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Ecological Health Assessment in a Sub-Tropical Lake: Integrating Water Quality Index with Multivariate Statistical Methods

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Research Article

Keywords: Kaptai lake, artificial lake, drinking water, public health, productivity, aquatic ecosystem

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Ecological Health Assessment in a Sub-Tropical Lake: Integrating Water Quality Index with Multivariate Statistical Methods

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Abstract

This study provides a comprehensive ecological health assessment of Bangladesh's Kaptai Lake through an integrated analysis of physicochemical and biological parameters across pre-monsoon, monsoon, and post-monsoon seasons. Data from five monitoring stations revealed significant seasonal variations, with the pre-monsoon period characterized by peaks in NH_3 (0.16 ± 0.04 mg L^{-1}), phytoplankton density ($14.28\pm1.52\times10^5$cells L^{-1}), and gross primary production (3.38 ± 0.30 g C m^{-2} d^{-1}), while post-monsoon exhibited maximum DO (6.56 ± 0.27 mg L^{-1}) and conductivity (112.6 ± 12.57 µS cm^{-1}). Spatial analysis identified distinct gradients, including significantly higher DO at Langadu (7.05 ± 0.46 mg L^{-1}, $p<0.01$) and WQI values indicated comparatively poorer water quality conditions at Naniarchar, although spatial differences were not statistically significant. Multivariate analysis identified mineralization and productivity gradients as major sources of environmental variability, with the first two principal components explaining 46.8–60.1% of the total variance. Ecosystem health assessment using the Direct Measurement Method (DMM) ranked post-monsoon conditions as the most favorable, with Kaptai Dam station maintaining the healthiest balance (Bz/Bp=0.48, structural Exergy=28.32 MJ mg^{-1}). Overall, WQI indicated generally favorable water quality conditions for aquatic life. The successful application of WQI coupled with DMM indicators demonstrates

that the lake is seasonally influenced by anthropogenic activities, highlighting the critical need for targeted management strategies to mitigate seasonal water quality deterioration and maintain critical ecosystem services in this economically vital freshwater resource.

Keywords: Kaptai lake, artificial lake, drinking water, public health, productivity, aquatic ecosystem

Introduction

Lakes are among the world's most vital freshwater resources, providing essential ecosystem services (Fardullah et al. 2025), including acting as a sink for contaminants. They also serve as critical sources of freshwater, supporting recreation and diverse aquatic habitats (Das et al. 2024). However, subtropical lakes and reservoirs across South and Southeast Asia are increasingly experiencing ecological pressure from land-use change, nutrient loading, and hydrological variability, threatening fisheries productivity and ecosystem services. Kaptai Lake, the largest artificial freshwater lake in Southeast Asia, exemplifies a multifunctional tropical water body with global ecological importance due to its rich biodiversity (Rana et al. 2025). Originally constructed for hydroelectric power generation in 1961 (Lima et al. 2023), the lake has become indispensable to local communities, sustaining fisheries, transportation, water supply, flood control, tourism, and irrigation (Suman et al. 2021). It covers an area of approximately 68,800 hectares, with a water surface area of 58,300 ha and an average depth of 9 m (maximum 32 m). This lake serves as the primary freshwater source for surrounding populations, who depend on it for domestic use, and other livelihood activities (Barua et al. 2016; Lima et al. 2023).

Artificial lakes across Asia increasingly support aquaculture and fisheries (Suman et al. 2021) . Kaptai Lake, a major reservoir system in this region, hosts diverse fish populations, including 74 species - six exotic and numerous small indigenous species (SIS) - that support small-scale fisheries (Suman et al. 2021; Rahman et al. 2024). In 2020–2021, it contributed 4.62 million metric tons of fish (0.27% of national production). The Clupeidae fishes, including *Gudusia chapra* (Indian River Shad), *Gonialosa manminna* (Ganges River Gizzard Shad), and *Corica soborna* (Ganges River Sprat), are found year-round in the Lake and are the most abundant, nutritious, and commercially important SIS there (Rahman et al. 2024). The lake's nutrient-rich waters support plankton growth, a vital food source for fish larvae, while its sediments facilitate nutrient cycling and plant growth (Rana et al. 2025).

However, pollution from agricultural runoff, domestic wastewater, and anthropogenic pressures, such as urbanization, navigation, tourism, and infrastructure development, threaten its ecological health and water quality (Karmakar et al. 2011). Natural stressors, including landslides and sediment inflow, degrade habitats, with siltation reducing lake volume by 25% over 30 years. All these pressures have been associated with the reported loss of eight fish species and the endangered status of eight others (Suman et al. 2021). Despite these challenges, very few studies in the past decade have examined the changes in water quality and ecological status of the lake. Therefore, it was imperative to conduct a comprehensive study to assess the ecological health and water quality parameters of Kaptai Lake.

Water quality encompasses physical, chemical, biological, radiological, and aesthetic characteristics that collectively influence aquatic ecosystem functioning and resource use (Shil et al. 2019). Maintaining good surface water quality is essential for sustaining ecosystem services, fisheries productivity, biodiversity, and human use, as water quality deterioration can harm public health, and ecological stability (Karmakar et al. 2011). The Water Quality Index (WQI), a unitless value calculated from multiple parameters, simplifies water quality assessment and is widely used around the world (Shil et al. 2019); however, understanding temporal and spatial variation in water quality is also crucial for identifying ecological stress, pollution control, biodiversity conservation, and fisheries development in aquatic environments (Rana et al. 2025). Physical and chemical properties of water affect the abundance, distribution, and behavior of aquatic organisms, while plankton communities act as sensitive bioindicators of environmental changes and eutrophication (Aravinth et al. 2023) . Therefore, integrated assessments combining physicochemical and biological indicators are increasingly emphasized, as reflected in the European Water Framework Directive, which recommends evaluating multiple biological communities, including phytoplankton, macrophytes, phytobenthos, benthic invertebrates, and fish assemblages, to assess the ecological quality of lake ecosystems (Poikane et al. 2016) .

In this context, the study aimed to evaluate the seasonal and spatial variation of physicochemical and biological parameters in Kaptai Lake to assess its water quality, ecological health, and suitability for sustaining aquatic ecosystem functioning and fisheries using WQI, spatial distribution mapping, and interactions between plankton abundance and water quality. The study also aligns with Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water), by contributing baseline

knowledge for sustainable freshwater ecosystem management and aquatic resource conservation.

Materials and Methods

Study Area

Kaptai Lake, the largest freshwater lake in Bangladesh, is situated in the southeastern hills of Rangamati district (Figure 1). Constructed on the Karnaphuli River, the Kaptai Dam generates power through five units, producing 230 MW in total (Parveen and Faisal 2002) . Three primary rivers—the Kassalong, Chengi, and Myani—supply water to the reservoir. The lake is naturally divided into two zones by hilly terrain: the upper basin in the northeast, fed by the Kasalong and Myani, and the primary reservoir in the southwest, sustained by the Chengi (Lima et al. 2023).

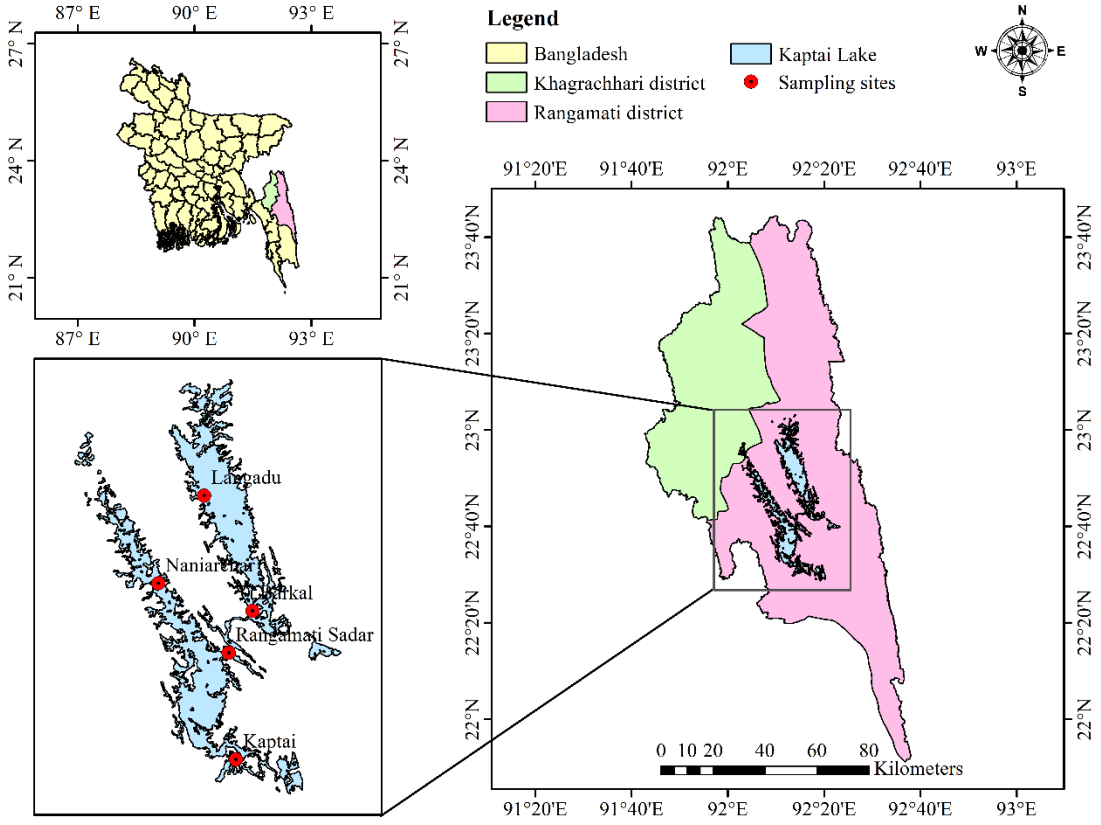


Figure 1. Sampling sites in Kaptai lake

Sampling points and sample collection

Water samples were collected during three seasonal periods—pre-monsoon, monsoon, and post-monsoon—from July 2021 to June 2022. Sampling was conducted monthly at five designated stations (Table 1), with two replicate samples collected at each station during each sampling event. The stations were selected to represent contrasting geographical and

hydrological conditions and based on accessibility. The limited number of stations relative to the lake's total area was primarily due to restricted accessibility in the hilly terrain and limited transportation resources.

Table 1. The sampling sites in Kaptai lake and their geographical coordinate locations

Site ID	Site names	Coordinates	
		Latitude	Longitude
RS	Rangamati Sadar	22.66482356	92.23948226
BK	Barkal	22.72025755	92.27107018
KP	Kaptai	22.52389977	92.24909555
LG	Langadu	22.87305556	92.20694444
NC	Naniarchar	22.75693015	92.14629609

Key water quality parameters, including temperature, electrical conductivity (EC), salinity, total dissolved solids (TDS), and pH, were measured on-site using a portable multiparameter meter (HANNA HI 98194). Dissolved oxygen (DO) levels were recorded with a portable DO meter (HANNA HI 9146), while water transparency was assessed using a Secchi disk (SD).

Samples were collected from approximately 20 cm below the water surface at representative locations within each station. After collection, the bottles were sealed tightly and transported to the laboratory under controlled cooling conditions (<4°C). Additional parameters—ammonia (NH_3-N), alkalinity, and hardness—were analyzed following established protocols (APHA 2005).

Plankton collection, identification, and counting

Plankton samples were collected by filtering 40 liters of water through a 25-µm-mesh plankton net. The concentrated samples were transferred to labeled bottles and transported to the laboratory for an initial examination. Following preliminary observation, samples were preserved with 5% buffered formalin and refrigerated at 4°C for further analysis. For identification and classification, samples were examined under an OLYMPUS CX22LED binocular microscope (Japan) using a Sedgwick-Rafter counting chamber. Taxonomic identification was performed using standard reference materials (Yamaji 1979; van Vuuren et al. 2006; Gopinathan et al. 2007). Phytoplankton density was quantified as the number of individuals or cells per unit volume. The abundance was calculated according to the method described by Stirling (1985) using the following formula-

$$N = \frac{A \times C \times 1000}{V \times F \times L} \quad (1)$$

Here,

N=Number of plankton cells or units per liter of original water; A=Total number of plankton counted; C=Volume of the final concentration of the sample in ml; V=Volume of a field =1 cu mm; F=Number of the field counted and L= Volume of original water in liter.

Primary productivity

Primary productivity was measured through the light-dark bottle technique, with samples incubated for three hours at peak daylight (11:00 a.m. to 2:00 p.m.). This approach relied on monitoring dissolved oxygen (DO) variations across three distinct bottle types: initial (IB), light-exposed (LB), and dark-incubated (DB) samples. The gross primary production (GPP), net primary production (NPP), and respiration (AR) were calculated equations adapted from (Britton and Greeson 1989),

$$\text{GPP (g C } m^{-2}\, d^{-1}) = (\text{LB} - \text{DB})/\text{T} \times 0.375 \times \text{D} \quad (2)$$

$$\text{NPP (g C } m^{-2}\, d^{-1}) = (\text{LB} - \text{IB})/\text{T} \times 0.375 \times \text{D} \quad (3)$$

$$\text{AR (g C } m^{-2}\, d^{-1}) = (\text{IB} - \text{DB})/\text{T} \times 0.375 \times \text{D} \quad (4)$$

Where, LB, DB, and IB represent the DO concentrations (mgL^{-1}) of the light, dark, and initial bottles, respectively.

T = the incubation time in hours (3 hours in this study)

0.375 = the O_2 to C conversion factor (Sreenivasan 1964)

D = photoperiod duration ($h\ d^{-1}$), used to convert hourly production estimates to daily rates (Trivedy and Goel 1984).

The water quality index (WQI)

The water quality index was calculated using the weighted arithmetic method, followed by (Brown et al. 1972). The weighted arithmetic water quality index (WQI) is represented in the following way:

$$WQI = \sum_{i=1}^{n} \frac{W_i Q_i}{W_i} \quad (5)$$

where n = number of variables or parameters, W_i = unit weight for the *i*th parameter, Q_i = quality rating (sub-index) of the *i*th water quality parameter. The unit weight (W_i) of the various water quality parameters is inversely proportional to the recommended standards for the corresponding parameters.

The value of quality rating or sub-index (Q_i) is calculated using the equation as given below:

$$Q_i = 100[(V_0 - V_i) / (S_n - V_i)] \quad (6)$$

where V_o = observed value of *i*th parameter at a given sampling site, V_i = ideal value of *i*th parameter in pure water, S_n = standard permissible value of *i*th parameter.

Here, $Q_i = 0$ implies complete absence of contaminants, while $0 < Q_i < 100$ implies that the contaminants are within the prescribed standard. And $Q_i > 100$ implies that the contaminants are above the standards. Hence, Numerical ranges of WQI status were classified into five classes namely Excellent (0–25), Good (26–50), Bad (51–75), Very Bad (76–100) and unsuitable (>100) (Brown et al. 1970; Chatterjee and Raziuddin 2002).

Aquatic Ecological Health Assessment

The direct measurement method (DMM) offers a systematic approach to assess ecosystem health by evaluating structural and functional indicators (Figure 2). Xu (1997) observed notable changes in freshwater ecosystem structure and function due to chemical stressors. Here, Exergy is a system-level indicator that quantifies the usable energy embodied in an ecosystem's organized biological structure, relative to its environment. These changes manifested as higher phytoplankton and microzooplankton biomass, while zooplankton size, biomass, and zooplankton-phytoplankton ratios showed marked reductions. Functional responses encompassed reduced algal carbon assimilation, resource use efficiency, as well as increased community production. These parameters provide a comprehensive basis for assessing ecosystem health (

Table 2). The direction of each indicator was assigned according to the ecological-health response defined by the DMM framework; therefore, higher or lower values do not uniformly represent better ecological condition across all indicators. This method is particularly suited for Kaptai Lake, where chemical and ecological stresses may influence freshwater biodiversity and productivity.

Table 2. The ecological indicators for lake ecosystem health assessment.

Parameter	Description	Unit
Phytoplankton Biomass (Bp)	Represents the total phytoplankton biomass present in the lake.	mg m^{-3}
Zooplankton Biomass (Bz)	Quantifies the total biomass of zooplankton.	mg m^{-3}
Bz/Bp Ratio	The zooplankton-to-phytoplankton biomass ratio, providing insight into trophic interactions.	-
Algal Primary Productivity (P)	Represents the carbon assimilation rate by algae, indicating the lake's primary production capacity.	g $C^{-1}m^{-2}d^{-1}$
Algal P/B Ratio	The production-to-biomass ratio of algae, indicating the turnover rate of algal biomass.	-
Exergy (Ex)	Quantifies the usable energy within the ecosystem.	MJ m^{-3}
Structural Exergy (Exst)	Reflects the complexity and organization of the ecosystem.	MJ mg^{-1}
Buffer Capacity ($\beta_{(TP)(Phyto)}$)	Indicates the resilience of phytoplankton communities to environmental changes.	-

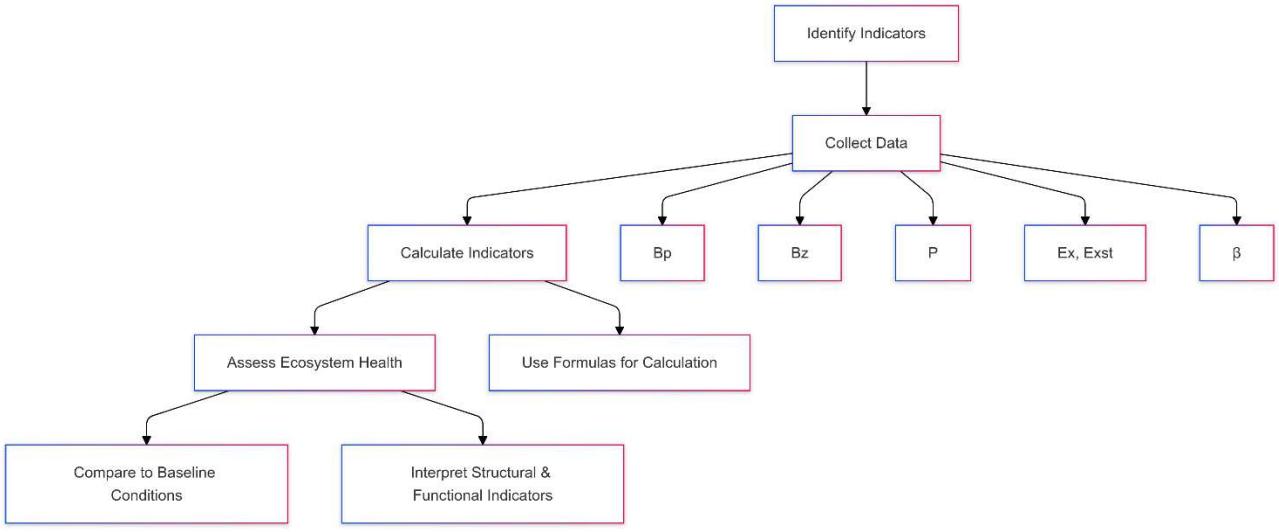


Figure 2. Flow diagram on ecosystem health assessment based on DMM (Created in Mermaid live editor)

Statistical analysis

Box plots were used to display the changes in water quality parameters across different seasons and among sampling sites. Normality was tested using the Shapiro–Wilk test. Depending on the skewness, log and cube-root transformations were applied and post-transformation diagnostics confirmed acceptable normality within each water body. Homogeneity of variances was evaluated prior to analysis. Two separate one-way analyses of variance (ANOVA) were conducted to evaluate spatial and seasonal differences in each water quality and biological parameter, when significant differences were detected, Tukey's HSD test was used for post-hoc pairwise comparisons at $P = 0.05$. Pearson correlation examined relationships between parameters and water quality indices. Multivariate analysis included PCA to identify key influencing factors (Jolliffe 2011) and CA to cluster similar variables and reveal patterns (Kettenring 2006). All those analyses were carried out using R software (version 4.4.1), accompanied by the packages including ggplot2, FactoMineR, cluster, and factoextra (Wickham and Chang 2012; Kassambara 2017; Barter and Yu 2018).

Results

Seasonal and spatial distribution of water quality parameters

Descriptive statistics of the measured physicochemical and biological parameters are presented in (Supplementary Tables 1 and 2), while their seasonal and spatial distributions are illustrated in Figure 3 and 4. Overall, both seasonal and spatial variations were evident among the measured parameters.

During the pre-monsoon period, relatively higher values were observed for pH (7.92 ± 0.14), NH_3 (0.16 ± 0.04 mg L^{-1}), free CO_2 (13.84 ± 2.12 mg L^{-1}), and salinity (0.05 ± 0.00 ppt). Primary productivity was also maximized during this season, with elevated GPP (3.38 ± 0.30 g C m^{-2} d^{-1}), NPP (1.52 ± 0.23 g C m^{-2} d^{-1}), and AR (1.86 ± 0.33 g C m^{-2} d^{-1}), alongside peak phytoplankton density (14.28 ± 1.52 × 10^5 cells L^{-1}). Spatially, higher phytoplankton abundance during this period was more pronounced at KP and BK, whereas relatively lower values were observed at RS, indicating site-specific productivity differences.

The monsoon season was characterized by maximum air temperature (29.54 ± 0.63 °C) and water temperature (28.52 ± 1.10 °C), along with increased hardness (72.19 ± 9.16 mg L^{-1}) and water depth (11.73 ± 3.03 m). Zooplankton abundance also peaked (1.32 ± 0.61 × 10^5 cells

L^{-1}), with higher densities observed at KP and LG compared to other stations. The violin plots further indicate broader distributions for temperature, CO_2, and biological parameters during this season, reflecting increased environmental heterogeneity driven by monsoonal runoff and mixing.

In the post-monsoon period, elevated levels of DO (6.56 ± 0.27 mg L^{-1}), alkalinity (95.04 ± 10.39 mg L^{-1}), EC (112.6 ± 12.57 µS cm^{-1}), and TDS (54.83 ± 6.70 mg L^{-1}) were recorded. Spatial patterns revealed comparatively higher alkalinity and TDS at NC and RS, suggesting localized geochemical influences and possible accumulation effects following the monsoon. Conversely, DO exhibited relatively higher and more stable values at KP and LG, indicating improved oxygenation conditions at these stations.

The Water Quality Index (WQI) did not differ significantly among stations across seasons (Table 3). However, relatively higher WQI values were observed at NC during the monsoon, LG during the pre-monsoon, and RS during the post-monsoon, although these variations were not statistically significant (Figure 4r).

Across all seasons, some parameters such as AT, WT, free CO_2, EC, TDS, NH_3, hardness, WQI, and plankton abundance showed relatively consistent spatial trends ($P > 0.05$), whereas DO, pH, alkalinity, depth, NPP, and AR varied significantly among stations ($P < 0.05$) (Supplementary Tables 1 and 2). For instance, depth showed marked spatial heterogeneity, particularly during the monsoon and post-monsoon periods, with higher values at NC. Similarly, alkalinity and hardness tended to be elevated at NC and RS, while comparatively lower values were observed at BK and KP.

Table 3. Results of one-way ANOVA examining spatial and temporal variations in water quality parameters of Kaptai Lake (F = ANOVA test statistic; p = significance value)

Parameters	Stations		Seasons	
	F	P	F	P
AT	2.00	0.12	6.06	**0.01**
WT	1.88	0.14	6.46	**<0.001**
DO	3.80	**0.01**	2.16	0.13
pH	6.21	**<0.001**	1.12	0.34
EC	0.35	0.84	2.18	0.13
Alk	4.27	**0.01**	1.81	0.18

CO_2	1.03	0.40	0.08	0.93
Salinity	0.49	0.75	2.53	0.09
SD	12.1	**<0.001**	1.58	0.22
TDS	0.49	0.33	0.09	0.92
Depth	8.21	**<0.001**	1.83	0.18
Har	1.77	0.16	0.15	0.86
NH_3	1.81	0.15	1.62	0.21
WQI	1.13	0.36	2.40	0.11
GPP	2.04	0.11	7.32	**<0.001**
NPP	3.78	**0.01**	2.85	0.07
AR	8.67	**<0.001**	2.20	0.13
Phytoplankton	1.70	0.17	3.96	**0.03**
Zooplankton	2.35	0.07	0.21	0.81

Significant p-values ($p < 0.05$) are highlighted in bold.

Correlation between water quality parameters and water quality index

Pearson correlation analysis revealed strong positive correlations exist between air temperature–water temperature (0.77), salinity–EC (0.82), alkalinity–hardness (0.81), WQI–NH_3-N (0.76), AR–GPP (0.68), phytoplankton–zooplankton (0.61) and negative correlations between salinity–DO (-0.80), GPP–WQI (-0.70) of pre-monsoon season (Figure 5a). In the monsoon season, alkalinity–EC (0.72), salinity–EC (0.91), EC–TDS (0.71), EC–salinity (0.74), Depth–water temperature (0.82), WQI–pH (0.73), NPP–GPP (0.68), phytoplankton–zooplankton (0.58) were positively correlated and water temperature–DO (-0.73) was negatively correlated (Figure 5b). Moreover, air temperature–water temperature (0.96), salinity–EC (0.96), SD–DO (0.73), EC–TDS (0.92), EC–salinity (0.95), EC–hardness (0.89), salinity–hardness (0.84), TDS–hardness (0.72), alkalinity–NH3, EC–WQI (0.77), WQI–hardness (0.81), alkalinity–WQI (0.71), salinity–WQI (0.70), AR–GPP (0.85), AR–depth (0.68) were positively correlated during the post-monsoon season and TDS–SD (-0.77) was negatively correlated during the Post-monsoon season (Figure 5c). Here, A positive correlation indicates that the variables tend to increase or decrease together, whereas a negative correlation indicates an inverse association. The actual values of the Pearson correlation coefficients are given in the correlation plots (Figure 5).

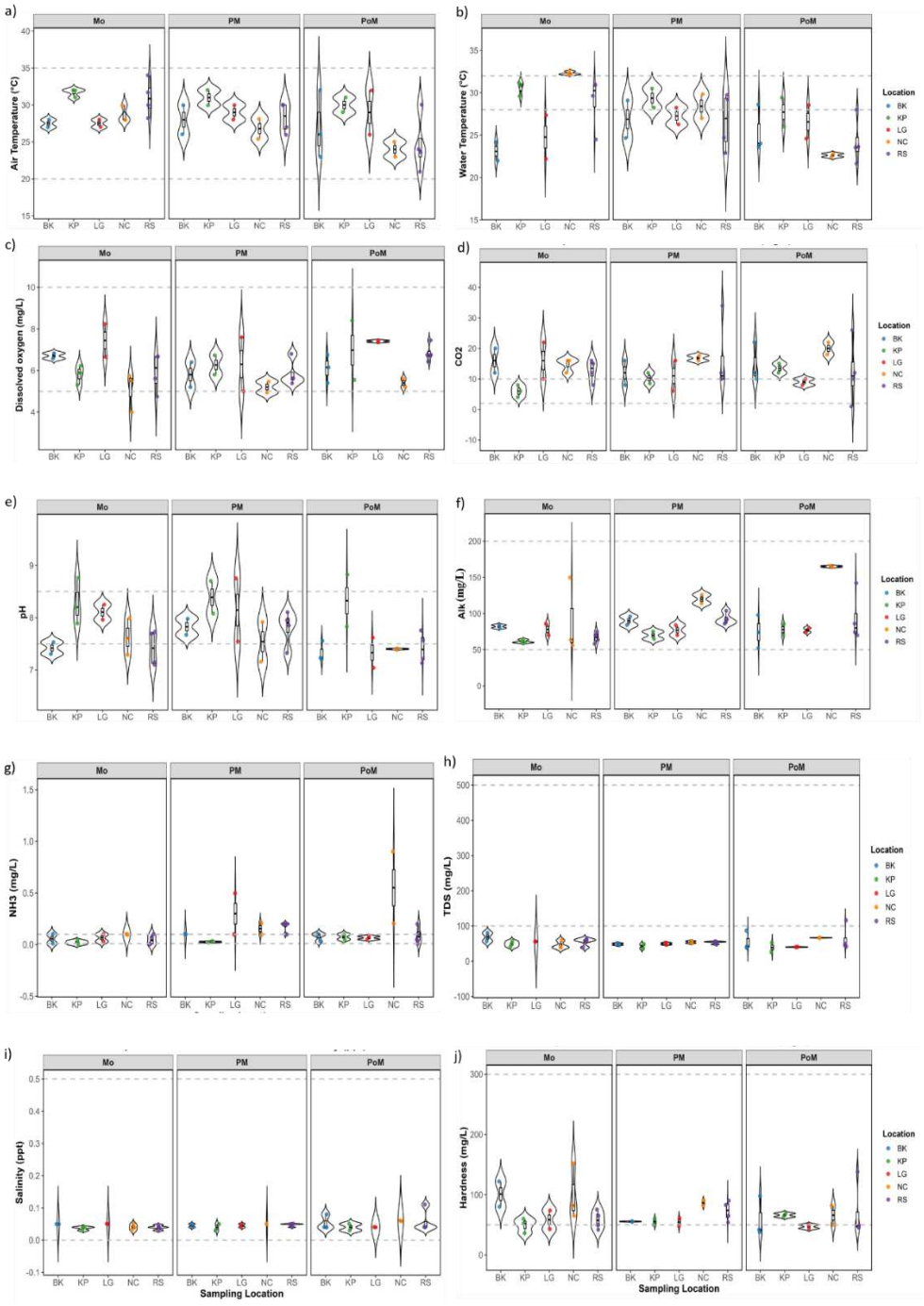


Figure 3. Violin plots (a-j) representing the seasonal and spatial variation of the water quality parameters of the Kaptai Lake. Dashed lines indicate ecological benchmark ranges adopted from APHA (2005) water quality guidelines, supported by recent freshwater and aquaculture studies (Khanjani et al. 2024). For the box plots, the whiskers denote the minimum and maximum values, the boxes denote the 25th and 75th percentile values, and the midlines of the boxes denote the mean values.

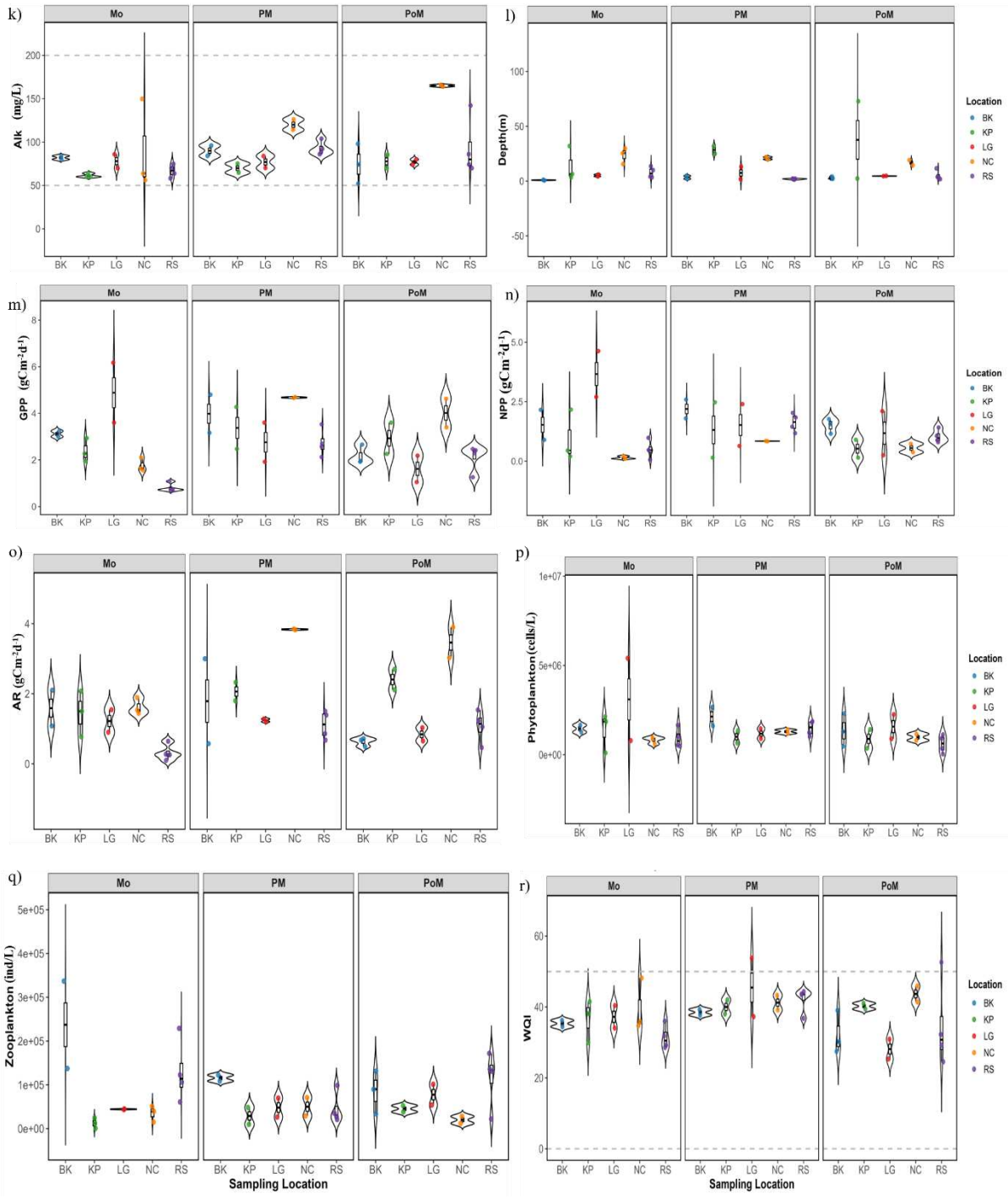
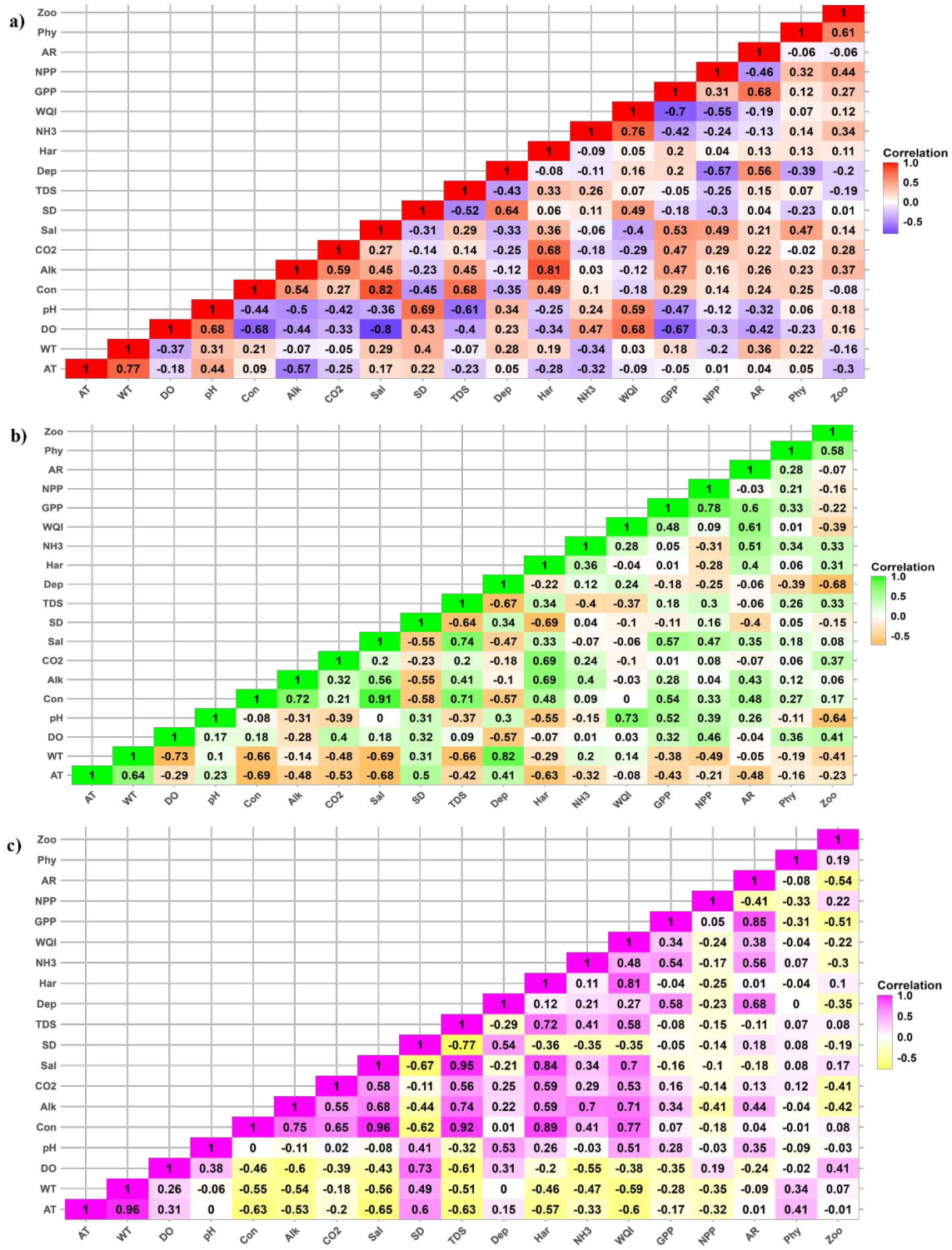


Figure 4. Continued (k-r).



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284 Figure 5. Correlation matrix plot showing Pearson correlation coefficient between water
285 quality parameters and arithmetic water quality index in the seasons (a: Pre-monsoon, b;
286 Monsoon and c: Post-monsoon).

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The principal component analysis (PCA) of physicochemical and biological variables revealed distinct gradients governing the aquatic ecosystem (Figure 6 and 7). The first two principal components (PC1 and PC2) explained a substantial proportion of the total variance, and adequately represent the structure of the dataset.

The PCA score plot (Figure 7) further clarified the spatial and seasonal distribution of sampling observations. Samples were distinctly distributed along the PC1 axis, reflecting a gradient from low to high mineralization. Observations located on the positive side of PC1 were associated with elevated conductivity, salinity, TDS, and related parameters, whereas those on the negative side corresponded to higher dissolved oxygen and temperature conditions.

Along PC2, samples separated according to biological productivity. Samples with higher scores on PC2 were characterized by elevated GPP, AR, and NPP, indicating season changed from Mo to PM and PoM increased primary productivity. In contrast, samples with negative PC2 scores were associated with lower productivity and relatively higher zooplankton influence.

The PCA loading plot (Figure 7) demonstrated that PC1 was primarily associated with ionic and mineral-related parameters. Conductivity (Con), salinity (Sal), total dissolved solids (TDS), alkalinity (Alk), hardness (Har), and CO_2 showed strong positive loadings along PC1, a mineralization gradient associated with dissolved ions and conductivity. Air temperature (AT), water temperature (WT), and dissolved oxygen (DO) were positioned on the negative side of PC1, suggesting an inverse relationship with ionic enrichment. Zooplankton abundance (Zoo) was positioned in the lower-right quadrant, showing a positive association with PC1 variables such as TDS and salinity, which indicates that zooplankton distribution may be more closely linked to ionic conditions than to primary productivity alone.

Whereas, PC2 was mainly driven by biological productivity variables. Gross primary productivity (GPP) and algal biomass exhibited strong positive loadings, with net primary productivity (NPP) also contributing positively but to a lesser extent. Nutrient variables such as NH_3 were located in the upper-right quadrant, indicating their positive association with both productivity and ionic gradients. Conversely, water transparency, pH, and depth were grouped in the upper-left quadrant, suggesting a negative relationship with ionic parameters but a positive association among themselves, indicative of clearer and less mineralized water conditions.

Overall, the combined interpretation of loading and score plots indicates two dominant environmental gradients: (i) a mineralization gradient driven by dissolved ions and

conductivity (PC1), and (ii) a productivity gradient governed by primary production and nutrient dynamics (PC2). The distribution of samples along these gradients highlights the strong coupling between physicochemical conditions and biological responses, as well as potential seasonal or spatial heterogeneity within the aquatic system.

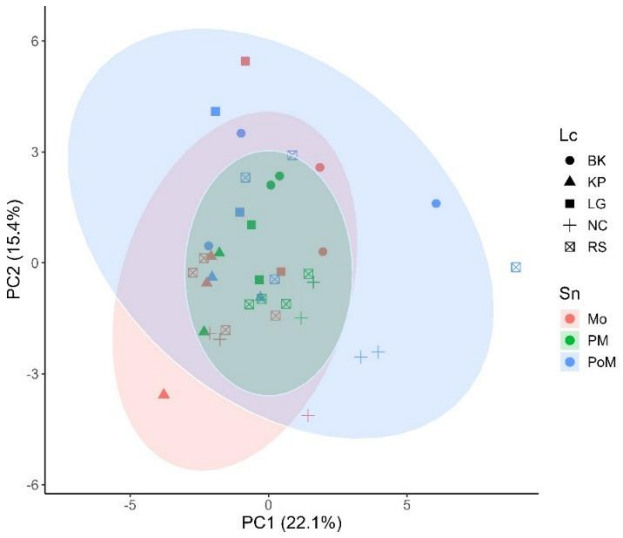


Figure 6. Principal component analysis (PCA) biplot of water quality parameters across sampling locations and seasons. The biplot shows the explanatory variables as vectors (in colors).

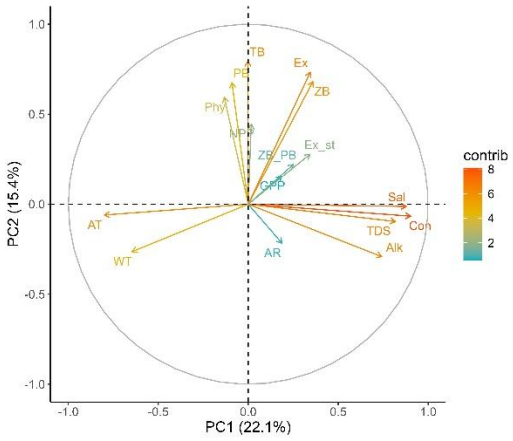


Figure 7. Principal component analysis (PCA) biplot of water quality parameters in the Kaptai Lake. The biplot shows the water quality parameters as points. Points on the same side as a given variable should be interpreted as having a high contribution on it. The magnitude of the vectors shows the strength of their contribution to each axis.

Seasonal and spatial cluster analysis (CA)

Seasonal observations and station-level observations of the measured water quality variables (19) at each of the five monitoring stations, were used separately for seasonal and spatial cluster analyses (CA). To investigate the seasonal changes in water quality characteristics, the variables were grouped into physical parameters (AT, WT, depth and SD), chemical parameters (pH, DO, free CO_2, hardness, alkalinity, TDS, conductivity, NH_3 and salinity) primary productivity (GPP, NPP, and AR), biological parameters (phytoplankton, and zooplankton abundance), for which the CA results are illustrated in Figure 8.

The seasonal CA grouped the measured variables into two main clusters representing relatively high and low concentrations. Whereas, WT, AT, depth, transparency, GPP, NPP, AR, phytoplankton, DO, pH and WQI formed cluster 1. Notably, the parameters of Cluster 1 showed greater variation across seasons and sampling stations. Besides, the parameters of cluster 2 showed almost similar pattern across the time and location. The spatial CA illustrated that the station near the electricity dam (KP), the tributary fed station heavily affected by urban runoff, effluent from the nearby agricultural/livestock (NC), and the main reservoir area (LG, RS and BK) were grouped into clusters 1, 2 and 3, respectively.

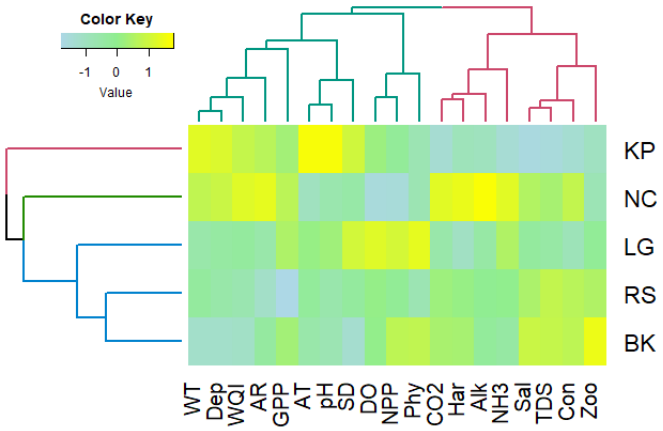
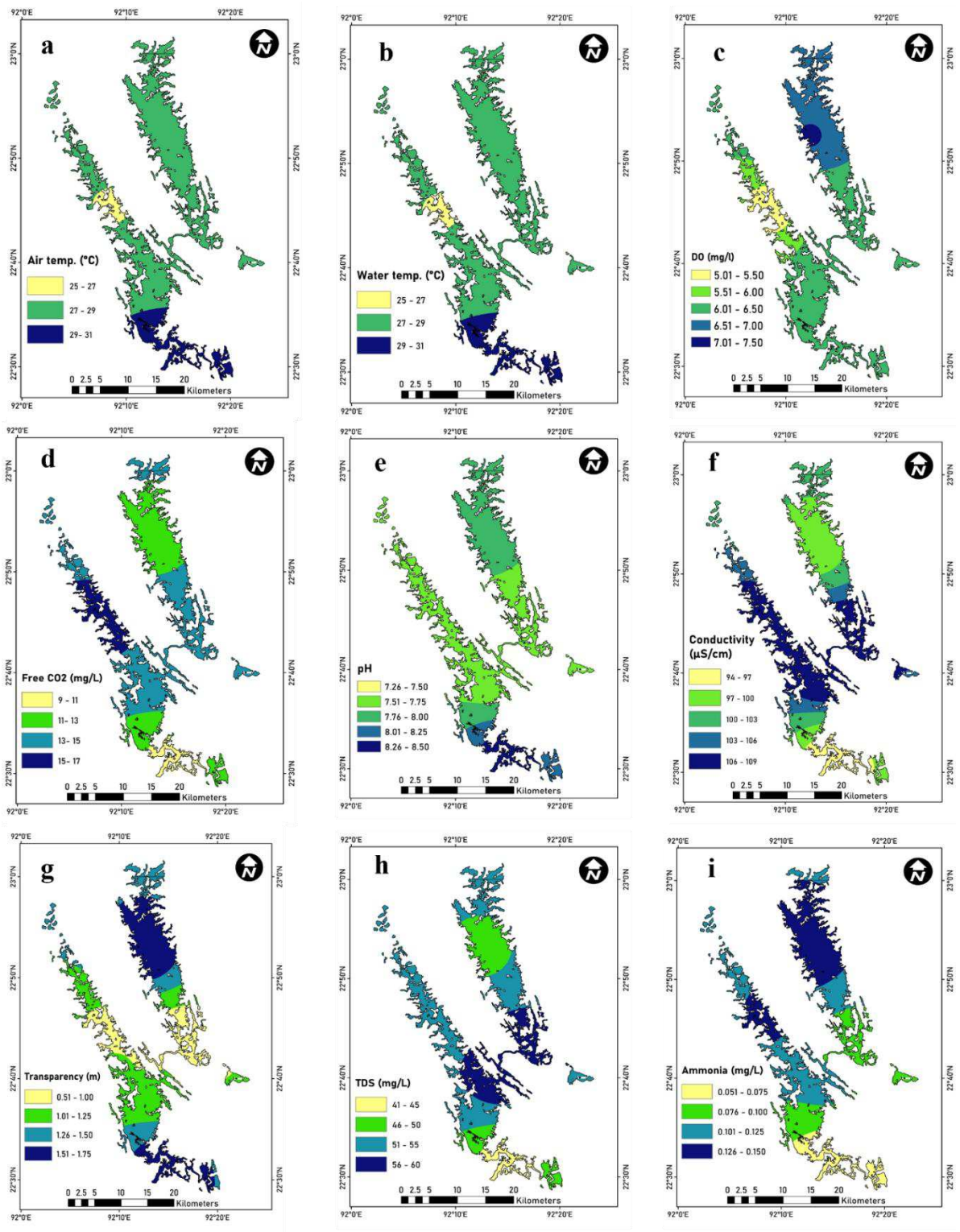


Figure 8. Heatmap displaying the results of a hierarchical cluster analysis (CA) conducted independently on both samples and variables. Hierarchical clustering was performed using Euclidean distance and Ward's linkage method.

Spatial distribution pattern

The spatial distribution contour maps of the lake water quality parameters have been generated and elucidated in Figure. 9 a-i. The air and water temperature were in range of 25-31°C, which showed similar pattern of distribution across the Lake. The highest air and water temperature was at KP. The DO varied with the sampling stations ($P \leq 0.01$) and the highest value

(7.05±0.46 mgL^{-1}) was at LG. The pH varied among stations ($P \leq 0.01$) and the highest value (8.40 ± 0.17) was recorded at KP, denoting slightly alkaline environment. Water transparency was significantly ($P \leq 0.01$) higher (1.75±0.20 m) in KP, located near the electricity dam, and lower (0.68±0.17 m) in RS, which is near the Rangamati city. The highest water depth (28.40±10.29 m) was recorded in KP and the lowest water depth (2.45±0.56 m) in BK. The NPP and AR showed significant variation ($P \leq 0.01$), the highest NPP (2.12±0.64 g C m^{-2} d^{-1}) was in LG and the highest AR (2.78±0.43 g C m^{-2} d^{-1}) in NC. The spatial distribution pattern of DO exhibit a well saturated status across the reservoir with the highest distribution at LG. The WQI map (Figure 10q) was developed using selected parameters to classify water quality into five categories: excellent, good, poor, very poor, and unsuitable. Overall, the results demonstrate good ecological water quality across the stations, suggesting that the lake environment remained conducive to aquatic productivity and biological sustainability throughout the study period.

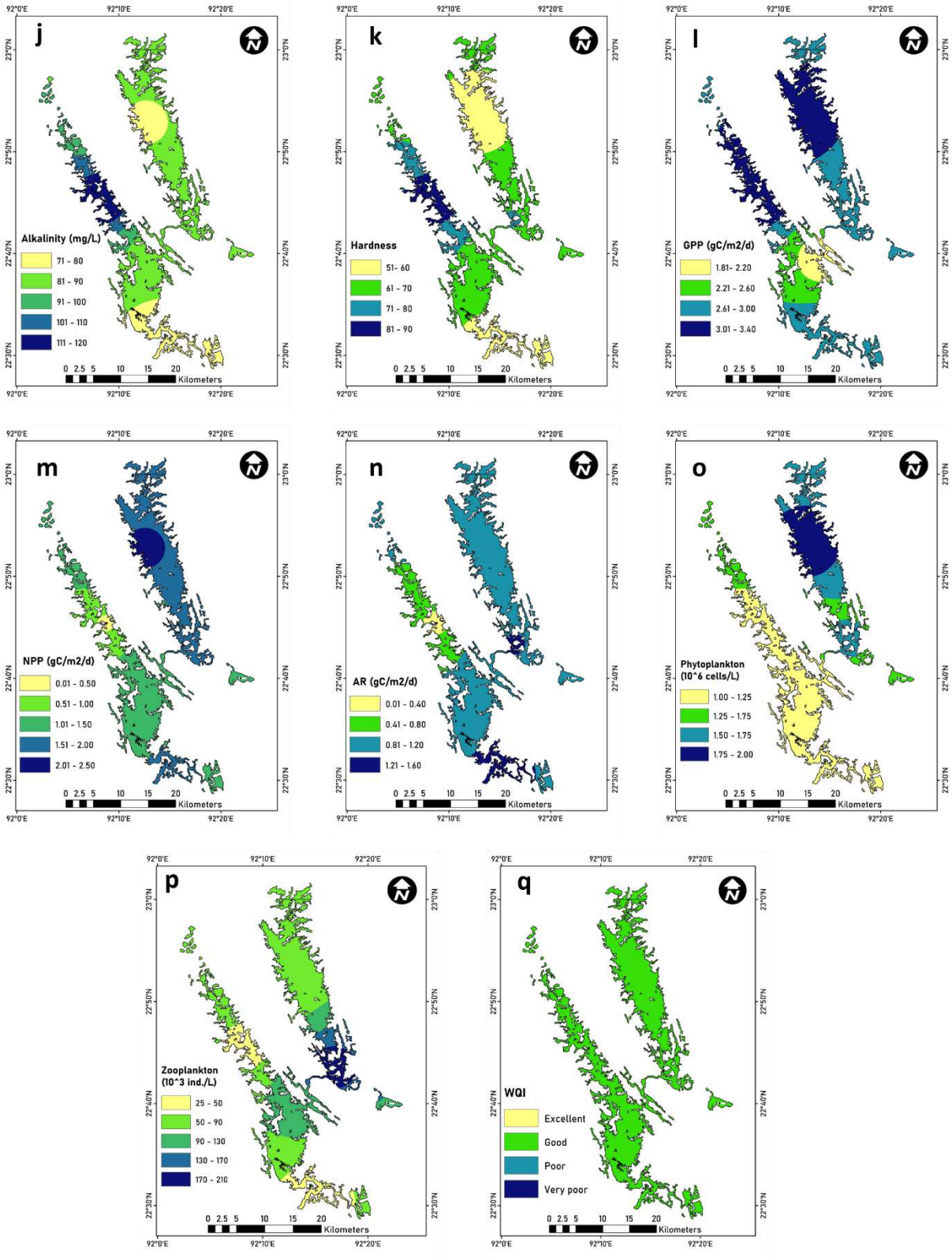


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373 Figure 9: (a-i) Spatial distribution map of physico-chemical parameters of Kaptai Lake (created

374 by ArcGIS version 10.8) (Continued in Figure 10)

375



376

377 Figure 10. (j-q) Spatial distribution map of physico-chemical parameters of Kaptai Lake

378 (created by ArcGIS version 10.8)

Ecosystem health assessment

The direct measurement method (DMM) incorporated several ecological indicators for assessment, including phytoplankton biomass (Bp), zooplankton biomass (Bz), Bz/Bp ratio, algal primary productivity (P), algal P/B ratio, exergy (Ex), structural exergy (Exst), and phytoplankton buffering capacity $\{\beta_{(TP)(Phyto)}\}$. Seasonal and spatial variations of these indicators are presented in Table 4, with corresponding assessment results in Table 5. Higher exergy and structural exergy indicate greater ecosystem organization and structural complexity within the DMM framework. The lake's ecological health showed seasonal variation, with post-monsoon conditions being most favorable, followed by pre-monsoon and monsoon periods. Spatially, the ecological health status decreased in the following order: KP > BK > RS > LG > NC.

393 Table 4: The seasonal and spatial distribution of ecological indicators in Kaptai Lake.

Ecological indicators	**Seasonal**			**Spatial**				
	PM (A)	**Mo (B)**	**PoM (C)**	**RS (A)**	**BK (B)**	**KP (C)**	**LG (D)**	**NC (E)**
Phytoplankton biomass (Bp) ($mg\ m^{-3}$)	137.51	123.46	103.81	73.97	176.78	72.17	249.91	78.14
Zooplankton biomass (Bz) ($mg\ m^{-3}$)	35.13	17.68	58.69	31.86	66.53	26.03	42.13	22.50
Bz/Bp ratio	0.25	0.22	1.23	0.93	0.59	0.48	0.33	0.26
Algal primary productivity (P) ($g\ C^{-1}\ m^{-2}\ d^{-1}$)	3.38	2.29	2.47	1.88	2.96	2.97	3.09	3.24
Algal P/B ratio	0.02	0.05	0.03	0.03	0.01	0.08	0.02	0.03
Exergy (Ex) ($MJ\ m^{-3}$)	405.74	217.57	646.27	355.13	747.22	293.09	507.82	257.33
Structural exergy (Ex_{st}) ($MJ\ mg^{-1}$)	21.90	19.95	47.25	35.32	32.42	28.32	25.56	23.19
Buffer capacity ($\beta_{(TP)(Phyto)}$)	-0.58	0.07	0.60	-0.29	-0.40	2.01	-1.12	0.74

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396 Table 5: The status of ecological indicators in different seasons and locations.

Ecological indicators	**Assessment principles**	**Relative order of health state during different season[a] (Good→Poor)**	**Relative order of health state at different location[b] (Good→Poor)**
Phytoplankton biomass (Bp) (mg m^{-3})	Low→ High	C>B>A	C>A>E>B>D
Zooplankton biomass (Bz) (mg m^{-3})	High→ Low	C>A>B	B>D>A>C>E
Bz/Bp ratio	High→ Low	C>A>B	A>B>C>D>E
Algal primary productivity (P) (g C m^{-2} d^{-1})	Low→ High	B>C>A	A>B>C>D>E
Algal P/B ratio	High→ Low	B>C>A	C>E>A>D>B
Exergy (Ex) (MJ m^{-3})	High→ Low	C>A>B	B>D>A>C>E
Structural exergy (Ex_{st}) (MJ mg^{-1})	High→ Low	C>A>B	A>B>C>D>E
Buffer capacity ($\beta_{(TP)(Phyto)}$)	High→ Low	C>B>A	C>E>A>B>D
Comprehensive results		C>A>B	C>B>A>D>E

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Discussion

Seasonal dynamics of water quality parameters

The water quality of freshwater lakes plays a crucial role in maintaining ecosystem health and determining water potability, governed by both physicochemical and biological characteristics. Among physical parameters, temperature significantly influences algal development and metabolic processes in aquatic species (Shil et al. 2019).

The violin plots (Figs. 3 and 4) clearly demonstrated that, in addition to seasonal shifts, the distribution width of several parameters (e.g., CO_2, alkalinity, phytoplankton, and zooplankton) varied notably among stations, indicating localized variability in environmental conditions. Overall, the results suggest that while seasonal forcing—especially monsoonal influence—plays a dominant role in regulating water quality and ecosystem productivity, spatial heterogeneity driven by site-specific factors such as depth, geochemistry, and nutrient inputs also significantly contributes to the observed patterns.

The WT and AT were highest during the pre-monsoon season due to higher seasonal temperatures, which likely accelerated metabolic activity, organic matter decomposition, and nutrient recycling within the lake ecosystem. However, the DO remained comparatively lower because warmer water can hold less DO (Umwali et al. 2021). During the monsoon season, the negative correlation (-0.73) between WT and DO suggests that increased runoff, turbidity, organic loading, and anthropogenic inputs intensified oxygen consumption. Similar findings were also reported in previous studies (Rahman and Akhter 2015; Saad et al. 2017). A previous study reported elevated DO during the monsoon despite higher temperatures in this lake, contrasting with our current findings. This difference may result from increased rainfall-induced turbulence, which can enhance oxygen levels (Bashar et al. 2015; Islam et al. 2021). Overall, the DO levels were within the permissible limit (>5.0 mg L^{-1}) for aquatic life (Khan 2009), suggesting that the lake maintained moderate ecological resilience despite experiencing seasonal environmental stress.

Water pH plays a vital role in maintaining aquatic ecosystem health, as extreme pH can disrupt biological processes and affect both aquatic organisms and human health. The slightly alkaline pH observed in our study is typical of productive freshwater lakes and reflects active photosynthesis, mineral weathering, and buffering processes that help stabilize water chemistry under seasonal environmental fluctuations (Groeneveld et al. 2022). The recorded pH remained within the optimal

range (6.5–8.5) for a healthy aquatic ecosystem (WHO 2017), consistent with previous findings from this lake (Bashar et al. 2015; Rahman and Akhter 2015). Similarly, the observed alkalinity indicates strong buffering capacity against pH fluctuations caused by runoff or other external stressors, while alkalinity levels above 50 mg L^{-1} suggest productive conditions favorable for fish culture and overall ecosystem functioning (Jhingran 1989). Water hardness indicates the concentration of dissolved minerals, primarily calcium and magnesium, which are essential for physiological processes of aquatic organisms, particularly for bone and scale formation in fish (Wurts and Durborow 1992). The harder water also reduces toxicity of heavy metals to aquatic life (Islam et al. 2015). The observed water hardness levels indicate moderately hard conditions, aligning with previous findings (Bashar et al. 2015; Lima et al. 2024; Rahman et al. 2024). The strong positive correlation between alkalinity and hardness (0.81) in the pre-monsoon season suggests these interdependent parameters contributed to active mineral buffering and stable water chemistry, thereby supporting ecosystem productivity and resilience. The observed NH_3-N concentrations remained below the cited threshold for fish culture (Pereira and Mercante 2005), suggesting limited direct ammonia toxicity during the study period (Dai et al. 2012).

The EC refers to the ability of water to conduct the current and mainly represents the total dissolved ions in the water. The significant positive correlations of EC with alkalinity, hardness, TDS, and salinity observed in this study, similar to previous findings (Bhateria and Jain 2016), indicate interconnected ionic and mineral dynamics that influence overall water chemistry. Higher EC values during the post-monsoon season may have resulted from increased ion concentration due to water evaporation and residual mineral accumulation following monsoonal flushing. Water transparency, which affects light penetration and, subsequently, primary production, ranged from 0.99±0.16 m during the pre-monsoon season to 1.37±0.21 m in the monsoon. Greater transparency during the monsoon may be linked to reduced algal biomass and seasonal dilution effects during periods of increased rainfall.

The GPP and NPP, the measures of the lake's biological productivity, were recorded for the higher values during the post-monsoon season. This suggests enhanced primary production driven by nutrient enrichment and improved environmental conditions after the monsoon, likely due to nutrient enrichment from runoff. Similarly, higher phytoplankton and zooplankton abundances during the post-monsoon and pre-monsoon seasons indicate increased primary and secondary

productivity under comparatively stable water conditions. Higher zooplankton densities in the pre-monsoon season further reflects favorable ecological conditions for energy transfer and secondary production within the aquatic food web.

Spatial distribution of water quality parameters

The study reveals significant spatial variation of water quality parameters in Kaptai Lake, particularly for DO, pH, alkalinity, transparency, depth, and productivity (NPP and AR). This heterogeneity is likely driven by lake's complex geomorphology, as surrounding hills create bends and deep pools that influence hydrodynamics, water retention and nutrient distribution in the lake (Lima et al. 2023). Significant variation in DO levels between LG and NC stations indicated differences in tributary inflow and seasonal water availability, while other locations exhibited similar distribution patterns influenced by both geographic and seasonal factors. The LG station, located on the northern side of the right arm of this H shaped lake and fed by two tributaries the Kassalong and the Miyani, remain inundated with sufficient water all the year round (Rahman and Akhter 2015). On the contrary, the NC station, which is situated on the northern side of left arm that fed by only one tributary, the Chengi, experiences scarce river flow during the post-monsoon and pre-monsoon seasons due to canal shrinkage and conversion of surrounding areas into agricultural land (Rahman and Akhter 2015; Hoque et al. 2021).

The pH level at KP exhibited notable variation compared to other locations, potentially due to its proximity to the hydroelectric dam. The variation in water transparency across stations may be associated with the sewage discharge from nearby residential areas and effluents from the Kaptai fish landing center. Similarly, the highest alkalinity recorded in NC may reflect the influence of surface runoff from surrounding agricultural fields during post monsoon season (Ahuja 2013). Water depth varied across sampling stations due to the reservoir's undulating topography and the presence of four feeder channels that previously functioned as mountain streams before dam construction (Rahman and Akhter 2015). The variation in water transparency across stations might have resulted from spatial variation in primary productivity (NPP and AR). Although NPP values were similar across RS, BK and KP stations, significant variations between NC and LG suggest the influence of geographic location, bottom sediment characteristics, and river run-off (Hoque et al. 2021). Since NPP is closely linked to algal respiration, higher algal productivity usually increases respiration rates within aquatic community (Tait and Schiel 2013). However, the

significantly lower AR observed at RS compared to NPP may indicate the dominance of certain plankton, potentially leading to increased primary productivity while contributing comparatively lower respiration due to their metabolic characteristics (Noges et al. 2008). The overall spatial heterogeneity of lake water quality was strongly influenced by seasonal variation, with fluctuations in feeder canal flow, geographic location, bottom sediment characteristics, agricultural runoff, and nearby human settlements collectively shaping the spatial distribution of water quality and ecosystem dynamics.

Assessment of Aquatic Ecological Health

The direct measurement method (DMM) of aquatic ecological health assessment was conducted, which includes structural, functional and system-level aspects of Kaptai Lake. Structural changes generally represent the first ecological response to anthropogenic stress, followed by alterations in ecosystem functioning and overall system stability.

Seasonally, the post-monsoon period exhibited better ecological conditions than the pre-monsoon and monsoon periods, as reflected by the combined assessment of phytoplankton biomass, zooplankton biomass, Bz/Bp ratio, primary productivity, exergy, structural exergy, and buffer capacity. Higher exergy and structural exergy indicate a more organized, energy-efficient, and stable ecosystem with improved biological structure and functioning. The transition from monsoon to post-monsoon stabilized hydrological conditions, allowing for better light penetration, reduced turbidity, elevated nutrient concentrations from runoff and improved water quality, which collectively promoted phytoplankton growth (Madhu et al. 2010; Naik et al. 2020). Increased phytoplankton productivity subsequently supported higher zooplankton biomass through improved food availability and trophic transfer within the aquatic ecosystem (Upreti and Ram 2020).

Additionally, the KP sampling location exhibited good ecological conditions, aligned with the cluster analysis findings. The area is the main downstream part of the Karnaphuli River where the hydroelectric dam regulates reservoir water levels. During monsoon periods, increased inflow from tributaries caused water levels in Kaptai Lake to rise, necessitating controlled water release through the dam gates to the downstream Karnaphuli River. Such regulated flow may have contributed to the outflow area likely enhanced nutrient redistribution, maintained buffer capacity, and supported balanced algal productivity, contributing to greater ecological stability. In contrast,

the BK, RS, and LG sampling sites represented the lake's main reservoir section. BK occupies the upstream portion of the Karnaphuli River while simultaneously forming the downstream section of LG, which receives inflow from the major Kassalong tributary. These areas' hydrological connectivity and geographical characteristics - including adjacent agricultural lands and semi-evergreen forest coverage - contribute to elevated nutrient inputs from both zones (Hoque et al. 2021).

The RS site, a main reservoir area located alongside the Rangamati city, experienced domestic sewage and tourism-related wastewater inputs that may contribute to increased nutrient loading, subsequently affecting zooplankton populations (Abd. Razak and Sharip 2019) and broader ecosystem health. The LG station, located at the confluence of the Kassalong and Myani tributaries, exhibited particularly high nutrient levels and eutrophic conditions, reflected in its maximal phytoplankton biomass. In contrast, the NC site - as previously discussed - experienced significant water level reductions during dry periods, which likely reduced hydrological stability and contributed to comparatively poorer ecological conditions among the studied locations.

Ecological and management implications

The observed seasonal and spatial variability in water quality and ecosystem health indicators demonstrates that Kaptai Lake is a dynamic freshwater ecosystem influenced by both natural processes and localized anthropogenic pressures. Moreover, the elevated pre-monsoon nutrient concentrations and phytoplankton productivity indicate the increased biological activity, whereas the decline in water quality during the monsoon season, particularly near urban inflow regions such as Naniarchar, highlights the impact of runoff and human-induced disturbances. From a management perspective, the integration of WQI, DMM indicators, and multivariate analyses provides an effective framework for identifying vulnerable zones and seasonal risk periods. The results support the need for targeted watershed management practices, controls on nutrient and pollution inputs from adjacent settlements, and the establishment of long-term monitoring programs to protect water quality; maintain fisheries resources; and preserve Kaptai Lake's ecological integrity.

Water quality evaluation of the lake

The WQI combines multiple parameters, including DO, pH, nutrients, and other physical characteristics, to provide a simplified overall assessment of water quality (Mnisi 2012). Seasonal

rainfall had a direct influence on the WQI of the Lake. The water quality index (WQI) showed seasonal variation, with relatively higher values during the pre-monsoon period and lower values during the monsoon season; however, these differences were not statistically significant (Kumar et al. 2021; Rao et al. 2022) Similar seasonal WQI patterns have also been reported in previous studies (Sen et al. 2023). Although most stations exhibited relatively similar WQI distribution throughout the year, station NC recorded the highest WQI, aligning with our earlier discussion about its geographic setting, water flow characteristics, and sediment dynamics. The finding is further supported by the cluster analysis showing distinct water quality patterns at this station. Overall, the findings indicate that the lake maintains moderate ecological suitability for aquatic life and fisheries despite experiencing localized seasonal water quality impairment. However, the present assessment was based only on selected physicochemical parameters, as heavy metals, pesticides, pathogens, and other toxic pollutants were not analyzed in this study.

Uncertainties and future research

Water quality studies inherently face methodological uncertainty due to difficulties in selecting suitable models and indices that accurately represent complex environmental conditions. Moreover, the evaluation is influenced by measurement variability, weather changes, water quality standards and parameter selection. Conducting comprehensive sampling and laboratory analysis across this large mountainous lake system is costly and labor-intensive, limiting broader temporal and spatial coverage in the present study. In addition, spatial interpolation uncertainty may exist because increasing the number of monitoring stations could provide more precise characterization of water quality heterogeneity. The present research was also constrained by the exclusion of pathogen analysis, heavy metals, pesticides, toxic contaminants, streamflow data, and higher trophic level assessments. Besides, the WQI assessment might vary due to the large variation of assigned weights of water quality parameters (Ewaid et al. 2018; Seifi et al. 2020). Therefore, the WQI in this study was assessed following the approach of Brown et al. (1970) and the weights were adopted from Chatterjee and Raziuddin (2002), which was also applied by Ram et al. (2021). Although several ecological health assessment frameworks have been proposed by the researchers (Schaeffer et al. 1988; Haskell et al. 1992; Jørgensen 1995), a more synchronized method was developed by Qi et al. (2018) incorporating higher trophic levels and social science factors. Nevertheless, despite these uncertainties and limitations, this study presented a useful baseline understanding of seasonal and spatial water quality dynamics for lake management and fisheries

sustainability, while emphasizing the need for long-term monitoring and more comprehensive future assessments incorporating land use, toxicological, hydrological, and ecological variables.

Conclusion

In this study, our assessment reveals that Kaptai Lake's water quality and ecological health exhibit distinct spatial and seasonal patterns influenced by both natural hydrological processes and anthropogenic pressures. The post-monsoon season demonstrates the most favorable ecological conditions, with higher exergy values and balanced plankton ratios, while the pre-monsoon period shows significant nutrient accumulation and phytoplankton blooms. Spatially, the Kaptai Dam area (KP) maintains the healthiest ecosystem status due to regulated water flows and sediment transport, whereas Naniarchar (NC) showed comparatively poorer ecological conditions, particularly during periods of reduced hydrological stability and increased influence of surrounding agricultural activities. The lake's central and northern regions show greater resilience to seasonal changes, with water quality parameters (DO, conductivity) maintaining stable ranges, while the southern tributary zones near urban areas exhibit progressive deterioration from pollutant accumulation. This spatial gradient highlights how localized anthropogenic impacts override natural hydrological benefits in vulnerable areas, similar to the weakening of positive water level effects observed in other lake systems. Our findings emphasize that sustainable management must address both seasonal nutrient loading and spatial hotspots of pollution, particularly in northern agricultural zones and southern urban-influenced areas, to maintain the lake's critical ecosystem services and biodiversity. The integrated WQI-DMM approach proves particularly effective for identifying these priority areas in tropical reservoirs subject to complex environmental stressors.

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Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.