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RESEARCH ARTICLE

Diatom-based tools for water quality assessment in Cambodian river systems: an exploratory approach

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Abstract
Diatom-based monitoring offers a cost-effective and reliable tool for assessing water quality in developing countries. As natural bio-indicators, diatoms respond sensitively to environmental changes, making them ideal for long-term ecological monitoring. The current paper aims to examine the potential use of a diatom-based tool at the genus level (generic diatom index (GDI)), when flora at the species level is poorly known, for water quality assessment in the Cambodian river systems. Nineteen monitoring sites within the Sangker River catchment have been chosen for the study, while eleven physicochemical parameters and trophic diatom index (TDI) values have been used to predict the response of GDI values. Basic statistical tests and linear regression (LM) were used to describe the spatio-temporal variation of water quality based on GDI classification. A total of 78 diatom genera were recorded, dominated by biraphid taxa (67%), and 13 genera accounted for ~ 90% of total abundance. GDI classification indicated that 10% of sites were of good quality, 53% moderate, and 37% poor, with water quality declining downstream and in areas influenced by urban and agricultural activities. The linear model revealed that GDI was significantly associated with nutrient- and oxygen-related parameters (orthophosphate, dissolved oxygen, and chloride) and correlated strongly with TDI (adjusted $R^2 = 0.96$). Seasonal variation was also significant, highlighting the importance of temporal dynamics in tropical rivers. The current findings provided clear evidence of potential uses of diatom indices to assess the water quality in the Sangker River and other Cambodian river networks even at the genus level of determination. More importantly, diatom indices could be potential tools for long-term biomonitoring in developing countries like Cambodia, where the data and resources are limited. Consequently, the study suggested further investigation on the ecological sensitivity of diatom flora to localize their values, improving GDI classification performance within the tropical environment.

Keywords Diatom · Bio-indication · Generic indices · Physico-chemistry · Water quality · Tonle Sap basin

Introduction

River ecosystem health is vital for maintaining biodiversity, water quality, and human well-being (Garrick et al. 2017). Healthy rivers support aquatic life, regulate nutrient and carbon cycles, and provide clean water for communities (Vörösmarty et al. 2010). However, degradation from pollution, agricultural intensification, habitat fragmentation, and climate change increasingly threatens these systems. As a result, the conservation and sustainable management of river basins have become top priorities for environmental managers (Grill et al. 2019). These issues are particularly critical in developing countries, where financial and technical resources are limited, and long-term environmental monitoring programs are often lacking (Kirschke et al. 2020). Environmental monitoring is essential not only for assessing ecosystem health but also for ensuring water quantity and quality, informing policy, and guiding mitigation measures. Furthermore, consistent monitoring efforts help to control, reduce, and mitigate detrimental human impacts on natural systems, while safeguarding both ecosystem integrity and public health (O'Brien et al. 2016).

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In response to these growing concerns, formal water quality monitoring programs emerged in the 1960s, notably in industrialized countries, to assess and maintain the health of aquatic ecosystems (US-EPA 1986; Bartram and Ballance 1996). However, this method of monitoring is mostly based on physical and chemical parameters, which reflect the conditions at the time of measurement and frequently fail to identify the source of pollution (Soeprobowati et al. 2021). As a result, biological assessment is recognized as the most important factor in establishing the ecological status of watercourses, and it is used in conjunction with physicochemical analyses (Szczepocka et al. 2014, 2018). The ecological state of surface waters is determined by analyzing four groups of aquatic organisms: fish, macrophytes, aquatic invertebrates, and diatoms, which cover primary and secondary producers. Specifically, the biological assessment of water quality using diatom-based tools, namely diatom indices, is used in many countries around the world. Diatom indices have been used extensively for water pollution and trophic status assessment in America, Asia, and Europe (Leclercq and Maquet 1987; Prygiel et al. 1996; Bak et al. 2004; Srivastava et al. 2016) and are slowly being introduced in several African countries (Bere et al. 2014). In Southeast Asia (SEA), countries such as Thailand, Vietnam, Malaysia, and Indonesia have increasingly adopted diatom-based indices to complement conventional physicochemical monitoring techniques (Pham 2018; Ladera et al. 2025). These tools are particularly useful in areas facing pollution from agriculture, aquaculture, and urban development, where nutrient loading and organic pollution are common (Chrea et al. 2024). However, the application of diatom indices in the SEA region often involves modifying or adjusting existing indices to suit tropical freshwater systems (Tan et al. 2017). So far, diatom-based assessment is becoming an integral part of sustainable water resource management across the SEA region, while a lot of efforts are also underway to build regional taxonomic expertise, develop comprehensive reference libraries, and establish long-term biomonitoring programs (Tan et al. 2021). However, diatom-based tools have never been widely introduced or implemented in the Mekong River basin, and more specifically in Cambodia, largely due to several significant challenges. One major issue is the limited taxonomic knowledge at the species level and the absence of comprehensive reference databases specific to Cambodian freshwater diatom flora, which makes accurate identification and ecological interpretation difficult (Chrea et al. 2024). Moreover, environmental data and long-term ecological records are scarce, further complicating the development of locally relevant diatom indices tailored to Cambodia's unique freshwater systems. More importantly, most established diatom indices were developed in temperate regions, and it remains uncertain whether they can be effectively applied to tropical ecosystems like those found in Cambodia without significant adjustment (Tan et al. 2017, 2021).

Various diatom indices have been developed and applied worldwide for water quality assessment. For example, the Biological Diatom Index (IBD) is standardized in France (Prygiel and Coste 2000), the Index of Biotic Integrity (IBI) is widely used in the USA (Wang and Stevenson 2005), the Diatom Index for Australian Rivers (DIAR) was developed for Australian ecosystems (Chessman et al. 2007), and Watanabe's Index (WAT) is applied in Japan (Watanabe et al. 1986). Diatom indices are generally categorized into two main types: generic indices**,** which rely on genus-level identification, and specific indices**,** which require identification at the species level. In developing countries such as Cambodia, where the diatom flora remains poorly documented, generic indices can serve as effective exploratory tools. Two widely used diatom-based indices are the Trophic Diatom Index (TDI) (Kelly and Whitton 1995), which evaluates the trophic (mainly orthophosphate) status of rivers, and the Generic Diatom Index (GDI) (Rumeau and Coste 1988), which provides a broader assessment of overall water quality (global generic index, as mentioned in Rumeau and Coste 1988, p. 15). While the GDI relies on genus-level identification, we note that the TDI can be calculated at both the species and genus levels. In Kelly and Whitton (1995), taxon sensitivity and indicator values are provided for both species and genera (see Table 4 in Kelly and Whitton 1995).

In France, a pioneering country in the development of diatom indices, the implementation of the GDI index was the prerequisite for the subsequent development of specific diatomic indices, such as the SPI (CEMAGREF 1982) used throughout the world (Blanco 2024). The GDI assesses global pollution, including mineralization, eutrophication, and organic matter content, while the TDI primarily focuses on trophic status. Numerous studies have employed the GDI to evaluate water quality across diverse freshwater systems (e.g., Feio et al. 2009; Costa and Schneck 2022; Kuturo et al. 2024). In our exploratory study, we applied the GDI to assess the water quality of the Sangker River in Cambodia.

The current study investigates the potential use of diatom indices to monitor water quality in the Cambodian river system. It is a perspective paper that builds on the recent work of Chrea et al. (2024), which highlights the potential use of GDI for quantifying the ecological health of river ecosystems by describing spatial patterns of benthic diatom diversity and community structure along the environmental gradient of the Sangker River catchment. Specifically, we aimed to describe water quality patterns along the Sangker River basin using generic diatom index (GDI) values and identify the key variables that influence diatom index variation. This is Cambodia's first case study, specifically in the biodiversity hotspot zone (Tonle Sap basin). We hypothesize that GDI provides a cost-effective and ecologically meaningful tool for long-term biomonitoring in data-scarce tropical river systems. The findings will provide, in the first place, scientific knowledge of diatom flora to scale up long-term biomonitoring programs using diatom-based techniques and, in the second place, a baseline for the further development of a specific diatom index adapted to Cambodian watercourses and to the Mekong basin in general.

Materials and methods

Study area

The Sangker River (Fig. 1) is a major tributary of the Tonle Sap Lake (TSL) basin, flowing from west to east across Cambodia. The river has great social, ecological, and cultural significance for people living in northwestern Cambodia. The river basin drains a large area in the northwestern part of the TSL basin, covering approximately 6051 km^2, which represents about 10% of the basin's total catchment area. Land cover is dominated by forest and agricultural areas, with only a tiny proportion of urban land (Sourn et al. 2022). Crops dominate the watershed's land use at its head, while Battambang City is located in the midstream, where land use is replaced by urban areas, industry, and paddy fields. After flowing 200 km from its source, the river enters the TSL floodplain. The river, which is part of the TSL basin, has two distinct seasons: wet (May–October) and dry (April–November), both of which are associated with the lake's tropical monsoon climate. Consequently, the construction of cascade dams (e.g., Sek Sak, Kahot, and Taorn dams), deforestation, the extension of agricultural land, and the explosive rise of urban areas are examples of recent basin development that has occurred over the last few

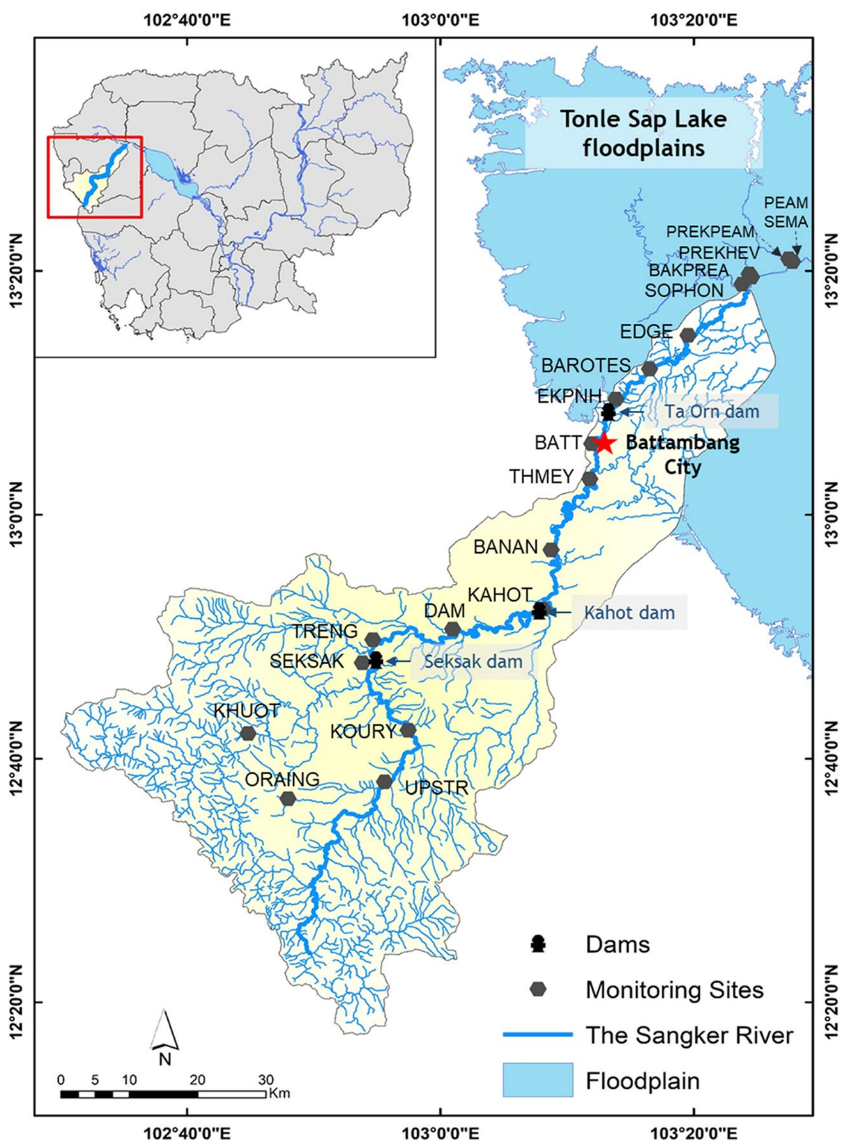

Fig. 1 The map of the Sangker River catchment (Tonle Sap Basin, Cambodia) shows the geographical position of the nineteen monitoring sites (gray polygons) and the main city inside the catchment region, indicated by the red star

decades and is concurrently harming the river's biodiversity and ecological health (Oeurng et al. 2019).

To ensure that the monitoring sites under study were indicative of evaluating water quality across the whole river catchment, nineteen sampling sites were chosen based on geographic circumstances and environmental gradients, such as floodplains, uplands, and mountainous areas (Fig. 1). Six monitoring sites were established upstream of the basin, six sites were located in the midstream section, and the remaining seven sites were situated in the TSL floodplain. Within these nineteen (19) sampling sites, four were located along tributaries (e.g., ORAING, SOPHON, PREKHEV, PREKPEAM), while the remaining fifteen (15) were located along the main channel. The choice of sites along the Sangker tributaries aimed to improve spatial representation, index reliability, and our understanding of catchment-scale processes, ultimately supporting more effective monitoring and water management strategies.

Benthic diatom and water quality data collection

During 5 years, from 2018 to 2022, benthic diatom and physicochemical data were collected twice a year, in June and November, to reflect the seasonality of a tropical river ecosystem as can be seen in the Sangker River. The initial sampling campaign began in November 2018 to study the whole Sangker River catchment, with only sixteen sites monitored during that time to determine the overall health of the Sangker River ecosystem and identify strategic locations for long-term biomonitoring (Fig. 1). Later in 2019, the number of sampling sites was increased to nineteen; three additional monitoring sites have been added in the Tonle Sap floodplain and Sek Sak reservoir (e.g., PREKPEAM, PEAMSEMA, SEKSAK) to expand our knowledge of benthic diatom flora and water quality dynamics within the Sangker River catchment (e.g., main channel *vs.* tributaries, lotic ecosystem *vs.* lentic ecosystem). Unfortunately, the sample campaign was cancelled in 2020 owing to the COVID-19 epidemic. As a result, the database contained information on seven different sample campaigns.

Benthic diatom samples were obtained from the river's available substratum (Fig. 1), in descending order of priority: stones (S), macrophyte stems (Sm), macrophyte roots (R), and wood. To obtain diatom samples, stones and wood were extracted from the water and scrubbed with a toothbrush, while roots and stems were chopped and squeezed. Diatom samples were prepared and identified in the laboratory following the standard procedure as described in the recent research work conducted by Chrea et al. (2024). Benthic diatom identification was carried out at the genus level using various reference sources, including mainly diatom identification handbooks from Europe and Asia (Krammer 2002, 2003; Tanaka 2007, 2014; Lange-Bertalot et al. 2017). Although samples were pooled for genus-level analysis in this study, the deployment of artificial substrates along the Sangker River may be a possibility in future surveys to quantify precisely benthic diatom density and colonization rates.

Twenty-six physicochemical parameters were measured either on-site or analyzed in the laboratory. In-situ measurements included water temperature (WT), dissolved oxygen (DO), oxygen saturation (OS), electrical conductivity (EC), and pH, all recorded using a multi-parameter probe (WTW Multi 3420 Set G). Turbidity (Turb) was assessed with a portable turbidity meter (HANNA-HI937030). Laboratory analyses were conducted following ISO standard methods, as described in our previous study Chrea et al. (2023), to determine chemical parameters such as total nitrogen (TN), nitrate (NO_3^-), orthophosphate (PO_4^{3-}), and various cations and anions. At each site, two 100-ml plastic containers were collected: one for raw water to determine total nitrogen (TN) and another for filtered water (passed through a 1.2 µm microglass fiber filter). The filters were preserved and later used to measure total suspended solids (TSS).

Diatom index calculation

In this study, the generic diatom index (GDI) and trophic diatom index (TDI) have been used for the first time to assess the water quality in the Sangker River catchment. The GDI was developed by Coste and Ayphassorho (1991) as a biological index to assess freshwater quality based on diatom community composition, with a weighted average of genus-specific sensitivity (1–5) and indicator values (1–3). This score detects organic pollutants and provides a general assessment of ecosystem health. Later on, Kelly and Whitton (1995) developed the TDI, which focuses on nutrient enrichment, specifically phosphorus, and includes additional nutrient-sensitive and planktonic taxa. Both indices have been widely used in Europe and Asia to monitor river and lake water quality and they provide complementary insights into ecosystem health.

The generic diatom index (GDI) is a biological index used to assess the water quality, particularly in freshwater ecosystems, based on diatom communities; in other words, diatom-based tools (Kelly and Whitton 1995; Kelly et al. 1995; Naz et al. 2025). GDI has been widely used in Europe and Asia for water quality assessment programs to detect water pollution and quantify ecosystem health. The GDI values typically range between 1 and 20; higher GDI values indicate cleaner water with low pollution, while lower values suggest higher organic pollution and nutrient enrichment, as indicated in Table 1. According to the threshold values in Table 1 for water quality classification, if the observed value of the GDI in the studied sites was higher than 17,

Table 1 Ranges of generic diatom index (GDI) values corresponding to their water quality status and the ranges of trophic diatom index (TDI) corresponding to trophic status of the aquatic ecosystem

GDI value	Water quality status	TDI value	Trophic status
> 17	Very good	< 35	Oligotrophic
14–17	Good	35–50	Oligo-mesotrophic
11–14	Moderate	50–60	Mesotrophic
8–11	Poor	60–75	Eutrophic
< 8	Bad	> 75	Hypertrophic

it indicated that the water quality was "very good"; if the assessed site was 14–17, it was classified as "good"; while if the site was 11–14, it was classified as "moderate." The sites were with 8–11, and bigger than 8; they were classified as "poor" and "bad."

Similarly, the trophic diatom index (TDI) is a metric used to assess water quality based on the composition of diatom communities, but it primarily reflects nutrient levels, especially phosphorus. In addition to the threshold values in Table 1 for water quality classification, if the observed value of the TDI in the studied sites was lower than 35 (TDI < 35), it revealed that the water quality was "oligotrophic"; if the assessed site was 35–50 (35 < TDI < 50), it was classified as "oligo-mesotrophic"; while if the site was 50–60 (50 < TDI < 60), it was classified as "mesotrophic". Finally, the sites with TDI values between 60 and 75 (60 < TDI < 75) and higher than 75 (TDI > 75); they were classified as "eutrophic" and "hypertrophic" (Table 1). While both indices are calculated from the diatom genera present, they differ in ecological focus: GDI reflects overall water quality through the sensitivity of diatoms to pollution, whereas TDI indicates nutrient enrichment and trophic status. These complementary indices together provide a more comprehensive understanding of water quality and ecological conditions in the studied sites.

The calculation of the diatom indices GDI and TDI, have been performed with the software OMNIDIA (https://omnidia.fr/en), a software for taxonomy, diatom indices and inventories management (Lecointe et al. 1993). Since its launch, the software's taxonomic, bibliographic and ecological databases have been regularly updated (several times a year). The Diatom indices (ID), Generic Diatom Index GDI (Coste and Ayphassorho 1991) and Trophic Diatom Index TDI (Kelly and Whitton 1995) are calculated from the weighted average equation of Zelinka and Marvan (1961) $ID = \sum_{j=1}^{n} AjSjVj / \sum_{j=1}^{n} AjVj$ where Aj = abundance or proportion of genus j in sample, Sj = pollution sensitivity (1–5) of genus, and Vj = indicator value (1–3). More details about these indices are given in Coste & Ayphassorho (1991), Kelly et al. (1995), and Kelly (1998). It is worth noting that not all diatom genera are represented in both indices. The GDI mainly includes benthic or motile species sensitive to general organic pollution, whereas the TDI incorporates additional planktonic and nutrient-sensitive genera. Consequently, some species are calculated only for TDI, reflecting their strong response to nutrient enrichment or eutrophication rather than overall pollution. Additional details on the type of index (GDI/TDI), functional guilds and the assigned ecological category (sensitivity/tolerance) are provided in Appendix 1 (Table S1).

Data analyses

Basic statistical tests were used to examine the temporal changes of diatom indices across the sampling period. Both diatom index values (GDI and TDI) and physico-chemical tables were averaged a priori to quantify the response of GDI to physico-chemical parameters and TDI values. Accordingly, a linear model (LM) was applied to the average dataset to investigate the response of GDI to physicochemical parameters and TDI values of the Sangker River catchment. All physicochemical variables were standardized to be dimensionless prior to model fitting to ensure comparability among variables with different units and scales and to reduce skewness. The linear model was computed using the package "base" in R programming, while the response plots were produced by the package "sjPlot" (Lüdecke 2023). All statistical analyses were performed in the R program (R Core Team 2024).

Results

Composition of benthic diatom flora in the Sangker River

A total of seventy-eight (78) diatom genera were recorded across nineteen monitoring sites within the Sangker River catchment, spanning 36 families, 18 orders, and 5 categories (Fig. 2, Table S1). Among these, biraphid diatoms were dominant, constituting 67% of all recorded genera, followed by centric (13%) and monoraphid diatoms (10%) (Fig. 2a). The most diverse orders were Naviculales, Cymbellales, and Achnanthales, together accounting for 61% of total genera (Fig. 2b). At the family level, Naviculaceae was the most represented, comprising 10% of genera, followed by Bacillariaceae and Achnanthidiaceae (8% each), and Cymbellaceae and Stauroneidaceae (6% each), with several other families such as Stephanodiscaceae, Diadesmidaceae, and Sellaphoraceae each contributing around 4% (Fig. 2c). Despite this high diversity, the diatom community was largely dominated by a few genera. Thirteen genera accounted for approximately 90% of the total relative abundance. *Gomphonema* Ehrenberg was

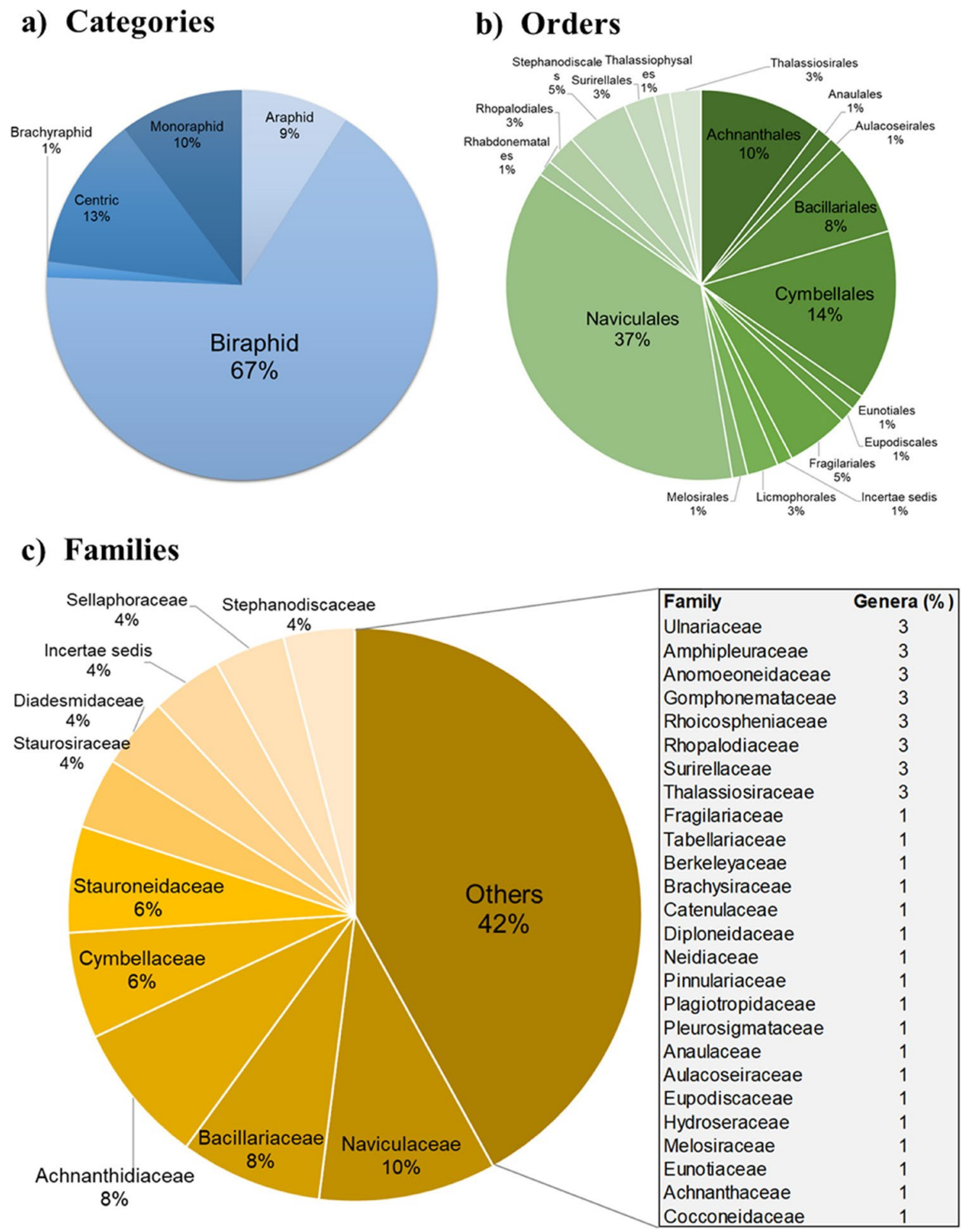

Fig. 2 Percentage distribution of benthic diatom genera in the Sangker River catchment (Tonle Sap Basin), classified by (**a**) ecological categories, (**b**) taxonomic orders, and (**c**) families. Families representing less than 3% of the total genera were grouped under "Others" and detailed in the adjacent box beside the respective pie chart (adopted from Chrea et al. (2024))

the most abundant (19.44%), followed by *Nitzschia* Hassal (17.24%), *Navicula* Bory (7.79%), and *Achnanthidium* Kützing (7.19%). In terms of ecological categories, the biraphid diatom corresponds mainly to the motile guild, represented by common genera such as *Gomphonema* Ehrenberg, *Nitzschia* Hassal, and *Navicula* Bory, while monoraphid and brachyraphid taxa are typically defined as the low-profile guild, e.g., *Achnanthidium* Kützing and *Karayevia* Round & L.Bukhtiyarova ex Round. In contrast, araphid diatoms are associated with the high-profile guild, including genera such as *Fragilaria* Lyngbye and *Ulnaria* (Kützing) Compère, while centric diatoms are characterized as the planktonic guild, represented by *Stephanodiscus* Ehrenberg and *Cyclotella* (Kützing) Brébisson.

Patterns of water quality based on diatom indices (GDI)

Water quality in the Sangker River catchment exhibited substantial variation from upstream to downstream. Key physicochemical parameters, including electrical conductivity, dissolved oxygen, chloride, nitrate, and chemical oxygen demand, showed important variation along the river course (Table 2). Electrical conductivity (EC) was relatively high, with a mean value of 181.08 µS/cm (±69.61). Nevertheless,

Table 2 Mean values and standard deviation (SD) of physico-chemical parameters in the Sangker River catchment from 2018 to 2022

Parameters	Units	Values	
		Mean	SD
Water temperature (WT)	°C	29.96	1.11
Electrical conductivity (EC)	µS/cm	181.08	69.61
pH	-	7.47	0.4
Oxygen saturation (Sat)	%	78.25	26.01
Dissolved oxygen (DO)	mg/L	5.86	2.04
Total suspended solid (TSS)	mg/L	47.1	31.23
Chloride (Cl^-)	mg/L	8.14	3.91
Chemical oxygen demand (COD)	mg/L	279.3	181.64
Nitrate (NO_3^-)	mg/L	0.67	0.79
Orthophosphate (PO_4^{3-})	mg/L	0.02	0.04
Ammonium (NH_4^+)	mg/L	0.05	0.11

the river remained generally well oxygenated, as indicated by the average dissolved oxygen (DO) concentration of 5.86 mg/L (±2.04) and an oxygen saturation (Sat) level of 78.25% (±26.01). Chemical oxygen demand (COD) varied markedly across sites, with a mean concentration of 279.3 mg/L (±181.64). In addition, nitrate (NO_3^-) concentrations averaged 0.67 mg/L (±0.79), while orthophosphate (PO_4^{3-}) levels remained consistently low, with a mean of 0.02 mg/L (±0.04).

According to the general diatom index (GDI) values, 10% of monitored sites (3 sites) were classed as good quality based on GDI scores, while 53% of sites (9 sites) were rated as moderate quality and 37% of sites (7 sites) as bad quality. No reference site without pollution was identified to be of particularly high quality throughout the Sangker River catchment (Fig. 3). Overall, the water quality in the Sangker River appears to be moderate, particularly in the upstream and middle course of the river, but it begins to decline substantially as it approaches the city and enters the Tonle Sap floodplains (Fig. 3).

In the Sangker River, spatial variation in water quality appears to be more important than temporal variation. Given that the annual variation in water quality based on GDI values fluctuated somewhat across the study period (2018–2022) (Fig. 4). Seasonal changes in water quality in the Sangker River were found to be significant (Fig. 4, $p < 0.05$), indicating that intra-annual variation was more relevant than inter-annual variation.

Determinants of generic diatom index (GDI)

The linear model showed a significant association of GDI values with key physicochemical parameters and with TDI (adjusted $R^2 = 0.96$; Table 3). Among the eleven physicochemical variables, four exhibited significant relationships with GDI variation, i.e., oxygen saturation (Sat), dissolved oxygen (DO), chloride (Cl^-), and orthophosphate (PO_4^{3-}). Accordingly, GDI values were strongly correlated with TDI and with nutrient- and oxygen-related parameters (PO_4^{3-} and DO), reflecting the simultaneous responses of diatom communities to eutrophication and other environmental stressors. Specifically, GDI was positively associated with TDI and DO, while negative associations were observed with PO_4^{3-} and Cl^- (Fig. 5a–-d). These results indicate that higher nutrient enrichment and chloride concentrations tend to reduce GDI, whereas higher oxygen availability corresponds to higher GDI values and better ecosystem health.

Discussion

Diatom-based tools for water quality assessment in the Sangker river catchment

Overall, we found a clear upstream–downstream gradient of water quality based on the generic diatom index (GDI) classification. This observed pattern was consistent with the previous work described by Chrea et al. (2023) using physicochemical parameters to investigate the water quality of the Sangker River. However, the GDI classification technique seems to be more strict compared to the previous classification using various physicochemical classification methods, e.g., the United Nations Environmental Protection Agency (US-EPA) framework and the Mekong River Commission Water Quality Index (MRC-WQI, Prati Index, etc.), where the majority of sites had been scored as very good (35%) and good (31%), whereas more than half of the monitoring was scored as moderate (53%) based on GDI classification. This stricter assessment reflects the sensitivity of diatom-based indices to cumulative environmental impacts over time (Sgro et al. 2012), making them a more integrative tool for detecting subtle or persistent changes in water quality that may be overlooked by physicochemical snapshots. In tropical rivers such as the Sangker, where seasonal dynamics, agricultural runoff, and human activities interact, GDI could provide a more refined and realistic assessment of ecological conditions than physicochemical measurements alone. The low GDI scores could link to the sensitivity scores of the diatom genera, since these scores were empirically developed in Europe; they could be less relevant to the tropical region of Cambodia (Taylor et al. 2007; Rimet and Bouchez 2012). The gradual decrease of the GDI index along the river course is linked to the nutrient accumulation induced by human activities and agricultural intensification (Smol and Stoermer 2010).

Indeed, classification using the generic diatom index (GDI) is generally stricter than that using physicochemical parameters alone. Since diatoms reflect longer-term

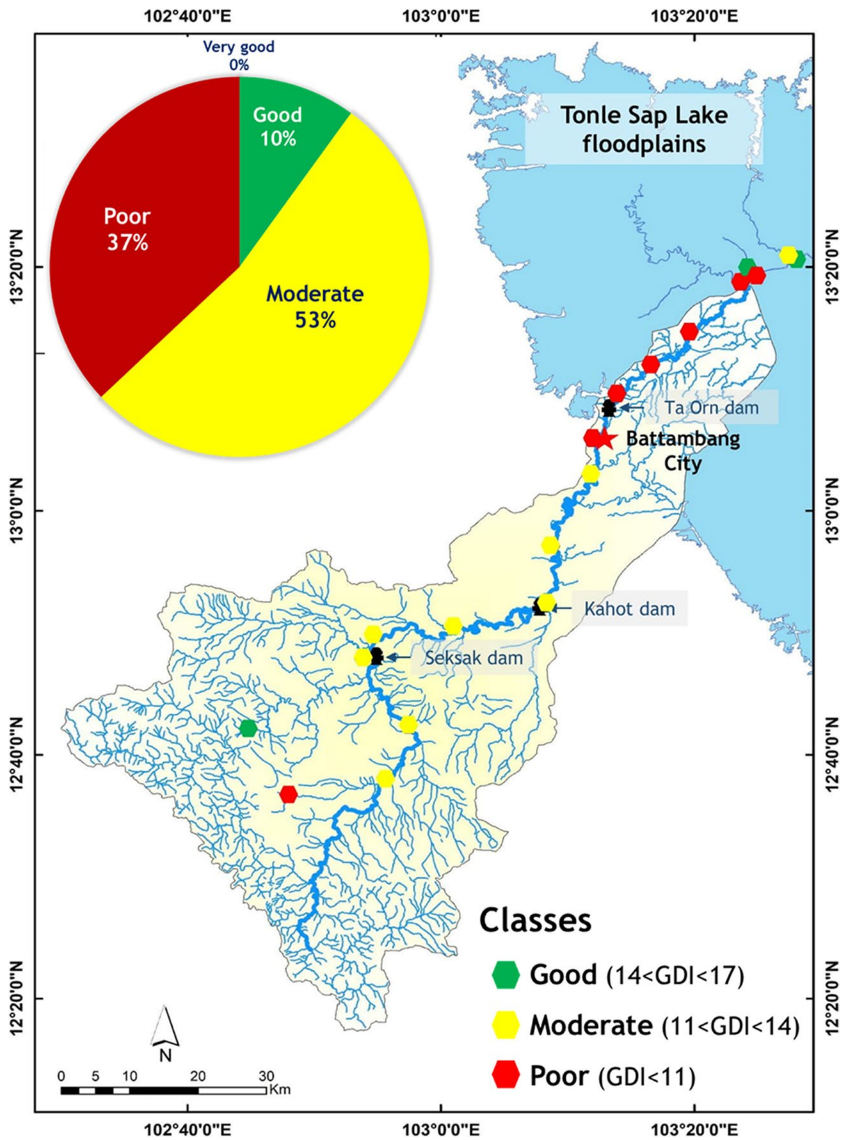

Fig. 3 Spatial variation of water quality based on generic diatom index (GDI) values within the Sangker River catchment. The pie chart (on the top left) indicates the total percentage by classes of water quality: good (green polygons), moderate (yellow), and poor (red)

conditions in the water, it is not a simple snapshot, as physicochemical data (e.g., phosphorus, nitrogen, pH) show conditions at the time of sampling, i.e., they can fluctuate daily or hourly (Pham 2017; Maraşlioğlu et al. 2020). Moreover, diatoms respond to multiple stressors (nutrients, pollution, pH, conductivity). GDI incorporates this multifaceted impact, while physicochemical parameters might only capture a subset of the stressors. Consequently, GDI is built on species-specific tolerance values (ecological sensitivity), making it sensitive to even subtle changes in water quality (Tan et al. 2021). A site might appear to have "good" status based on nutrient levels, but diatom indices might show "moderate" or even "poor" status due to cumulative pollution impacts, as we observed in the case of the Sangker River catchment (e.g., sites UPSTR, KOURY, TRENG) (Pham 2017; Tan et al. 2021).

Furthermore, the spatial variation of the water quality seems to play a more important role than the temporal variation in the Sangker River catchment based on the GDI assessment; this outcome is consistent with the previous study conducted by Chrea et al. (2023). Consequently, significant seasonal variation of the water quality was observed based on the GDI. This important variation of water quality could be explained by the climatic conditions in the tropical environment, where ecosystems experience distinct wet and dry seasons that dramatically affect water quality and ecological dynamics (Douglas et al. 2005). Similarly, many case studies in the region have highlighted the importance of seasonal variations in water quality, suggesting the necessity of seasonal assessment and biomonitoring in tropical river systems (Kannel et al. 2007; Tan et al. 2013). Consequently, we could observe the relevance and effectiveness of GDI to assess the water quality in tropical

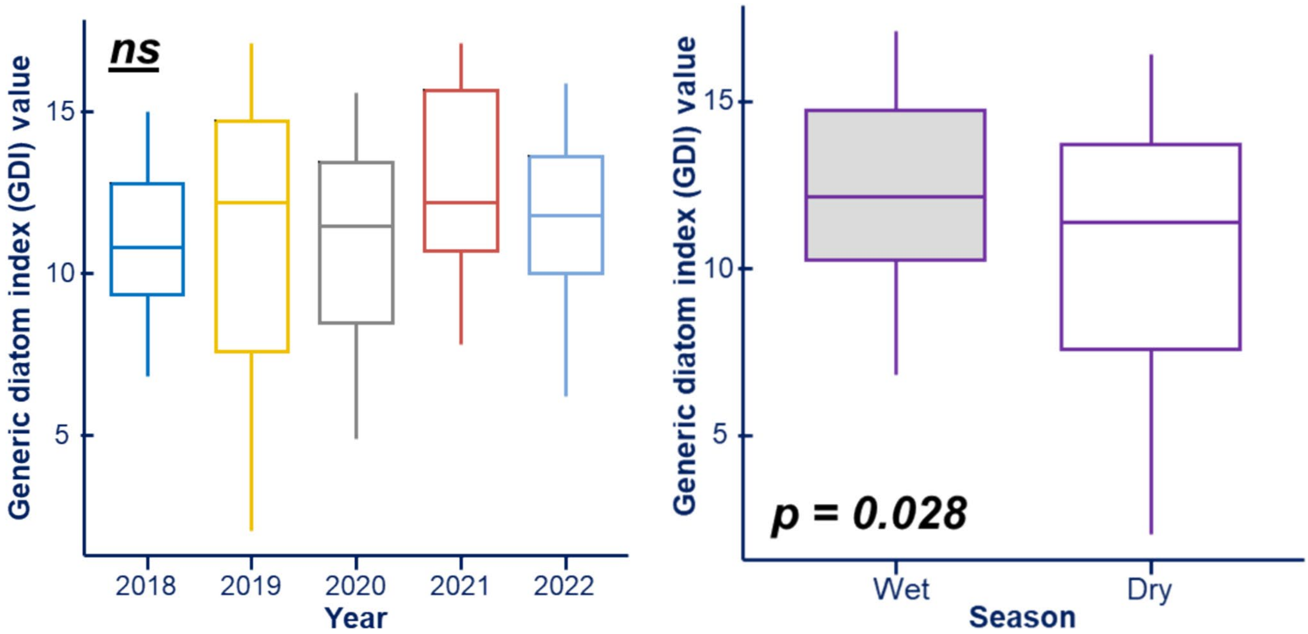

Fig. 4 Temporal change of water quality based on generic diatom index (GDI) values within the Sangker River catchment. The left boxplot shows the annual variation from 2018 to 2022, while the right-hand side exhibits the seasonal variation of GDI values (Wilcoxon test, $p < 0.05$)

Table 3 Linear model (LM) showing the response of the Generic Diatom Index (GDI) to physicochemical parameters (adjust $R^2 = 0.96$). Parameters in *italics* indicate significant predictors of the variation of GDI value (*p*-value < 0.05). The Trophic Diatom Index (TDI) is included to show its correlation only and is not treated as a predictor

Parameter	Unit	p-value	Significant levels
Trophic diatom index (TDI)	-	0.001	**
Water temperature (WT)	°C	0.864	ns
Electrical conductivity (EC)	um/S	0.202	ns
pH	-	0.257	ns
Oxygen saturation (Sat)	%	0.004	**
Dissolved oxygen (DO)	mg/L	0.008	**
Total suspended solid (TSS)	mg/L	0.532	ns
Chloride (Cl^-)	mg/L	0.019	*
Chemical oxygen demand (COD)	mg/L	0.917	ns
Nitrate (NO_3^-)	mg/L	0.259	ns
Orthophosphate (PO_4^{3-})	mg/L	0.004	**
Ammonium (NH_4^+)	mg/L	0.210	ns

river systems (Rimet and Bouchez 2012; Pham 2018). More importantly, the combination of monitoring sites throughout the Sangker River's main channel and tributaries contributed to the diatom index's resilience and usefulness in a complex system such as the Sangker River and TSL systems. Therefore, sampling a diverse range of environmental conditions across the river network improves the accuracy of the diatom index for river health assessment while supporting the calibration and validation of the index. Given the fact that tributaries often receive direct inputs from agricultural runoff, domestic discharges and land-use changes, leading to localized variations in water quality (Rimet and Bouchez 2012; Pajunen et al. 2020). Diatoms are known to be highly sensitive to physicochemical changes, and their community structure reflects environmental gradients, including nutrient levels, pH, and conductivity (Kelly and Whitton 1998). Sampling only the mainstream risks overlooking localized degradation or underestimating cumulative impacts. Thus, tributary data enhance the precision of diatom indices such as the Trophic Diatom Index (TDI), which depend on fine-scale ecological variation (Kelly 1998). Consequently, the current study integrated both monitoring sites along the main course and tributaries and provided evidence to generalize the use of the diatom index to other Cambodian river networks. The current findings are consistent with previous research in tropical regions such as Malaysia (Wan Omar and Mansor 2002), Indonesia (Al Falah et al. 2025), and South America (Feio et al. 2021; Matovelle et al. 2024), where genus-level diatom indices effectively captured spatial variations and reflected eutrophication and cumulative pollution effects. Moreover, the findings indicated that the diatom index integrates various stressors throughout time, whereas physicochemical snapshots solely reflect short-term conditions (Pham 2017; Tan et al. 2021).

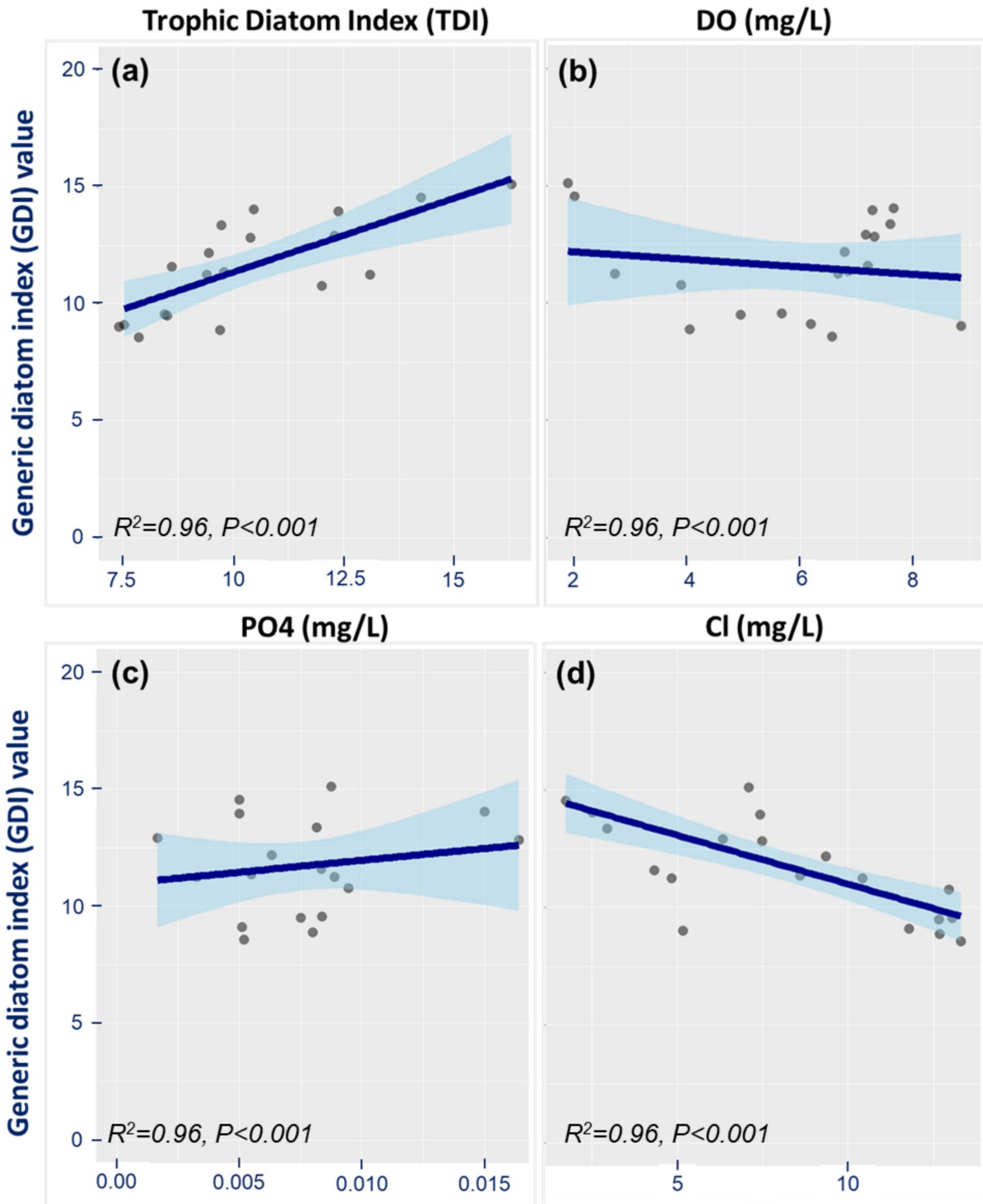

Fig. 5 Response of generic diatom index (GDI) values to trophic diatom index (TDI) value (**a**) and important physicochemical parameters (**b** dissolved oxygen (DO), **c** orthophosphate (PO_4^{3-}), and **d** chloride (Cl^-))

Determinants and perspectives on diatom indices in Cambodian river systems

The Sangker River catchment showed a substantial response of GDI to TDI values and physicochemical factors. Indeed, the Generic Diatom Index (GDI) and the Trophic Diatom Index (TDI) frequently exhibit a strong correlation because both are based on diatom communities' ecological responses to nutrient pollution, particularly eutrophication, in relation to other important nutrient indicators such as PO_4, NH_4, and DO. In real-world freshwater ecosystems, these indexes GDI and TDI, frequently rise and fall concurrently (Wu and Kow 2002; Szczepocka et al. 2014). Furthermore, physicochemical characteristics such as PO_4, DO, NH_4, and Cl were found to strongly impact water quality and GDI values. In fact, numerous studies have highlighted the importance of physicochemical aspects in determining diatom communities, as well as the effectiveness of indices such as the GDI in assessing water quality (Wu and Kow 2002; Kalyoncu et al. 2009; Sushmitha and Mahesh 2021). Indeed, nutrients such as PO_4 and NH_4 promote eutrophic (pollution-tolerant) diatom growth, while nitrogen enrichment favors more tolerant species. Moreover, diatoms produce oxygen, but they are also sensitive to low oxygen levels; low DO promotes resistant taxa, resulting in lower GDI, like what we observed in the Sangker River catchment. Eutrophication was identified as the principal source of water quality degradation in the Sangker River basin, owing to a combination of stressors from human activities, agriculture, and livestock (Sourn et al. 2022; Chrea et al. 2023). TDI levels and nutrient-related indicators (PO_4, NH_4, DO, Sat) were identified as key drivers of GDI, highlighting water quality concerns in the river system. As a result, regulating the source of nutrient inputs (e.g., riparian zonation, conservation agriculture practices, environmental flow from cascade dam operation) will considerably improve both GDI values and Sangker River ecosystem health. In the context of global change, river basin management can benefit from the use of locally adapted tools; particularly those accessible to local governments, stakeholders, and practitioners, along with biomonitoring approaches suited to tropical freshwater environments (Taurozzi et al. 2024).Therefore, diatom-based tools should be one of the options for water quality assessment and biomonitoring in Cambodia and other developing countries where data and resources are scarce. A recent study conducted in China (Mbao et al. 2020), where the use of diatom-based tools is in its infancy and undergoing improvement, compared different metrics of diatoms such as diatom guilds, diversity indices, and diatom index (in this case the TDI). The main result has shown that "TDI works better and can be used alongside physical and chemical parameters […] in watersheds". Thus, among the available parameters relating to diatoms, indices such as the TDI and GDI are of primary interest for monitoring watercourses in developing countries.

This is the first study to use genus-level indices along the Sangker River and in Tonle Sap Basin, Cambodia's biodiversity hotspot. Unlike previous research that relied on physicochemical metrics or species-level indicators from temperate regions, our findings showed in particular that the genus-level GDI may identify both spatial and seasonal differences in water quality in tropical river systems with limited taxonomic resources (Tan et al. 2021; Chrea et al. 2023). This represents a novel application of diatom-based indices in tropical Southeast Asian river systems, where species-level identification is often limited by scarce taxonomic references and resources (Bere 2016). By integrating monitoring sites along both the main course and tributaries according to the river topology, this study provides the first evidence that genus-level GDI can reliably reflect water quality patterns in Cambodia and capture environmental gradients under multiple stressors.

Given current knowledge gaps in tropical diatom taxonomy, particularly in Southeast Asia, genus-level identification remains a practical starting point. In regions such as Cambodia, where references, inventories and taxonomic handbooks at the species level are limited, working at the genus level enables initial ecological assessments and helps detect major environmental patterns (Bere 2016). While we acknowledge that genus-level analysis reduces the resolution of the ecological assessment, since species within a genus may have different sensitivities, this approach allows for progress where otherwise no assessment could be conducted. It represents a necessary first step until taxonomic capacity and ecological databases are strengthened. We highlight that this study follows a previous one (Chrea et al. 2024) that demonstrated the presence of diatom biotypes based on generic composition, which was a favorable sign leading us to undertake the application of generic indices. Despite these limitations, GDI has been effectively applied in both temperate and tropical contexts. In Europe, it is a standard tool under the EU Water Framework Directive (Kelly et al. 2008; Masouras et al. 2021). Similarly, successful applications have been reported in South America, including in Brazilian rivers (Feio et al. 2021) and Andean river systems (Matovelle et al. 2024). In tropical Asia, adaptations of GDI and perspectives on the application of diatom indices have been used in Malaysia (Wan Omar and Mansor 2002) and Indonesia (Al Falah et al. 2025) and, more recently, in Cambodia's Tonle Sap tributaries (Chrea et al. 2023, 2024). Moving forward, species-level refinement will be essential to enhance index reliability. Nevertheless, genus-level diatom tools remain a valuable option for biomonitoring in data-limited regions such as Cambodia, offering accessible and cost-effective solutions for local governments, stakeholders, and practitioners in managing freshwater ecosystems under increasing environmental pressures (Costa and Schneck 2022; Taurozzi et al. 2024). Although assigning ecological categories to each diatom genus or higher taxonomic group would allow more precise interpretation of specific environmental pressures (e.g., eutrophication, industrial pollution, climate change), the current genus-level assignments represent a novel approach in tropical Southeast Asian rivers and effectively capture key water quality gradients, providing a practical framework for initial ecological assessment in a data-scarce environment and laying the groundwork for future species-level enhancements.

Conclusion

The current study demonstrated the applicability and consistency of diatom indices at the genus level of identification for water quality assessment in the Sangker River basin, as well as their prospective application in other Cambodian river systems. The generic diatom index (GDI) clearly described a pattern of water quality along the Sangker River, showing on the one hand the decrease of the water quality from upstream to the Tonle Sap floodplain and on the second hand the importance of seasonal change in water quality, emphasizing the environmental characteristics of tropical river systems. As a result, these findings validated the use of diatom-based techniques at the first stage of identification to assess the health of the Sangker River ecosystem. Furthermore, eutrophication and nutrient pollution were the key drivers of GDI and degradation in Cambodian river ecosystem health. Thus, regulating nutrient inputs to the water system would help improve the health of Cambodia's river ecosystems. Nonetheless, the study recommended further research into the ecological sensitivity of diatom flora in Cambodian water systems in order to alter and localize GDI values, as the current GDI computations were slightly strict, reducing the ecological condition of river systems. Furthermore, additional investigations into the specific effects of other physicochemical parameters such as temperature, pH, total suspended solids (TSS), and electrical conductivity (EC) could be an attractive avenue for future research. Last but not least, long-term biomonitoring using diatom-based tools was recommended for developing countries in order to create a smart and flexible river basin management strategy to restore and preserve river ecosystem health in the face of rapid global climate change.

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Declarations

Ethical approval This is not applicable.

Consent to participate This is not applicable.

Consent for publication All authors have read and approved the manuscript and provided consent to publish.

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