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RESEARCH

Spatial and seasonal dynamics of desmid communities in relation to water quality in a shallow connected reservoir-waterway system in Northern Thailand

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Background: Desmids are sensitive bioindicators whose community composition is influenced by spatial and temporal influences. However, the interaction of these elements in interconnected tropical freshwater systems remains inadequately understood. This study examined the spatial and seasonal dynamics of desmid communities related to water quality in a shallow, interconnected reservoir-waterway system in northern Thailand to discover the main drivers of their community shifts.
Results: Our findings revealed that seasonal dynamics, were the primary factors influencing both water quality and the desmid community, surpassing spatial variations across habitats. The system experienced distinct seasonal disturbances: the summer/hot-dry season triggered a pollution pulse characterized by elevated temperature, biochemical oxygen demand, turbidity, ammonium nitrogen and chlorophyll-*a* concentration, while the rainy season was marked by a significant surge in coliform bacteria. This seasonal disturbance directly affected the desmid community. The waterway exhibited markedly reduced density in both abundance and diversity compared to the reservoirs. The composition of the community was markedly different: the Upper Reservoir supported a stable population dominated by *Staurastrum*, whereas the disturbed waterway and the downstream Lower Reservoir were dominated primarily by the resilient genus *Closterium*. Multivariate studies (non-metric multidimensional scaling and canonical correspondence analysis) confirmed that the community shift during the rainy season was statistically significant and closely linked to indications of organic pollution (fecal coliforms), with species such as *Closterium acutum* var. *variabile* serving as major indicators of these disturbed conditions.
Conclusions: This research underscores the significant influence of seasonal event-driven pollution on the ecological integrity of tropical freshwater systems. The response of the desmid community composition suggests its potential as a sensitive bioindicator for assessing ecosystem health. Our results underscore the critical need for watershed management strategies adapted to address the distinct environmental pressures present during both the hot-dry and rainy seasons to preserve the biodiversity of these vital aquatic ecosystems.

Keywords: bioindicators, desmids, monsoon pollution, reservoir-waterway system, seasonal dynamics, water quality

Introduction

Wetland habitats provide essential resources and support ecotourism (Wang et al. 2019). They play a crucial role in biodiversity conservation by maintaining species diversity and ecosystem complexity (Thorslund et al. 2017). Furthermore, wetlands contribute to economic and environmental stability through water purification, drought mitigation, flood regulation, groundwater recharge, storm protection, climate stabilization, erosion control, and nutrient retention (Marazzi et al. 2019). In addition, urban wetlands offer aesthetic, recreational, and ecological services, providing habitats for birdwatching, fishing, canoeing and breeding grounds for fish, invertebrates, and birds (Murungweni

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2013). Despite their importance, wetlands worldwide face major threats from anthropogenic activities such as drainage, agriculture, urbanization, mining, and climate change (Adeeyo et al. 2022; Xu et al. 2019; Zhu et al. 2022). These disturbances lead to habitat loss, declining aquatic biodiversity, and water quality degradation, affecting both ecosystems and local livelihoods (Hempattarasuwan et al. 2021; Ostad-Ali-Askari 2022). Alarmingly, more than 80% of the world's wetlands have been lost or degraded, with economic and environmental pressures being the main drivers and Asia experiencing the most severe losses (Adhya and Banerjee 2022). In Thailand, wetlands cover only 7.5% of the land area and are increasingly vulnerable to changes in land use. Kwan Phayao and Nong Leng Sai, the largest freshwater reservoirs in northern Thailand, are particularly susceptible to deterioration of water quality due to human activities (Kulsoontornrat and Ongsomwang 2021).

As key primary producers, freshwater algae make a major contribution to aquatic biodiversity and ecosystem stability. Furthermore, many algal species serve as effective bioindicators of water quality (Coesel and Meesters 2007). Desmids, a diverse group of phytoplankton with 2,943 documented species (Guiry and Guiry 2021), are particularly sensitive to environmental changes. Characterized by symmetrical cell division into two semicells separated by a constriction, desmids possess well-developed chloroplasts with pyrenoids, essential for carbon fixation and starch storage (Coesel 2001). Their preference for oligotrophic waters makes them valuable indicators of ecosystem health (Choudhary et al. 2021). Although previous studies have explored the relationship between water quality and desmid diversity in northern Thailand, the distinct ecological dynamics within interconnected systems, which include both lentic (reservoir) and lotic (waterway) habitats, are still not completely understood. The desmid community structure is significantly influenced by the interaction between spatial habitat differences and strong seasonal fluctuations, such as monsoon-driven pollution incidents, which shapes the desmid community structure and is a critical knowledge gap. Therefore, this study aimed to investigate the spatial and seasonal dynamics of the desmid community in relation to water quality in a shallow, connected reservoir-waterway system in northern Thailand. The main objectives were to (1) characterize and compare the desmid community structure and water quality among the different habitats and seasons, and (2) identify the key environmental drivers responsible for major community shifts. The findings of this study will provide crucial information on the ecological resilience of tropical freshwater systems and highlight the primary factors that threaten their biodiversity.

Materials and Methods

Research sites

Water sampling was carried out for 12 months from January to December 2022 to evaluate the physical, chemical, and biological parameters and biodiversity of desmid algae. In total, 10 sampling stations were specified: three stations located in the Upper Reservoir (Nong Leng Sai stations 1–3), four located on the waterway starting from the Upper Reservoir to the Lower Reservoir (stations 4–7), and three located in the Lower Reservoir (Kwan Phayao stations 8–10), as shown in Figure 1.

Analysis of physico-chemical and biological parameters of the water

Physico-chemical parameters

Surface water samples were collected in separate polyethylene bottles. After being packaged, the bottles were sent to a laboratory for analysis of physicochemical and biological parameters. The water temperature, pH, and electrical conductivity (EC) of each sampling site were measured *in situ* using a CyberScan PCD 650 multiparameter meter (Eutech Instruments, Singapore). During the laboratory studies, turbidity was measured using a turbidity meter (Thermo Scientific, Waltham, MA, USA). Nitrate nitrogen NO_3–N), ammonia nitrogen NH_4–N), and orthophosphate PO_4^{3-} parameters were determined using a HACH spectrophotometer model 880 (HACH, Loveland, CO, USA). Dissolved oxygen (DO) and biochemical oxygen demand (BOD) were determined using the azide modification technique (APHA 1995).

Biological parameters

(1) Photosynthetic pigment analysis (chlorophyll-a)

The water sample (500 mL) from each site was passed through Whatman GF/C glass fiber filters using a vacuum filtration system. The remaining material on each filter was extracted with 10 mL of methanol (90% v v^{-1}), then inoculated at 70°C for 20 min. After 10 min of centrifugation at 3,000 rpm, the supernatants were transferred to quartz cuvettes and the absorbance was measured at 630, 645, 665, and 750 nm using a UV-VIS spectrophotometer (Thermo Fisher Scientific, Dreieich, Germany). The chlorophyll-*a* concentration was calculated using the equation (Saijo 1975; Wintermans and De Mots 1965):

$$\text{Chl-}a\ (\mu\text{g mL}^{-1}) = \frac{[11.6\ (A_{665}\text{-}A_{750})\ \text{-}\ 1.31(A_{645}\text{-}A_{750})\ \text{-}\ 0.14\ (A_{630}\text{-}A_{750}) \times \text{methanol (mL)}}{\text{Volume of filtered water (L)} \times 1\ \text{cuvette}}$$

Where:

- Chl-a (μg mL^{-1}) = Chlorophyll-*a* concentration in micrograms per milliliter.
- A = Absorbance values at wavelengths 665 nm, 645

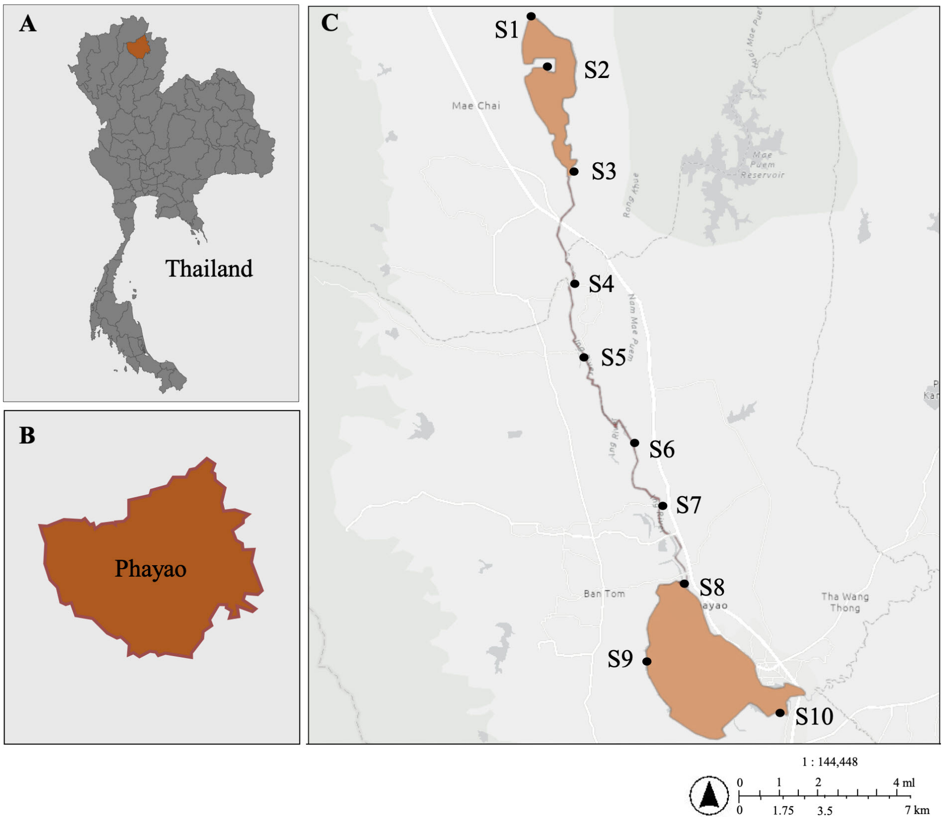

Fig. 1 Map of study area and sampling locations in Phayao Province, Thailand. (A) Location of Phayao province (highlighted in orange) in northern Thailand. (B) Boundary map of Phayao province. (C) Map of Upper (Nong Leng Sai Reservoir) - Lower (Kwan Phayao Reservoir) connecting system showing 10 sampling stations (S1–S10).

nm, 630 nm, and 750 nm, respectively, measured by a spectrophotometer.

- Methanol (mL) = Volume of methanol used to extract chlorophyll from the sample, in milliliters.
- Volume of filtered water (L) = Volume of water sample filtered to collect phytoplankton, expressed in liters.
- 1 cuvette = Refers to the standard path length of the cuvette used in spectrophotometric measurement (typically 1 cm).

(2) Total coliform bacteria (TCB) and fecal coliform bacteria (FCB)

The water samples were collected using 150 mL sterilized amber glass bottles. Samples from each site were determined for TCB and FCB using the most probable number (MPN) counts and the multiple tube fermentation technique (Clesceri et al. 2005).

Water quality index (WQI)

The Thailand WQI was used to evaluate water quality by aggregating many measurable factors into a single index. Five parameters were used to calculate the Thailand WQI (DO, BOD, TCB, FCB, and NH_4–N). Surface water quality was classified into five categories: Class 1, excellent, extra-clean water quality (score 91–100); Class 2, good, very clean water quality (score 71–90); Class 3, medium water quality (score 61–70); Class 4, unsuitable water quality (score 31–60); and Class 5, very unsuitable water quality (score 0–30), based on Pollution Control Department (1994).

Study of desmids algae

Desmids samples were collected using the squeezing method (Coesel 2001); subsequently, samples were preserved in amber bottles with a solution of Lugol's iodine solution (Ngearnpat and Peerapornpisal 2007). A desmid count was performed using the whole count method (Ngearnpat et al. 2018) in which 0.02 mL of sample was analyzed under a light microscope in triplicate (objective ×40). The taxonomic identification of desmids was based on Flora of New Zealand: Desmids Vols. l, ll and lll (Croasdale and Flint 1986, 1988; Croasdale et al. 1994) and other tropical publications, such as Ling and Tyler (2000), Vyverman (1991) and Desmids of Southeast Asia (Kanetsuna and Yamagishi 2018).

The phytoplankton diversity index consists of the Shannon diversity index, the Simpson diversity index, the Pielou evenness index, the species richness (Margalef) index, and the dominance index that were evaluated according to the methods described in the literature in Table 1.

Statistical data analysis

Data for the physicochemical and biological parameters were analyzed using one-way analysis of variance and the difference between means was evaluated using Duncan's new multiple range test at a significance level of 0.05 using the SPSS program. To analyze the desmid community structure, several multivariate techniques were employed using PAST software (version 4.11). Hierarchical cluster analysis, based on the Bray-Curtis similarity index, was used to assess the similarity among desmid communities

Table 1 Biodiversity indices and their formulas applied in desmid algae ecological analysis

Index	Formula
Shannon's diversity index (H′) (Shannon 1948)	$-\sum_{i=1}^{S}(P_i)(\mathrm{Ln}P_i)$
Simpson's index (Simpson 1949)	$1-\left[\frac{\Sigma n_i(n_i-1)}{N(N-1)}\right]$
Pielou Evenness index (Pielou 1966)	$H' \times [\ln(S)]^{-1}$
Species richness (Margalef index) (Türkmen and Kazancı 2010)	$(S-1) \times [\ln(N)]^{-1}$
Dominance index (Simpson 1949)	$\sum(n_i/N)^2$

S: total number of species observed in the sample; P_i: proportion of individuals belonging to the *i*th species, calculated as n_i/N; n_i: number of individuals of the *i*th species; N: total number of individuals across all species in the sample; ln: natural logarithm; s: number of species.

across different locations and seasons. Non-metric multidimensional scaling (NMDS) was applied to visualize the overall patterns of community structure. Finally, canonical correspondence analysis (CCA) was performed to identify the key environmental variables that were most strongly associated with the variation in desmid species composition.

Results

Spatial and seasonal variation of water quality

Physicochemical and biological parameters demonstrated significant spatial and seasonal variations in the three groups of ecosystems, the Upper Reservoir, the Connecting Waterway and the Lower Reservoir (Fig. 2). The results showed significant effects of the relationships between location and season for most parameters, revealing that the seasonal dynamics differed markedly between the waterway and the reservoirs.

Physical and chemical parameters

A distinct spatial gradient for DO was observed. In the summer and rainy seasons, the DO levels in the Connecting Waterway and the Lower Reservoir were much lower than those in the Upper Reservoir ($p < 0.05$) (Fig. 2A). Conversely, the BOD was markedly reduced in the Upper Reservoir throughout the cool-dry season, indicating a decreased organic load compared to the other two sites. During summer, elevated levels of BOD were observed throughout all three ecological groups (Fig. 2B). The temperature had a typical seasonal trend, reaching its maximum during the summer in all locations. EC was often elevated in summer and decreased during the rainy season, apparently according to the dilutive impact of rainfall (Fig. 2E). Spatially, the Upper Reservoir often maintained a lower EC compared to the downstream sites. Turbidity was markedly elevated during the summer/hot-dry season in all three habitat groups compared to the other seasons (Fig. 2F). The pH exhibited seasonal variation, often reaching its highest point in summer and lowest during the rainy season, a trend that was statistically significant in the Waterway and Lower Reservoir (Fig. 2C).

Nutrients and biological indicators

Nutrient dynamics exhibited distinctive trends for different nitrogen forms, while orthophosphate remained constant. Ammonium nitrogen (NH_4^+-N) concentrations reached a notable maximum throughout the summer at all sites. The Upper Reservoir had markedly lower ammonium concentrations compared to the downstream waterway throughout the cool-dry and rainy seasons. Nitrate (NO_3^--N) had a distinct seasonal pattern, with the highest levels frequently recorded during the cool-dry season, especially in the Upper Reservoir. In summer, nitrate levels decreased, and Upper Reservoir had a lower quantity than the other two locations. A major finding was the stability of orthophosphate (PO_4^{3-}). Although there were differences in other parameters, orthophosphate concentrations did not show statistically significant changes in any location or season, indicating that its availability may be regulated by distinct processes within the system.

The biological indicators revealed that the rainy season was a period of maximum ecological stress. In addition, its height reaches during the rainy season for all geographical groups. The TCB did not show significant geographical variations throughout the year. However, the highest count was observed in the Lower Reservoir during the cold dry season. Chlorophyll-*a* concentrations increased in the summer, especially in the Lower Reservoir, indicating that elevated temperatures and steady conditions throughout this season promoted optimal phytoplankton growth.

Evaluation of WQI

The comprehensive assessment of water quality, using the Thailand WQI, indicated major variations affected by seasonal changes rather than spatial differences (Fig. 3). The WQI scores ranged from Medium to Unsuitable across all situations, with no locations achieving Good or Excellent ratings. Throughout the year, both the Upper and Lower Reservoirs consistently exhibited significantly higher water quality ($p < 0.05$) compared to the Connecting Waterway. The reservoir systems are typically rated within the "Medium" quality category, indicating a more stable and resilient environment.

A clear seasonal pattern was observed throughout all habitat groups. The highest WQI values, indicative of superior water quality, were observed during the cool-dry season. A notable decline in water quality occurred throughout the summer/hot dry season, with WQI values decreasing to their lowest at all three sites. The decrease was most evident in the Connecting Waterway, where the water quality categorically dropped to the Unsuitable rating. In the rainy

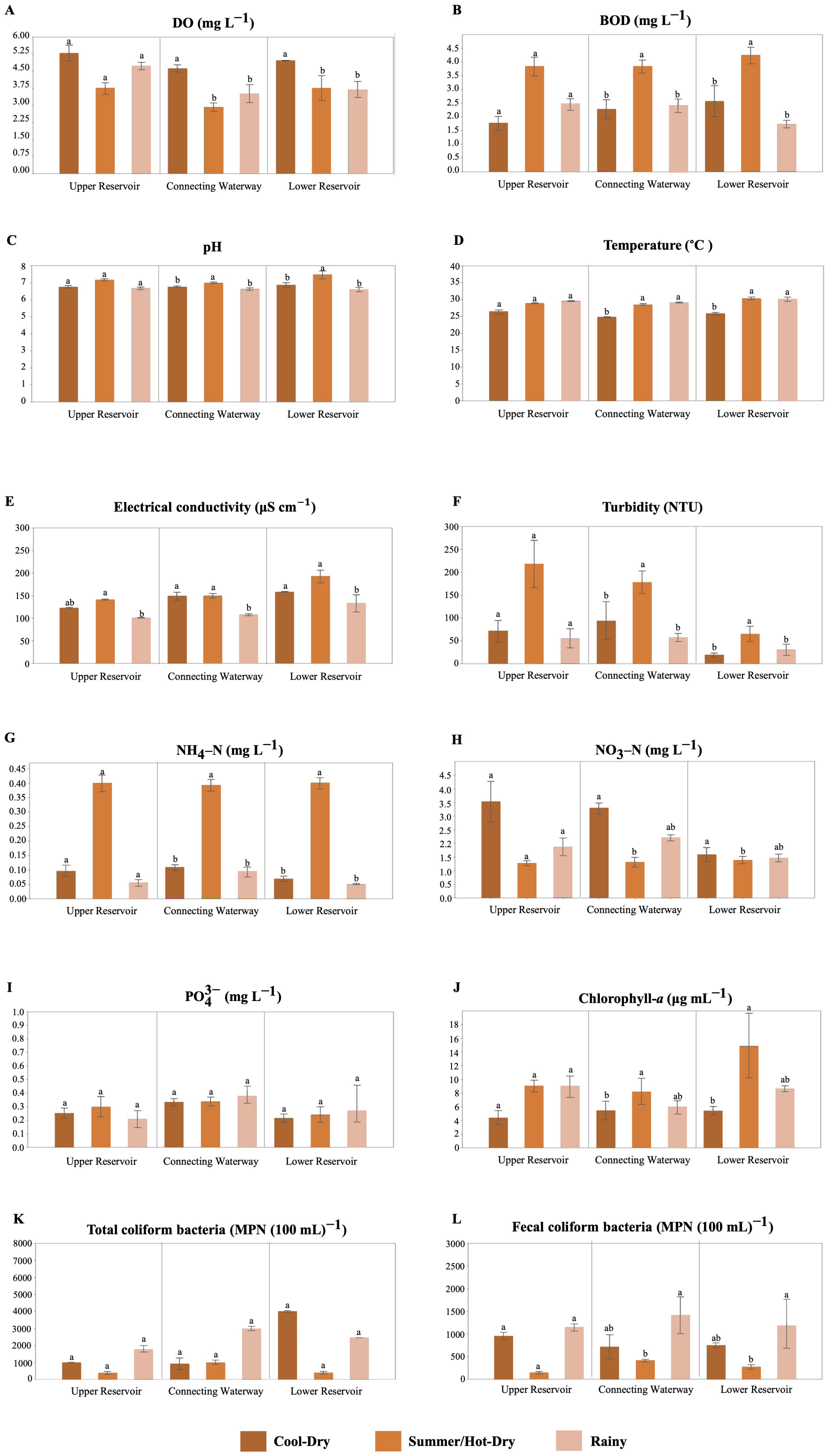

Fig. 2 Comparison of physicochemical and biological parameters across three ecosystem groups (Upper Reservoir, Waterway, Lower Reservoir) and three seasons (Cool-Dry, Summer/Hot-Dry, Rainy). Panels show mean values for (A) dissolved oxygen (DO), (B) biochemical oxygen demand (BOD), (C) pH, (D) temperature, (E) electrical conductivity, (F) turbidity, (G) ammonium, (H) nitrate, (I) orthophosphate, (J) chlorophyll-*a*, (K) total coliform bacteria, and (L) fecal coliform bacteria. Error bars represent the standard deviation. Within each parameter, bars with different letters indicate a statistically significant difference within the ecosystem group (Duncan's multiple range test, $p < 0.05$). MPN: most probable number.

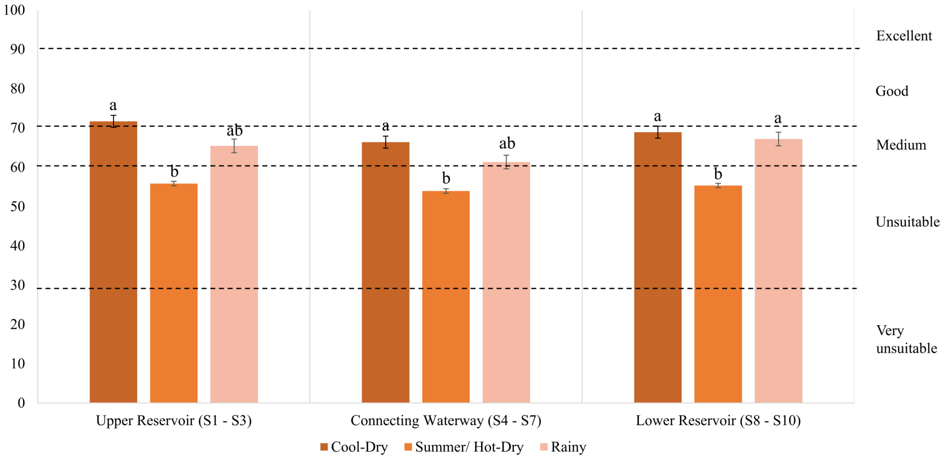

Fig. 3 Spatial and seasonal variation of the water quality index. Bars represent the mean score for each ecosystem group across three seasons. Error bars indicate the standard deviation. Bars with different letters are significantly different within the ecosystem group (Duncan's test, $p < 0.05$).

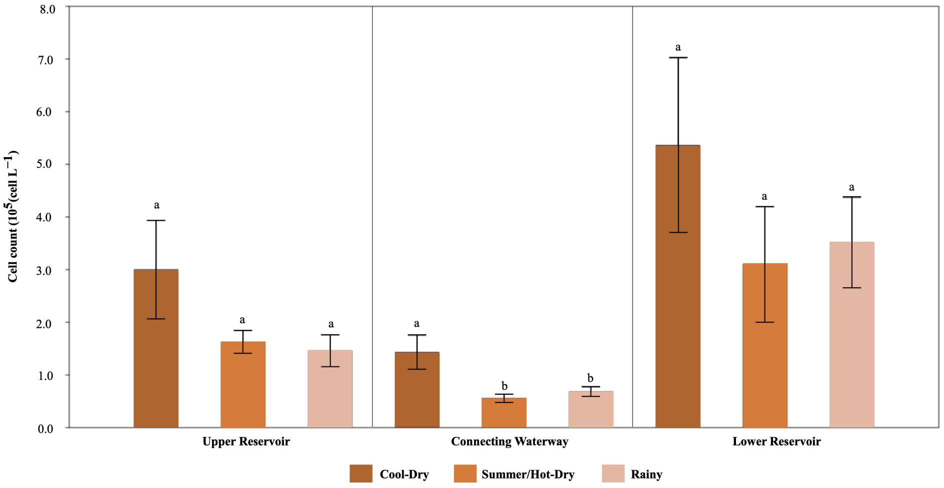

Fig. 4 Comparison of desmid cell density across the Upper Reservoir, the connecting waterway and the Lower Reservoir during three seasons. The error bars represent the standard deviation. Bars with different letters are significantly different within the ecosystem group (Duncan's test, $p < 0.05$).

season, a slight improvement in WQI was detected across all groups compared to summer, however, scores did not revert to the elevated levels seen during the cool-dry season.

Spatial and seasonal dynamics of the desmid community

Taxonomic overview

In total 10 genera and 70 species were identified and grouped into four families. The Mesotaeniaceae included one genus, *Roya*, with one species (1.40%). The Gonatozygaceae contained one genus, *Gonatozygon*, with one species (1.40%). The Closteriaceae consisted of one genus, *Closterium*, with 18 species (25.35%). The Desmidiaceae comprised seven genera: *Actinotaenium* with two species (2.81%), The *Cosmarium* with 20 species (28.16%), *Euastrum* with one species (1.40%), *Micrasterias* with one species (1.40%), *Spondylosium* with one species (1.40%), *Staurastrum* with 21 species (29.57%) and *Staurodesmus* with four species (5.63%). The dominant species in this study was *Closterium acutum* var. *variabile*, while several species had significant distributions or relative frequencies: *C. acutum* var. *variabile*, *Staurastrum bloklandiae*, *Closterium gracile*, *Closterium limneticum*, *Staurastrum tetracerum*, *Closterium moniliferum*, and *Euastrum biverrucosum*. Collectively, these species accounted for 65% of the relative frequency and therefore were classified as Common-to-Abundant.

Desmid abundance and diversity indices

Reflecting the patterns observed in the water quality parameters, considerable spatial and seasonal variations were observed in the abundance and diversity of the desmid community. The abundance of desmid, measured by cell density, was considerably lower in the Connecting Waterway than in the Upper and Lower Reservoirs during all seasons. The Lower Reservoir recorded the highest abundance (536,121 cells L^{-1}) during the cool-dry season, while the reservoir systems maintained relatively high and stable cell densities. In contrast, the waterway maintained a significantly reduced population throughout the year, with densities decreasing to a minimum of 60,417 cells L^{-1} during the summer. This represents a nearly ninefold reduction in comparison to the reservoir's peak abundance (Fig. 4).

The diversity indices also highlighted the distinct and stressful conditions within the waterway. The Shannon (H′) diversity and Margalef (d) richness indices were consistently and significantly lower in the Connecting Waterway, particularly during the summer and rainy seasons. For example, the Shannon index on the waterway decreased to a minimum of 0.29 during summer, while Lower Reservoir reached its highest diversity of 1.49 during the rainy season. Similarly, the species richness of the waterway was notably low (d = 0.07–0.08) during the summer and rainy seasons. In contrast, the Dominance Index (C) was maximal in the Connecting Waterway, with a value of 0.79 in summer. This suggests that adverse conditions on the waterway, probably associated with pollution incidents, eliminated sensitive species, allowing only a limited number of tolerant taxa to flourish and dominate the ecosystem. A notable observation was that, despite low species richness and diversity, the Evenness (J′) index in the waterway was surprisingly the highest reported (0.98–0.99) (Table 2). This indicates that although only a limited number of species could survive in the waterway, those that did distributed in relatively equal numbers, with no single species significantly outcompeting the others.

Community composition

The study of relative abundance at the genus level indicated different community structures across the three habitat groups (Fig. 5). The Upper Reservoir had a stable, co-dominant community. Throughout all seasons, the genera *Staurastrum* (47%–53%), *Closterium* (33%–37%) and *Cosmarium* (8%–12%) consistently comprised the majority of the community. In contrast, the Connecting Waterway was dominated by a single genus, *Closterium*. This dominance was most apparent during the summer/hot-dry season, where *Closterium* constituted 83% of the overall population. While *Staurastrum* was the second most abundant genus (17%–30%), the genus *Cosmarium*, which was dominant in the Upper Reservoir, was nearly absent. The community in the Lower Reservoir was mainly composed of *Closterium*, particularly during the cool-dry season (78%). During the summer, this ecosystem demonstrated a distinct seasonal shift, characterized by a reduction in *Closterium* dominance to 55%, with a notable rise in the relative abundance of *Staurastrum* to 41%.

Community structure and similarity

Hierarchical cluster analysis using the Bray-Curtis similarity score was performed to clarify the relationships between the desmid communities under varying geographical and seasonal conditions (Fig. 6). The analysis showed three separate main groups, indicating that the community structure was influenced by a complicated interaction between location and season.

The first and most prominent cluster included only the Lower Reservoir in the cool-dry season. This group was separated from all other circumstances at the lowest similarity threshold (approximately 45%), indicating it had the most distinctive desmid community structure among all conditions examined. The second cluster included the Connecting Waterway throughout the summer and rainy seasons. The two conditions exhibited a high degree of similarity and were distinctly separated from all reservoir conditions, indicating that the waterway environment during potential thermal stress (summer) and elevated runoff (rainy) promotes a unique and consistent desmid community. The third and largest cluster included a comprehensive integration of all six reservoir conditions (Upper and Lower Reservoirs throughout all three seasons) and, significantly, the Connecting Waterway during the cool-dry season. The incorporation of the cool-dry waterway into this large reservoir-dominated group is an important finding, indicating that under low-flow, dry conditions, the community structure in the waterway is similar to that of the more stable lentic reservoir ecosystems. Within this major cluster, all reservoir communities showed a high degree of similarity to each other, reinforcing the stability of the reservoir ecosystems compared to the dynamic waterway.

Community ordination and species-environment interactions

NMDS was utilized to illustrate an overall pattern of desmid community structure, whilst CCA was applied for understanding the principal environmental factors influencing this structure. The NMDS ordination indicated that seasonality was the predominant factor influencing the

Table 2 Spatial and seasonal variation in desmid diversity indices

Location group	Season	Index				
		Shannon (H′)	Simpson (D)	Evenness (J′)	Margalef (d)	Dominance (C)
Upper Reservoir (S1–S3)	Cool-Dry	1.11	0.18	0.82	0.31	0.44
	Summer	1.08	0.58	0.96	0.22	0.42
	Rainy	0.94	0.51	0.92	0.20	0.49
Connecting Waterway (S4–S7)	Cool-Dry	1.09	0.60	0.92	0.22	0.40
	Summer	0.29	0.21	0.99	0.08	0.79
	Rainy	0.48	0.29	0.98	0.07	0.67
Lower Reservoir (S8–S10)	Cool-Dry	1.21	0.59	0.73	0.35	0.41
	Summer	0.93	0.55	0.86	0.51	0.45
	Rainy	1.49	0.72	0.86	0.32	0.27

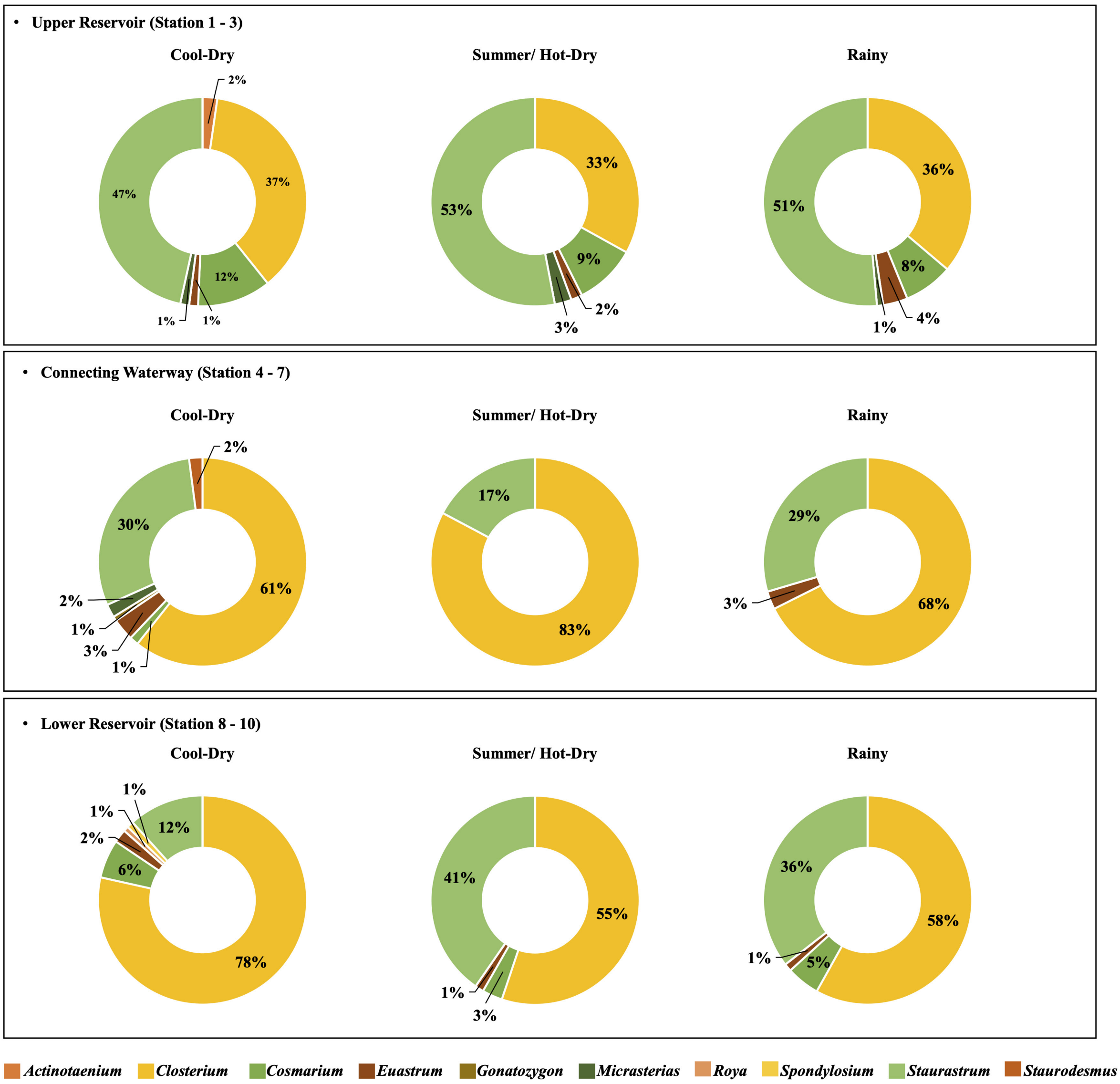

Fig. 5 Average relative abundance (%) of dominant desmid genera across the three ecosystem groups and seasons.

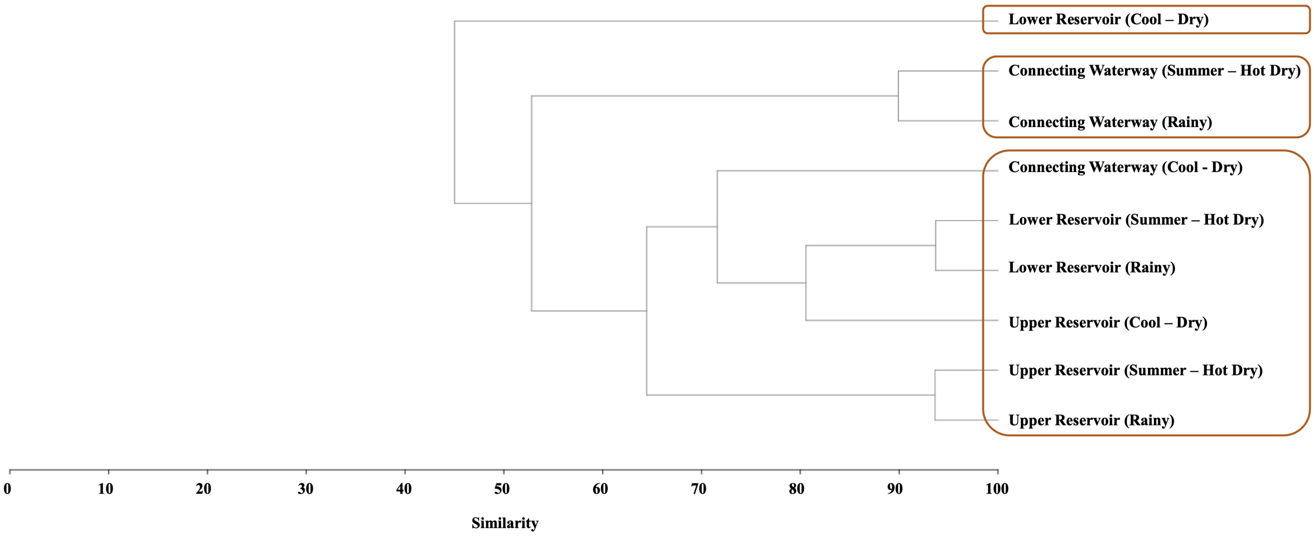

Fig. 6 Hierarchical cluster analysis dendrogram of desmid communities based on the Bray-Curtis similarity index. The dendrogram illustrates the similarity relationships among the nine environmental conditions (three locations × three seasons).

structure of desmid communities, rather than the specific location (Fig. 7). A clear separation was observed along the first axis (NMDS1), separating the communities of the dry seasons (cool-dry and summer) from those of the rainy season. The communities of the Upper Reservoir, the Connecting Waterway, and the Lower Reservoir throughout the cool-dry and summer seasons formed a large relatively compact cluster on the left side of the coordination space, indicating a high level of similarity. In contrast, the communities of the rainy season were clearly delineated on the right side, demonstrating a significant community shift influenced by the conditions of the rainy season.

The CCA further clarified the environmental factors responsible for this separation (Fig. 8). The investigation confirmed that the environmental variables evaluated significantly accounted for the variation in the composition of the desmid community. The coordination axes differentiated the communities according to the gradients of ecosystem production and specific types of pollution. The CCA ordination positioned the majority of the community samples within a large cluster on the left side of the plot. This major group was associated with high temperatures, chlorophyll-*a*, and BOD, with the communities therein exhibiting a strong correlation with a variety of co-occurring species, including *S. bloklandiae* and *C. limneticum.*

Conversely, particular communities were notably affected by a combination of organic pollution and nutrient enrichment. The Lower Reservoir in the cool-dry season and the Connecting Waterway in summer were located in the lower-left quadrant, exhibiting a strong relationship with the vectors for FCB, TCB, conductivity (EC), and orthophosphate (PO_4^{3-}). The conditions were closely related to the *C. acutum* var. *variabile* species. In addition, *C. gracile* inhabited a distinct niche at the lower end of the ordination space, indicating a preference for conditions that are not clearly represented by other groups. The *S. tetracerum* species was recognized as an outlier, significantly related to the unique conditions of the Upper Reservoir during the cool-dry season, characterized by high concentrations of nitrate and DO.

Discussion

This study demonstrates that the ecological dynamics of the interconnected reservoir-waterway system is primarily influenced by significant seasonal variations, which largely overwhelms the physical differences between the lentic reservoir and lotic waterway habitats. Our research reveals that this seasonal disruption serves as the principal environmental filter that influences both the overall water quality and the composition of the resident desmid community, demonstrating how event-driven processes can define ecosystem states in tropical freshwater systems.

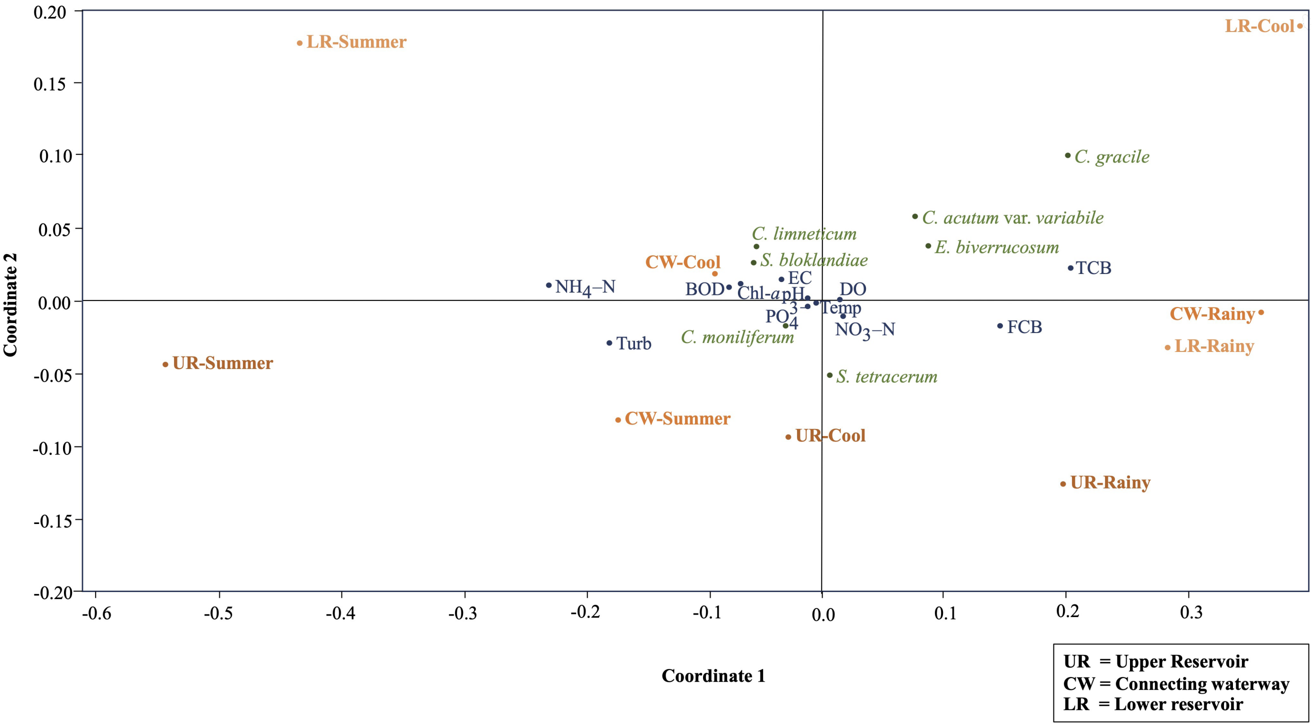

Fig. 7 Non-metric multidimensional scaling ordination of desmid communities. The plot shows the separation of community samples (brown-orange text), with key environmental variables (blue text) and dominant species (green text) plotted to show their correlation with the community structure. EC: electrical conductivity; DO: dissolved oxygen; BOD: biochemical oxygen demand; TCB: total coliform bacteria; FCB: fecal coliform bacteria; Chl-*a*: chlorophyll-*a*; Turb: turbidity; NH_4-N: ammonium nitrogen; NO_3-N: nitrate nitrogen; $PO^{3-}{}_4$: orthophosphate.

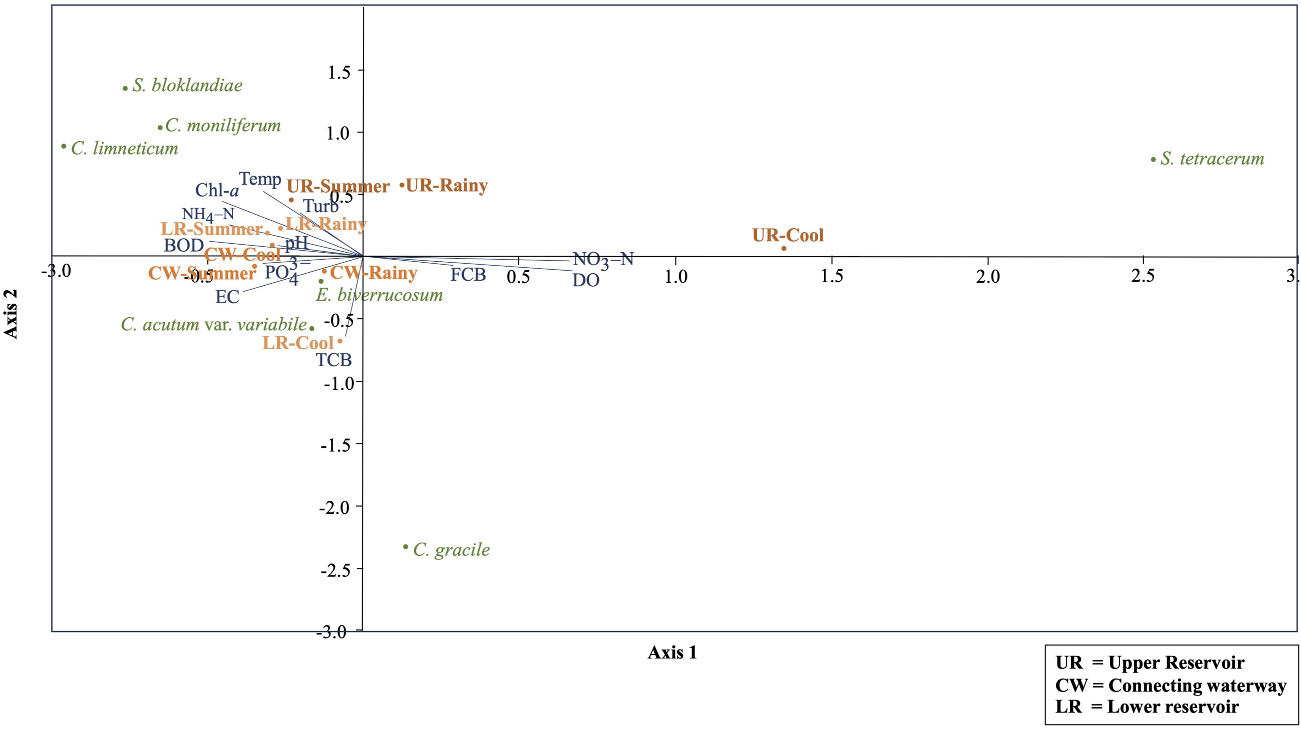

Fig. 8 Canonical correspondence analysis ordination diagram showing the relationships between environmental variables (black vectors), dominant desmid species (green text), and the community samples from each location and season (brown-orange text). EC: electrical conductivity; DO: dissolved oxygen; BOD: biochemical oxygen demand; TCB: total coliform bacteria; FCB: fecal coliform bacteria; Temp: temperature; Chl-*a*: chlorophyll-*a*; NH_4-N: ammonium nitrogen; NO_3-N: nitrate nitrogen; PO^{3-}_4: orthophosphate; Turb: turbidity.

Spatiotemporal water quality patterns and ecosystem stress

The notable seasonal changes in water quality parameters indicate that the summer/hot-dry season is a critical period of maximum ecological stress for all habitat groups. During this period, a cascade of interconnected environmental stressors occurs by a combination of elevated temperatures, reduced DO, increased BOD, and elevated ammonium concentrations. This seasonal pattern is consistent with previous studies conducted in tropical freshwater systems, where temperature-driven processes significantly influence biogeochemical cycling and ecosystem metabolism (Zeng et al. 2022).

The nitrogen dynamics discovered in our study are indicative of typical seasonal patterns in tropical reservoirs. The cool-dry season is suitable for the accumulation of nitrates as a result of efficient nitrification processes that occur under favorable oxygen conditions. The summer transition toward ammonium dominance indicates that the decomposition of organic matter and the potential depletion of oxygen are increased, mechanisms that further become accelerated by high temperatures (Fadum et al. 2024). The consistent stability of orthophosphate concentrations in all seasons and locations is particularly interesting, suggesting either strong internal phosphorus cycling or that the system operates under phosphorus limitation, a common characteristic of many tropical freshwater ecosystems (Li et al. 2022).

The increased stress from pollution during the summer periods is likely the result of concentrated waste input during low-flow conditions and enhanced bacterial survival in higher temperatures, as indicated by the increase in FCB. This pattern has major consequences for the management of water quality, as it illustrates the seasonal susceptibility of freshwater systems to microbial contamination (Díaz-Gavidia et al. 2022; Rochelle-Newall et al. 2015).

The different patterns of water quality observed in reservoir and waterway systems illustrate fundamental differences in ecosystem functioning between lentic and lotic environments. The DO levels were higher in the reservoirs compared to the connecting waterway. This could be related to the shallow depth and high aquatic vegetation cover that promoted light penetration and photosynthetic activity (Scheffer and van Nes 2007). The chlorophyll-*a* concentrations followed a similar trend, with increased values in lentic areas, particularly in the Lower Reservoir. This aligned with other findings that linked higher levels of chlorophyll-*a* with increased concentrations of DO, pH, and nutrients in standing water bodies (Manasrah et al. 2006; Zang et al. 2011).

The consistently elevated scores of the WQI in both the upper and Lower Reservoirs, in contrast to the Connecting Waterway, indicate the buffering capacity and self-purification abilities of reservoir systems, in accordance with other assessments in this region (Pinmongkhonkul et al. 2002; Soontornprasit and Khungboon 2017). The variation could be related to longer durations of hydraulic residence in reservoirs, which allows improved sedimentation, biological assimilation, and natural attenuation processes (Harvey and Schmadel 2021; Jones et al. 2017).

The Connecting Waterway's ranking as "Unsuitable" under summer conditions indicate the combined effects of decreased dilution capacity, concentrated pollution influx, and restricted self-purification during low-flow conditions (Boeraş et al. 2024). This geographical pattern highlights the susceptibility of flowing water systems to point- and non-point source contamination, especially during times of environmental stress. The intermediate water quality status of the Lower Reservoir indicates its function as a transition zone, absorbing inputs from the affected waterway while preserving some reservoir-like characteristics (Smith et al. 2014).

Desmid community as a sensitive indicator of environmental changes

The desmid community served as a sensitive and direct indicator of environmental shifts, with its diversity reflecting the underlying gradients in water quality. The considerable difference in community composition between the Upper Reservoir and the Connecting Waterway illustrates this sensitivity. The high density of *Closterium* in the waterway and Lower Reservoir corresponds with reports that characterize this species as ruderal or r-strategists, flourishing in nutrient-rich, eutrophic environments which promote rapidly colonization of deteriorated habitats (Yusuf 2020). Their capacity to dominate the waterway, where the total cell density was almost nine times lower than in the reservoirs, indicates that while the environment was severe, it was very selective for the characteristics exhibited by *Closterium*. In contrast, the abundance of *Staurastrum* in the relatively undisturbed Upper Reservoir aligns with its classification as a K-strategist, preferring cleaner, more stable, oligotrophic to mesotrophic environments where competitive ability is prioritized over rapid growth (Barbosa et al. 2013).

The CCA also identified certain indicator species, providing a more detailed understanding of these relationships. The productivity gradient, characterized by the temperature-chlorophyll-*a*-BOD axis, reflects the fundamental importance of metabolic processes in determining the composition of the community. High-temperature conditions promote both primary productivity (evident from elevated chlorophyll-*a*) and decomposition processes (reflected in increased BOD) (Richardson et al. 2019), creating a complex environment that favors different species assemblages. The pollution gradient, defined by coliform bacteria, conductivity, and orthophosphate, represents anthropogenic impacts on the structure of the community. The positioning of specific communities along this gradient provides clear evidence for the bioindicator potential of desmid species.

Closterium acutum var. *variabile* demonstrated a strong correlation with high-pollution conditions (TCB, FCB, PO_4^{3-}), therefore supporting its utility as an indicator of organic pollution and eutrophication. This species is recognized for its wide ecological tolerance and its ability to flourish in an extensive range of trophic states (Coesel 1993; Lenard and Ejankowski 2017). Its occurrence in diverse freshwater environments, including those in Thailand (Ngearnpat and Peerapornpisal 2007) and Amazonian lakes (França et al. 2011). A notable contrast was the elevated evenness (J′) in the waterway, despite its relatively low Shannon diversity (H′ = 0.29) and the high dominance (C = 0.79) under summer conditions. This demonstrates that the severe climatic situation functioned as an important "ecological filter," eliminating the majority of species (Jiang et al. 2025). The limited number of highly tolerant species that survived were unable to outcompete each other, possibly due to the primary limitation being external environmental stress rather than resource competition. This could occur in severely disturbed or contaminated ecosystems where constant stress prevents any species from achieving complete dominance over the other survivors (Siegel et al. 2023).

Conclusions

This study effectively characterized the spatial and seasonal dynamics of the desmid community within an interconnected tropical freshwater system, demonstrating that seasonal event-driven pollution is the main driver influencing the ecosystem, surpassing the inherent differences between reservoir and waterway habitats.

The summer/hot-dry season, in particular, triggered a significant pollution pulse within the connecting waterway, characterized by elevated temperature, BOD, EC, turbidity, ammonium and chlorophyll-*a* concentrations. This pulse was reflected in deteriorated water quality and a marked shift in the structure of the desmid community, while the rainy season introduced a distinct disturbance characterized by a significant increase in TCB and FCB.

Our results highlight the significant importance of desmid communities as sensitive bioindicators of ecological integrity. The evident contrast between the stable *Staurastrum* dominated community of the less disturbed Upper Reservoir and the low-diversity *Closterium*-dominated community in the severely impacted waterway suggests that they are a promising biological tool for evaluating ecosystem health. In addition, the identification of specific indicator species, such as *C. acutum* var. *variabile* in polluted environments, provides a more detailed approach for assessing environmental stress.

This study emphasizes the important susceptibility of tropical freshwater systems to non-point source contamination originating from the surrounding watershed. The direct link between seasonal runoff and the influx of pollutants underscores the urgent need for improved watershed management strategies to alleviate the effects of agricultural and community waste. Protecting the biological integrity and biodiversity of these important aquatic habitats requires controlling pollution at its source, with management strategies tailored to address the distinct environmental pressures present during both the hot-dry and rainy seasons.

Abbreviations

EC: Electrical conductivity
DO: Dissolved oxygen
BOD: Biochemical oxygen demand
TCB: Total coliform bacteria
FCB: Fecal coliform bacteria
WQI: Water quality index
NMDS: Non-metric multidimensional scaling
CCA: Canonical correspondence analysis
Chl-*a*: Chlorophyll-*a*
MPN: Most probable number
NH_4-N: Ammonium nitrogen
NO_3-N: Nitrate nitrogen
PO^{3-}_4: Orthophosphate
UR: Upper Reservoir
CW: Connecting Waterway
LR: Lower Reservoir

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Authors' contributions

KI was responsible for the experimental design, data analysis, and drafting all versions of the manuscript. NN primarily planned the project and prepared the first draft of the manuscript. RL and JW collected field data, performed experiments, and analyzed data. NW contributed to the manuscript drafting. All authors have read and approved the final manuscript for submission.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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