' oxygen tolerance. The U.S. Environmental Protection Agency (EPA) has also used the Rapid Biological Assessment Protocol (RBP) to assess 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. 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, the water quality assessment of river systems has progressed through the application of biomonitoring methods based on macroinvertebrates. (Nguyen 2001, Pham & Le 2004, Hoang 2009, Nguyen 2013, Pham 2014). These organisms serve as bioindicators because of their sensitivity to changes in environmental conditions, making them reliable indicators 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 major river systems in Vietnam (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 of benthic macroinvertebrates were conducted to assess the ecological health of the Vam Co Dong and Vam Co Tay rivers using integrated approaches that combine 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, and biological variables. Only a few studies have combined these variables or explored their correlations. This study aimed 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.

MATERIALS AND METHODS

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 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), converge at the Ban Quy junction, and flow through Vietnam's eastern Mekong Delta. From here, the river flows approximately 50 km into the Nha Be River before entering the sea at the Soai Rap River Mouth (Dao & 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 abiotic and macroinvertebrate samples. These sites are located near human activities, such as agriculture, aquaculture, villages, and industries, which are potential sources of anthropogenic pressure on water quality (Table 1).

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 water monitoring guidelines (APHA 2017). Surface water samples were collected from the middle of the river using 2-liter polyethylene bottles and stored on ice at approximately 4°C until laboratory analysis.

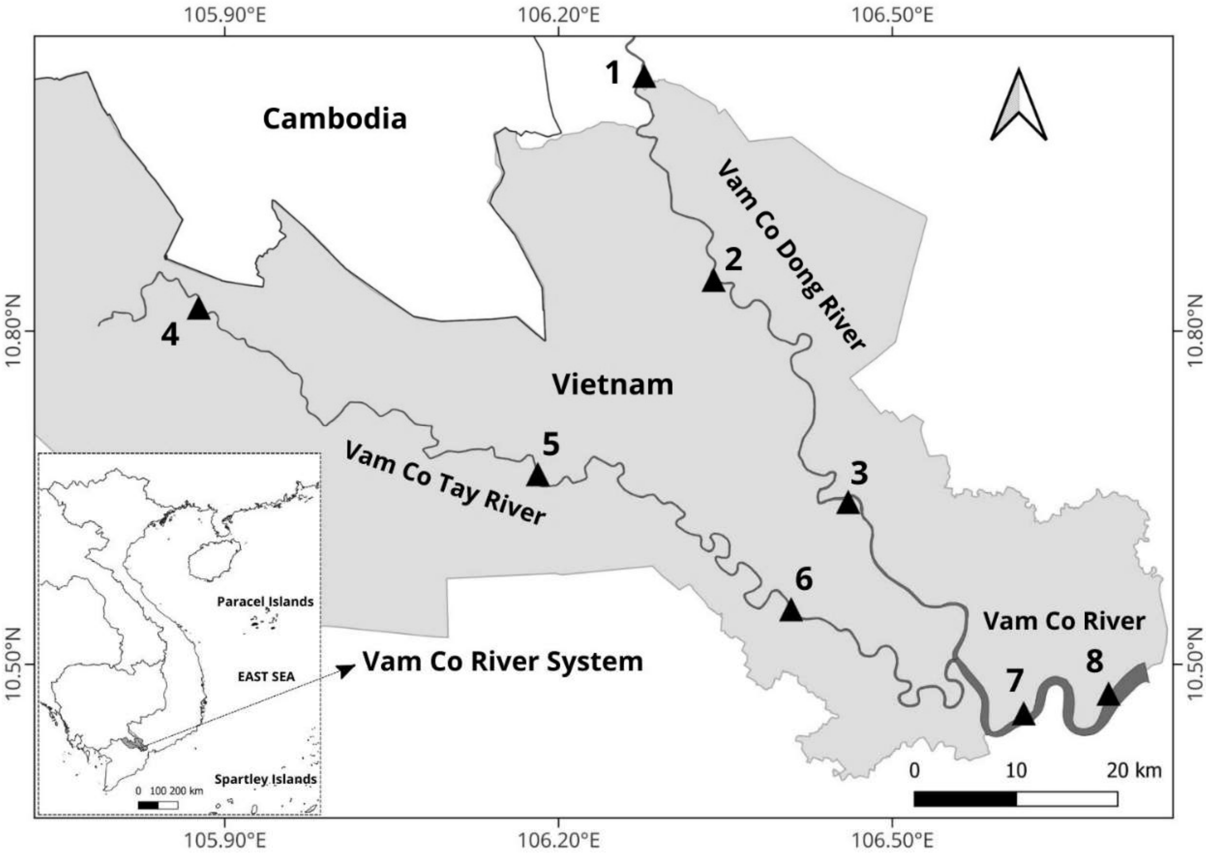

Fig. 1: Map of the study area showing the locations of the sampling sites in the Vam Co River system. Vam Co Dong River (numbers 1, 2, and 3), Vam Co Tay River (4, 5, and 6), Vam Co River (7 and 8).

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

On-site measurements of water environmental parameters, including pH and dissolved oxygen (DO, mg.L^{-1}), were made using a Portable Multi-Meter (HACH HQ2200). Salinity (Sal, ‰) was measured using an EXTECH RF20 Salinity Refractometer equipped with automatic temperature compensation (ATC). The total suspended solids (TSS, mg.L^{-1}), biochemical oxygen demand (BOD$_5$, mg.L^{-1}), total nitrogen (T_N, mg.L^{-1}), and total phosphorus (T_P, mg.L^{-1}) were measured under laboratory conditions. To determine the TSS, a well-mixed sample was filtered through a pre-weighed standard glass microfiber filter, and the residue retained on the filter was dried to a 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 was determined by digesting the sample to convert phosphorus compounds to orthophosphate, which was then quantified spectrophotometrically (APHA 2017).

To assess the habitat conditions for 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, $m.s^{-1}$), 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: right, left, and middle of the river. Water depth and bottom substrate were recorded simultaneously during benthic macroinvertebrate sampling. Depth was measured using a sounding rope weighted with 8 kg, which was 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 & Ward 1957, Blott & Pye 2012).

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 for maintaining data integrity and ensuring the 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, for a total of ten locations per site. At each location, four sediment grabs were collected using a Petersen sampler, with each grab covering an area of approximately 0.025 m². This resulted in a total of 40 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) and preserved with formalin solution at a final concentration of 5% (MRC 2010, Pham 2014). Benthic macroinvertebrates were identified using a compound microscope (Olympus CX41) at 40–100× magnification based on morphological characteristics according to 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.m^{-2}).

Data Analysis

Benthic macroinvertebrate data are presented as minimum (Min), maximum (Max), mean, and standard deviation (SD) values for each sampling site and period. One-way analysis of variance (ANOVA) was conducted to test for significant differences in species density, species richness, and biotic indices among sites. Before ANOVA, the assumptions of normality and homogeneity of variance were assessed using Shapiro–Wilk and Levene's tests, respectively. All faunal population data were recorded in Microsoft Excel and analyzed using R statistical software. Pearson's 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 the community. This index was calculated as the abundance-weighted average of species-specific tolerance scores. Water quality and ecological condition classifications were based on the threshold values for H′ and ATSPI, as defined by Pham (2014) (Table 2). To further explore the relationships between environmental factors and macroinvertebrate assemblages, canonical correspondence analysis (CCA) was performed. This multivariate technique was used to identify how physicochemical variables influenced community structure, dominant species distribution, and bioindex 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):

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

where p_i is the ratio of the number of species i to the total number of benthic macroinvertebrates (M).

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

$$ATSPI = \frac{\sum(n_i \times t_i)}{\sum n_i} \quad ...(2)$$

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

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.

RESULTS AND DISCUSSION

Environmental Variables

The Vam Co River system exhibited significant spatial variations in physicochemical parameters, transitioning from inland areas to the river mouth. The pH values ranged from 4.72 to 7.05, decreasing in regions influenced by acid sulfate soils and increasing toward the river mouth. Salinity (0.1-16.3‰) followed a typical estuarine gradient, rising downstream owing 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, the 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 because it flows 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^{-1} in the Vam Co Dong River, 20 to 84 mg.L^{-1} in the Vam Co Tay River, and 38 to 82 mg.L^{-1} 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^{-1} and 7.4 to 16.1 mg.L^{-1}, respectively (Table 3). In the Vam Co Tay River, DO concentrations fluctuated between 3.5 and 5.1 mg.L^{-1}, while BOD_5 ranged from 7.1 to 12.8 mg.L^{-1}. In the Vam Co River, DO concentrations varied between 3.8 and 5.3 mg.L^{-1}, and BOD_5 ranged from 7.3 to 9.4 mg.L^{-1}. DO concentrations were lowest in the Vam Co Dong River, whereas BOD_5 levels were highest, 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^{-1} and 0.190 to 0.340 mg.L^{-1}, respectively (Table 3). In the Vam Co Tay River, T_N ranged from 1.38 to 2.07 mg.L^{-1}, and T_P ranged from 0.190 to 0.290 mg.L^{-1}. In the Vam Co River, T_N values ranged from 1.29 to 1.69 mg.L^{-1} and T_P from 0.150 to 0.220 mg.L^{-1}. DO levels generally increased downstream, whereas BOD_5, T_N, and T_P tended to decrease due to dilution and sedimentation within the Vam Co River system. The physicochemical parameters also indicated that water quality generally improved during the rainy season (DO: 2.9-5.3 mg.L^{-1}, BOD_5:7.1-14.2 mg.L^{-1}, T_N: 1.29-2.69 mg.L^{-1}) compared to the dry season (DO: 2.7-4.3 mg.L^{-1}, BOD_5:7.1-16.1 mg.L^{-1}, T_N: 1.39-2.84 mg.L^{-1}), although this trend was not clearly demonstrated. Downstream improvements in DO and reductions in BOD_5, T_N, and T_P suggest that 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. Seasonal differences were observed, such as slightly higher DO and lower BOD_5 and nutrient concentrations during the rainy season; however, these trends were not consistent across all parameters or sites.

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

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

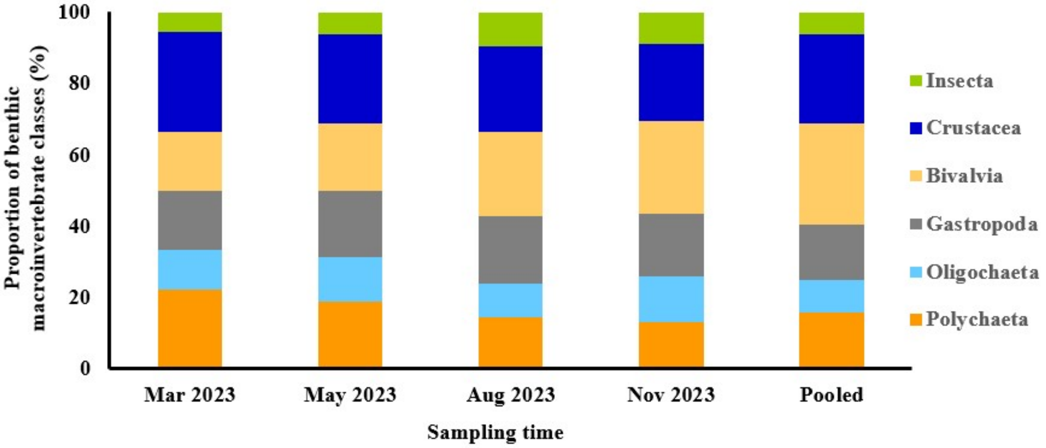

Fig. 2: Proportions of benthic macroinvertebrate classes in the Vam Co River system during the study period. Pooled, pooled data of all four monitoring times.

The flow velocity and water depth in the Vam Co River system ranged from 0.34 to 1.37 m.s^{-1} 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, whereas fine sand (41%-56%) and silt (21%-29%) dominated the Vam Co River. Flow velocity and water depth measurements are crucial for understanding the hydrodynamic conditions of river systems. 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, thereby supporting larger aquatic populations. Consistent with general hydrological models (Allan & Castillo 2007), water flow in the Vam Co River system is generally higher in the wet season than in the dry season.

Assemblages of Benthic Macroinvertebrates

During the four monitoring periods, 32 species from six major taxonomic groups were identified in the study area. Among these groups, bivalves and crustaceans were dominant, comprising 17 species, which accounted for approximately 53.1% of the total species identified (Fig. 2). Among the identified benthic macroinvertebrates, there were five species of polychaetes (accounting for 15.6% of the total), five species of gastropods (15.6%), three species of oligochaetes (9.4%), and two species of insects (6.3%). The Vam Co River flows through 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 the seasonal variations in ecological conditions.

The number of species of benthic macroinvertebrates in the Vam Co River system ranged from 6 to 13 species.m^{-2}, with the lowest richness at Site 2 and the highest at Site 4 (Fig. 3a). Although the overall species numbers varied only slightly among the sampling sites, the composition of the benthic macroinvertebrate communities differed substantially, especially between the freshwater and estuarine zones. This difference may be due to variations 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 and Vam Co Tay Rivers 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* and *Branchiura sowerbyi* (Oligochaeta), *Sermyla tornatella* and *Melanoides tuberculatus* (Gastropoda*), Corbicula* and *Ensidens ingallsianus* (Bivalvia), and *Ablabesmyia* and *Chironomus* (Insecta). In contrast, estuarine and coastal species were more prevalent at the confluence sites (Sites 7 and 8), indicating increased salinity and a shift from freshwater to brackish macroinvertebrate communities. This distribution pattern emphasizes the influence of salinity, hydrological connectivity, and environmental heterogeneity on the benthic macroinvertebrate community structure.

Benthic macroinvertebrate density fluctuated from 28 to 167 individuals.m^{-2}, 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 species. In the Vam Co Dong River and Vam Co Tay River, communities were dominated by freshwater taxa such as *Limnodrilus hoffmeisteri*, *Melanoides tuberculatus, Corbicula leviuscula,* and *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.

The ecological characteristics of the Vam Co Dong and Vam Co Tay rivers are 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.* The presence of estuarine or marine benthic macroinvertebrates, such as *Namalycastis abiuma, Nephtys polybranchia* (Polychaeta), and *Melita* sp. (Crustacea), further underscored the dynamic nature of these inland waters (e.g., 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 $mg.L^{-1}$, Le 2015) and the tidal-influenced parts of the Mekong River (3.9-7.6 $mg.L^{-1}$, 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., indicates declining ecological conditions. Thus, the presence of rich, organic-

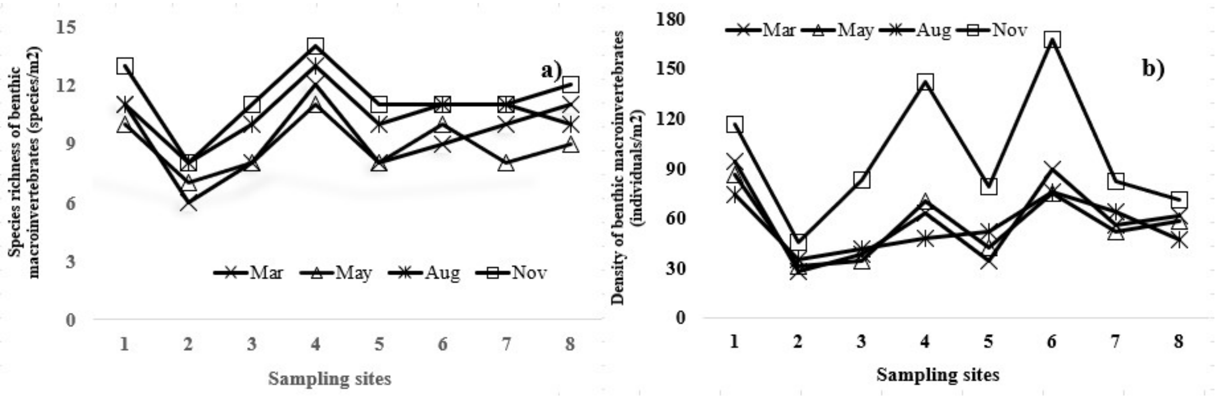

Fig. 3: Species richness (a) and density (b) of benthic macroinvertebrates in the Vam Co River system during the study period.

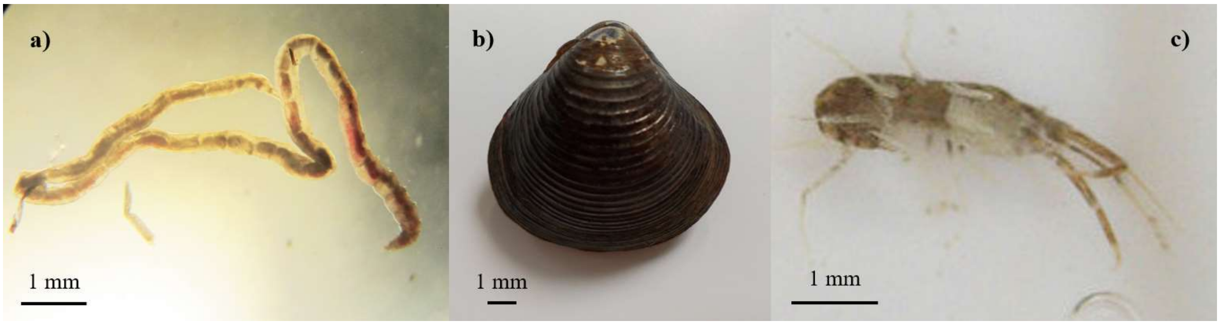

Fig. 4: Some dominant species of benthic macroinvertebrates in the Vam Co River system during the study period: *Limnodrilus hoffmeisteri* (a), *Corbicula leviuscula* (b), and *Grandidierella lignorum* (c).

tolerant macroinvertebrates indicates worsening ecological health. Additionally, the elevated concentrations of T_N and T_P in the Vam Co River system indicate a nutrient-rich, eutrophic environment (Reynolds 2007), exceeding the typical global range for riverine systems (4-800 μg.L^{-1}, 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 & Goldman (1994).

According to Le et al. (2012), macroinvertebrate abundance may be higher in upland streams because of 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 exhibit specific preferences for different substrate types for specific substrate types, ranging from mud and sand to gravel and rocks (Dudgeon 1999, Allan & Castillo 2007). Kostanda et al. (2025) demonstrated that various substrate types, such as loamy sand, clay, and coarse sand, create distinct habitats that can affect benthic macroinvertebrate communities in different ways. Muddy or sandy sediments are the 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 the water clarity, substrate composition, and habitat structure.

The benthic macroinvertebrate 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 & Ngo 2014, Pham & Dang 2016). These ecosystems share similar macroinvertebrate groups, including oligochaetes, gastropods, bivalves, crustaceans, insects, and estuarine polychaetes in tidal zones. Bivalves and crustaceans contributed the highest number of species to the Vam Co River system. Most benthic macroinvertebrates in the Vam Co Dong and Vam Co Tay rivers 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 the increasing salinity. However, the Vam Co River system displayed lower overall species richness and macroinvertebrate density than the Dong Nai and Mekong rivers. 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, which limit habitat suitability.

Biological Indices

The mean H’ values for benthic macroinvertebrates in the Vam Co River system ranged from 1.65 to 2.80, while the mean ATSPI values fluctuated from 38 to 50 during the four monitoring periods 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).

Temporally, both H’ and ATSPI values tended to be higher during the rainy season (August and November) and lower during the dry season (March and May). This seasonal trend is likely due to increased discharge, dilution of pollutants, and expanded habitat availability. However, excessive flow can also mobilize sediments and cause physical disturbances, potentially affecting macroinvertebrate communities. In contrast, dry season conditions may be especially present 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 the H′ and ATSPI metrics provides insights into how environmental pressures and hydrological dynamics

Table 4: Biodiversity index values (H’) and average tolerance score per individual (ATSPI) of benthic macroinvertebrates from the 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

interact to shape river health, highlighting the complex interplay between seasonal variability, spatial gradients, and ecological indicators.

Relationships of Benthic Macroinvertebrates to Environmental Variables

Statistical analysis showed that the species richness of benthic macroinvertebrates in the Vam Co River system was moderately positively 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), and 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 for total phosphorus (T_P, r = –0.26). Additionally, the ATSPI values moderately correlated with BOD_5 (r = 0.34) and T_N (r = 0.31), and negatively correlated with pH (r = -0.58), TSS (r = -0.33), and DO (r = -0.47). Interestingly, macroinvertebrate densities were moderately correlated with water quality variables, suggesting that other factors, such as habitat structure or substrate type, may play a more dominant role (Fig. 5).

Statistical analysis further showed that the species richness of benthic invertebrates was positively correlated with flow velocity (FV) (r = 0.25) and water depth (WL) (r = 0.20), and negatively correlated 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 owing 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 are rich in organic matter.

Insights from Canonical Correspondence Analysis (CCA)

CCA effectively illustrates the effects of environmental

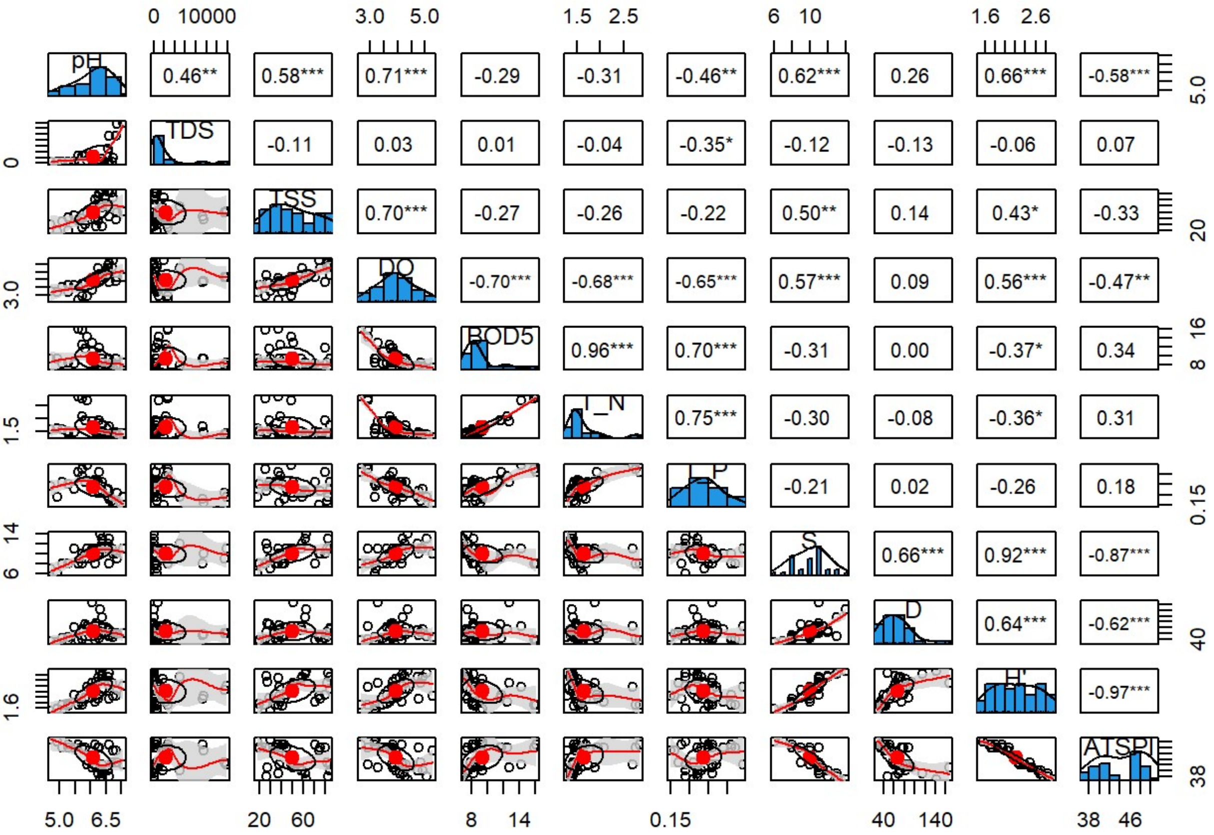

Fig. 5: Correlation between benthic macroinvertebrates and water quality parameters in the Vam Co River system based on the Pearson correlation test, r, correlation coefficient during the study period (“*”: significant levels, the higher the number of “*”, the higher the correlation level).

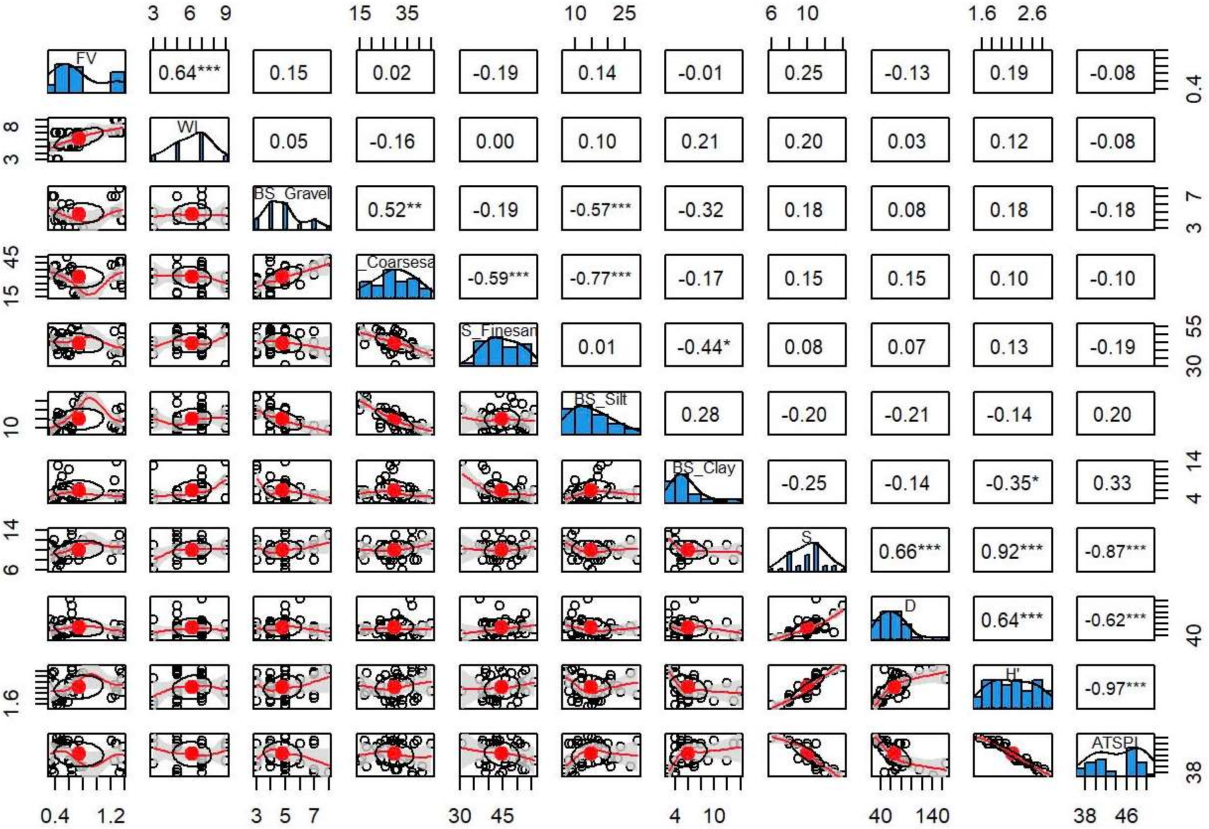

Fig. 6: Correlation between benthic macroinvertebrates and physical habitat variables in the Vam Co River system based on the Pearson correlation test, r, correlation coefficient during the study period ("*": significant levels, the higher the number of "*", the higher the correlation level).

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 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 that are 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 pH, Sal, and DO values. These features are characteristic of dynamic, oxygenated habitats with complex structures that support more sensitive and ecologically specialized species (Fig. 7b).

The positive correlation between the 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 the findings of Yazdian et al. (2014), who reported that suitable ranges of pH and DO enhance macroinvertebrate diversity and abundance. Moderate TSS may reflect organic content or stable substrates favorable to some taxa, whereas 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 unexpectedly low correlations between the abundance of benthic macroinvertebrates and water quality parameters could be due to several reasons: benthic macroinvertebrate abundance may respond to seasonal or short-term fluctuations in water quality parameters, and 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 influenced by seasonal variations and geographical factors. In addition, ATSPI was positively correlated with physical habitat substrate (BS), which indicated that the type of substrate significantly influenced the characteristics of benthic macroinvertebrate communities.

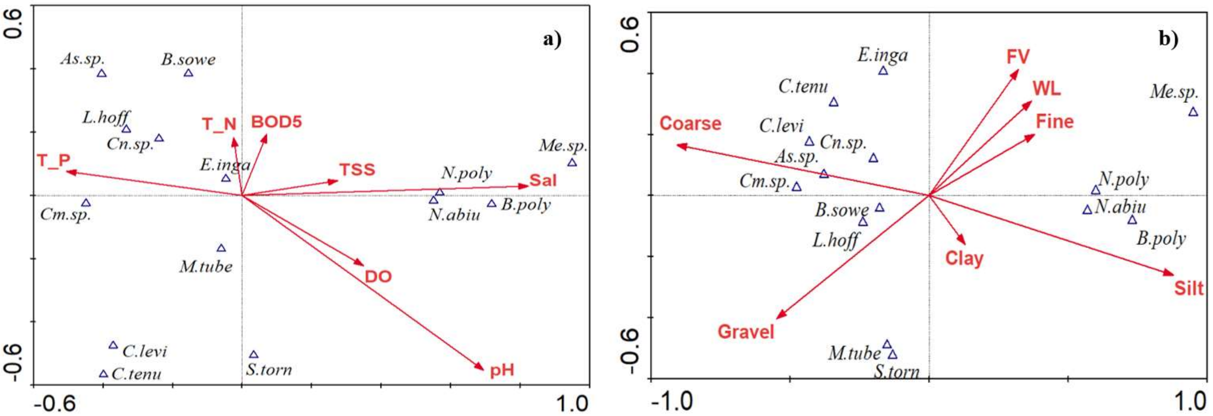

Fig. 7: Canonical correspondence analysis plot relating the dominant species of benthic macroinvertebrates to water quality parameters (a) and physical habitat variables (b) at the sampling sites of the Vam Co River system. *Ablasbesmyia* sp.: Ab.sp., *Bispira polymorpha*: B.poly, *Branchiura sowerbyi*: 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.

Further studies should focus on sediment composition and hydrodynamic variability to better understand the effects of habitat on macroinvertebrate populations in the region. These 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 ecological traits and microhabitat structure of the species. Additionally, the substrate composition differed markedly between the upper and lower reaches, with coarser materials in the upstream areas and finer sediments 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, whereas taxa such as mayflies or certain bivalves prefer gravel or coarse sand substrates (Gao et al. 2006).

River biodiversity is 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, and T_P) and physical factors such as flow velocity and substrate type. These environmental gradients influence habitat suitability, affecting 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 conditions. 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.

CONCLUSIONS

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

A total of 32 species were recorded, with bivalves and crustaceans as the dominant taxa, indicating their moderate biodiversity. This is comparable to the 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 than in other sections. The correlation and CCA analyses confirmed moderate relationships between macroinvertebrate communities and environmental variables, particularly pH, DO, BOD□, 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 factors, 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 loss of biodiversity. Addressing acidification from acid-sulfate soils and preserving habitat heterogeneity, especially substrate variability and flow, are also essential. Long-term biomonitoring using benthic macroinvertebrates as reliable bioindicators is vital for tracking ecological changes, informing adaptive management, and supporting science-based policies. These efforts are crucial for maintaining biodiversity and ecosystem services in the face of increasing human pressure.

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