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Application of water quality indices and geostatistical methods for analyzing mountain lakes in relation to anthropogenic influences and catchment features: a case study in East Sikkim, India

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ABSTRACT

Water quality, pollution level, and trophic conditions were assessed in Aritar Lake located in the Himalayas in East Sikkim, India, in relation to geo-environmental influences and anthropogenic activity in its catchment. A comprehensive method involving indexing and multivariate analyses was used. Geostatistical tools were employed to interpolate seasonal and spatial deviations in water quality, and nutrient and organic load distribution. Lake water nutrient index (NI) values were between 4.61 and 7.31, and 2.65 and 4.69 during pre- and post-monsoon seasons, respectively, indicating significant nutrient enrichment and eutrophic conditions. For both seasons, the estimated organic pollution index (OPI) showed class II contamination (contamination starting), with post-monsoon values being higher. The study shows clear signs of eutrophication and early organic pollution. Effective management plans and sustainable tourism practices may benefit the lake, by reducing contamination and protecting the integrity of its ecosystem.

Key words: eutrophication, organic pollution, sustainable tourism, Water Quality Index (WQI), water resource management

HIGHLIGHTS

- Assessment of nutrient dynamics, organic pollution, and trophic state of the lake on a spatio-temporal scale.
- Appraisal of water quality and lake health using the WQI, OPI, and geostatistical methods.
- Multivariate analysis to delineate influencing factors and pollution sources.

GRAPHICAL ABSTRACT

1. INTRODUCTION

India has many natural lakes. Their presence in the Himalayas is critical because they are the primary source of freshwater in remote locations. The Himalayas in India extend almost 2,400 km east to west and incorporate hundreds of glacial and non-glacial lakes, which are mostly perennial, receiving freshwater from monsoon rain and snowmelt. The lakes and wetlands of the Himalayas are geographically and environmentally significant and possess enormous value, as they are hotspots for trekking enthusiasts and travelers, and are enriched with biodiversity and aquatic life forms (Bhat *et al.* 2011). Mountain lakes, an essential water source, are highly valued for livelihoods, and have enormous ecological and economic importance (Ho & Goethals 2019). Natural lakes in mountain regions are susceptible to anthropogenic use (Dynowski *et al.* 2019). As a result, they are affected by environmental shifts, which threaten lake organisms and ecosystem services (Sterner *et al.* 2020). Recreational use and livestock farming also put a strain on mountain lakes (Senetra *et al.* 2020).

As mountain lakes are used as local water sources for subsistence, they are vulnerable to tourists' irresponsible behavior, which affects ecosystems and causes environmental degradation (Senetra *et al.* 2020). With increasing tourist inflow and local population in the lake catchment, it is important to keep track of the quality of the water, its productivity, and the health of the lake's ecosystem. Nutrient enrichment and organic pollution can degrade the ecological integrity of the lentic ecosystem and cause human health concerns. Nutrient concentrations in the lake are likely to increase due to the influx of runoff, weathering, and erosion loads. The accumulation of organic matter may alter nutrient levels and, subsequently, the system's trophic relations (Liu *et al.* 2011). Enrichment of nutrients in aquatic systems stimulates algal growth with consequential impacts on trophic relations, habitat quality, community structure, pH, dissolved O_2 concentrations, and aesthetic qualities (Miltner & Rankin 1998), so it is vital to identify the sources and factors contributing nutrients to the lake's water. Sustainable management strategies and appropriate plans are also required to ensure human livelihoods and conserve mountain lakes for their aesthetic and ecological values.

Aritar Lake is one of the oldest in Sikkim and has high social and eco-geological importance. Local communities depend on it, for economic revenue that it generates through tourism and lake-centric activities, as well as the water resource. Historic data on nutrient concentrations and organic pollution in Sikkim Himalayan lakes and streams are sparse. However, little importance has been given to exploring the bio-geophysical and chemical processes that influence water quality and productivity of the lake ecosystem. Previously, Nayek *et al.* (2017, 2018) studied the seasonal variations in the physicochemical properties of Aritar Lake water and investigated its trophic state. However, insufficient information is available regarding potential sources of nutrient loading, organic pollution, and other diverse factors on lake water systems to develop effective strategies for sustainable use and conservation of the resources. In this study, spatial and seasonal water quality variations with respect to organic pollutant load and nutrient enrichment were investigated. Indexing methods such as water quality index

(WQI), organic pollution index (OPI), and nutrient index (NI) were used to assess water quality and the water's trophic classification. Multivariate analysis and geostatistical tools were used to delineate the influence of many factors and interpolate water pollution levels and trophic conditions on spatial and temporal scales.

1.1. Study area

Aritar Lake, locally known as Lampokhari Lake, is a natural alpine lake in East Sikkim, India (Figure 1). It is in the Middle Himalayas at an elevation of 1,400 m. Recently, the lake embankment was rebuilt in concrete, and a

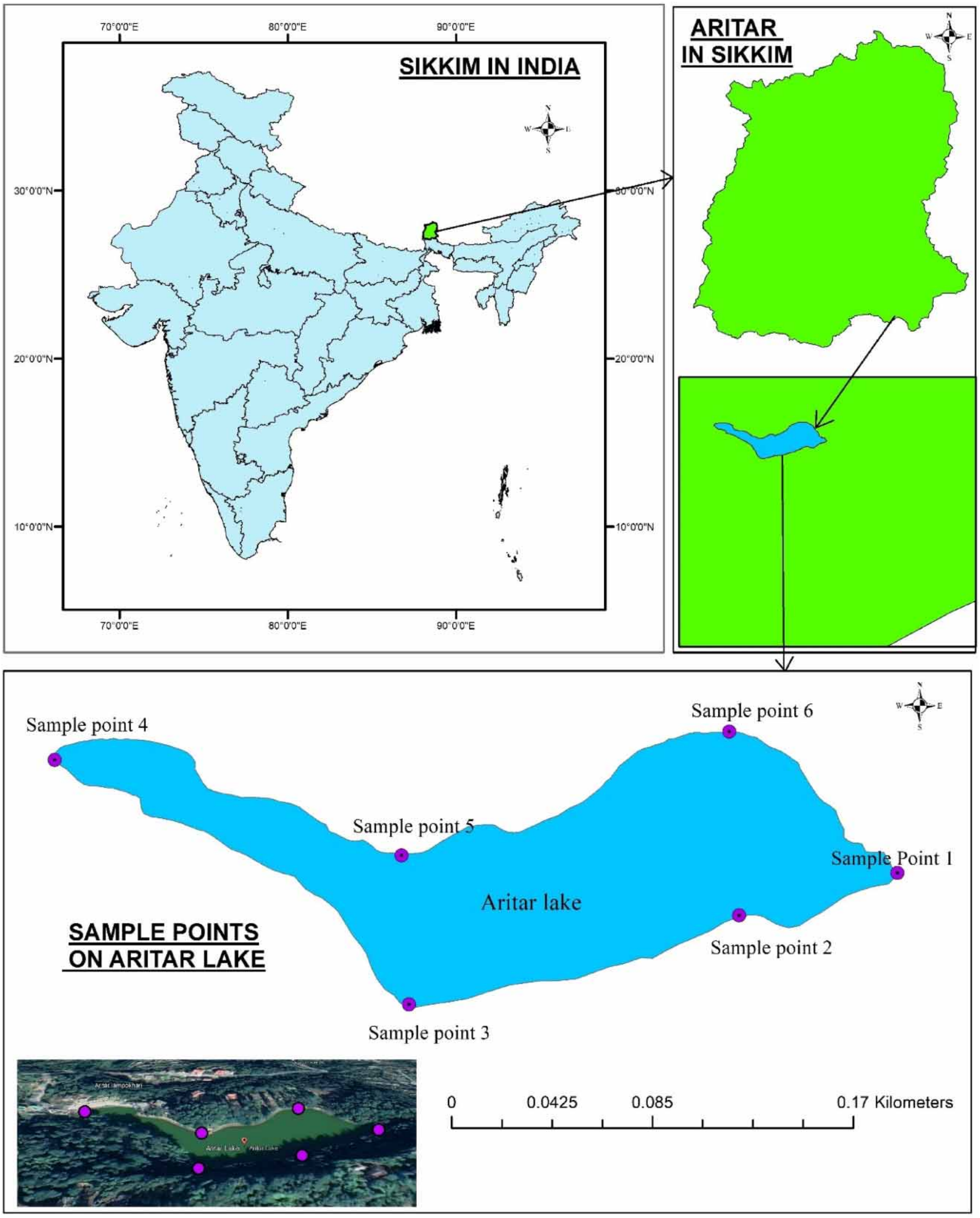

Figure 1 | Study area.

walkway was constructed around it. The lake watershed is predominantly Darjeeling gneiss, with a rich, mixed forest cover dominated by pine trees. The lake has boating facilities and other recreational activities, which attract tourists as well as local visitors.

Aritar Lake is perennial, and fed by an artificial supply, surface runoff from the catchment, and atmospheric precipitation during the rainy season (Nayek *et al.* 2017). It is a prime location for bird-watching and is increasingly popular with tourists. The lake's catchment has been transformed by anthropogenic pressure recently. The forest and lake watershed have been encroached on to facilitate tourist hotels and rest houses, which has impacted the lake's water quality and eco-hydrological conditions significantly.

2. METHODOLOGY

2.1. Sample collection and investigation

Field sample collection and analysis were performed between 2019 and 2021, during pre- and post-monsoon seasons. Six sampling locations were chosen along the lake's margins. Sterilized 1-L PVC bottles were used for collection, and samples were collected 0.3 m below the water surface. pH, electrical conductivity (EC), total dissolved solids (TDS), and dissolved oxygen (DO) were measured on-field by using a multi-parameter hand analyzer (Eutech instruments). The bottles were transported to the laboratory at 4 °C in an ice container. APHA standard methods (APHA 2005) were followed for collection, preservation, and analysis. To maintain accuracy, all parameters were determined three times, and the mean values were used for data analysis, representation, and interpretation. Multivariate statistical analyses such as Pearson's correlation, cluster analysis (CA), and principal component analysis (PCA) on the analytical results were performed using statistical software (SPSS, version 20.0) to assess possible sources of contamination, relative behavior, and parameter interdependency. After laboratory examination and consecutive statistical analysis, the data were analyzed using GIS. The geostatistical tool of ARC GIS was used to interpolate water quality data. The inverse distance weighted (IDW) method was used with the spatial analyst extension of ArcGIS 10.8. The experimental results from the analysis were collated as an Excel file and converted into a shapefile in ArcGIS. Ground-checking proved the interpolation's validity.

2.2. Water quality classification by indexing

2.2.1. Nutrient index

The application of NI helps classify the lake water with respect to its nutrients. Comparison and indexing of the components with their respective standards to provide a single-value trophic conditions can be analyzed effectively. Nutrient enrichment is widely regarded as a serious environmental concern, resulting in water quality degradation in any lentic ecosystem. The calculation and classification of NI were introduced by the Chinese National Environmental Monitoring Center (Lin 1996; Xiao *et al.* 2007).

NI was formulated using Equation (1):

$$\mathrm{NI} = \frac{C_{\mathrm{COD}}}{S_{\mathrm{COD}}} + \frac{C_{\mathrm{TN}}}{S_{\mathrm{TN}}} + \frac{C_{\mathrm{TP}}}{S_{\mathrm{TP}}} + \frac{C_{\mathrm{Chl-a}}}{S_{\mathrm{Chl-a}}} \tag{1}$$

where C_{COD}, C_{TN}, C_{TP}, and $C_{\mathrm{Chl-a}}$ are the concentrations of chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) (mg/L), and chlorophyll-a (Chl-a) (μg/L) in lake water, respectively. S_{COD}, S_{TN}, S_{TP}, and $S_{\mathrm{Chl-a}}$ are the recommended maximum concentrations for COD (3 mg/L), TN (45 mg-NO_3/L), TP (0.03 mg/l), and Chl-a (12 μg/L) (IS:2296 1982).

2.2.2. Organic pollution index

The OPI is comprehensive and measures the composite effects of multiple parameters such as COD, DIN (dissolved inorganic nitrogen), DIP (dissolved phosphate), and DO on surface water quality. The OPI was calculated using Equation (2) (Liu *et al.* 2011):

$$\mathrm{OPI} = \frac{\mathrm{COD}}{\mathrm{CODs}} + \frac{\mathrm{DIN}}{\mathrm{DINs}} + \frac{\mathrm{DIP}}{\mathrm{DIPs}} + \frac{\mathrm{DO}}{\mathrm{DOs}} \tag{2}$$

where CODs, DINs, DIPs, and DOs are the recommended maximum concentrations (IS:2296 1982). OPI is categorized as <1 = uncontaminated (Class I), 1–2 = contamination beginning (Class II), 2–3 = lightly polluted (Class III), 3–4 = moderately polluted (Class IV), and >4 = heavily polluted (Class V).

2.2.3. Water quality index

Surface water quality assessment for human use and consumption is frequently performed using the weightage-based arithmetic WQI. The composite influences of different surface water physicochemical parameters are reflected by the single numerical WQI value, which also evaluates the influence of geogenic and anthropogenic activity as they affect drinking water quality (Gupta *et al.* 2016; Singh *et al.* 2018; Kumar *et al.* 2019). In this study, 11 physicochemical parameters including pH, EC, TDS, total hardness (TH), turbidity, DO, COD, chloride (Cl^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), Chl-a, and their recommended/prescribed maxima by WHO (2006) and BIS (2012) were used for pre- and post-monsoon WQI calculation. For this, the weightage (W_a) for each parameter is set between 1 and 5, based on their relative influence on water quality (Table 1). Initially, the relative weight (W_r) is estimated using Equation (3).

$$W_r = \frac{W_{ai}}{\sum_{i=1}^{n} W_{ai}} \tag{3}$$

where W_r and W_a are the relative and assigned weightage of the parameters, and n denotes the number of parameters.

Table 1 | Water parameter weightage assignment for the WQI, using WHO (2006) and BIS (2012) standards for human consumption

		BIS standards (2012)			
Parameter	**WHO recommendations (2006)**	**Desirable**	**Permissible**	**Weight (W_i)**	**Relative weight (W_r)**
pH	6.5–8.5	6.5–8.5	NX	4	0.114
EC (μS/cm)	2,000	2,000	NX	3	0.086
TDS	1,000	500	2,000	4	0.114
TH	–	200	600	3	0.086
Turbidity	–	1	5	2	0.057
DO	5	≥ 5	NX	2	0.057
Cl^-	250	250	1,000	4	0.114
COD	10^a	–	–	3	0.086
NO_3^-	45	45	NX	5	0.143
PO_4^{3-}	0.3	0	NX	3	0.086
Chl-a	10^b	–	NX	2	0.057
				$\sum W_a = 35$	$\sum W_r = 1.000$

[a] INWQS 2008.
[b] Carlson & Simpson 1996.
NX, no relaxation.

Secondly, the quality rating scale (Q_i) of each parameter is calculated using Equation (4):

$$Q_i = \left[\frac{(C_i - V_i)}{(S_i - V_i)}\right] \times 100 \tag{4}$$

where Q_i is the quality rating; C_i is the concentration of each chemical parameter; V_i is the ideal value of each parameter (taken as 0 for all except pH (7) and DO (14.6)); and S_i is the standard recommended/permissible maximum prescribed by WHO (2006) and BIS (2012) for each parameter.

Finally, the WQI is estimated using the parameters' sub-indices (SI) values as per Equations (5) and (6):

$$\mathrm{SI}_i = W_r * Q_i \tag{5}$$

$$\mathrm{WQI} = \sum \mathrm{SI_i} \tag{6}$$

The computed WQI was categorized following the suggested categorization of water quality (Gupta *et al.* 2016; Singh *et al.* 2018; Kumar *et al.* 2019) as: excellent ($WQI < 25$), good (WQI: 25–50), moderate (WQI: 51–75), poor (WQI: 76–100), and very poor ($WQI > 100$).

3. RESULTS AND DISCUSSIONS

3.1. General characterization of Aritar Lake

The physio-chemical analytical results are presented in Table 2. The water temperature showed distinct seasonal fluctuations, with values between 17 and 19 °C during the pre-monsoon season, and between 7 and 10 °C during the post-monsoon season. The pH value of lake water ranged 6.5–6.7 (pre-monsoon) and 6.3–6.6 (post-monsoon) during the observation periods, with the majority of samples being within the recommended pH tolerance limits (6.5–8.5) (IS:2296 1982).

Table 2 | Statistical summary of Aritar Lake's physicochemical parameters during pre- and post-monsoon seasons

	Pre-monsoon				Post-monsoon			
Parameter	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**
Temp. (°C)	15	18	16.50	1.26	6	10	8.17	1.34
pH	6.5	6.7	6.62	0.09	6.3	6.6	6.45	0.10
EC (μS/cm at 25 °C)	71.25	84.4	77.83	4.67	67.2	151.5	109.35	27.14
TDS (mg/L)	36.7	47.2	41.95	3.75	32.5	66.15	49.33	11.46
Turbidity (NTU)	19.2	23.8	21.65	1.49	15.6	38.75	27.18	7.79
TH (mg/L)	20	25.8	22.88	2.04	16.8	21.6	19.24	1.65
DO (mg/L)	2.6	3.8	3.20	0.46	3.6	5.8	4.53	0.76
COD (mg/L)	14.5	17.6	15.70	1.02	18.2	25.6	21.02	2.59
Cl- (mg/L)	4.9	6.6	5.75	0.52	4.3	5.6	4.95	0.50
TN (mg/L)	0.92	1.34	1.15	0.16	1.2	1.8	1.52	0.20
TP (mg/L)	0.06	0.09	0.08	0.01	0.1	0.14	0.12	0.01
Chl-a (μg/L)	52	83	67.50	10.74	27	49	38.00	7.92

TDS was between 36.7 and 47.2 mg/L, and 32.5 and 66.15 mg/L during pre- and post-monsoon seasons, respectively; all within the permissible limits (500–1,500 mg/L) (IS:2296 1982). EC, an indirect form of measure of TDS, relating only to ionic species, was invariably higher – 67.2 to 151.5 μS/cm – post-monsoon, while comparatively low – 71.25 to 84.4 μS/cm – pre-monsoon. Turbidity was between 19.2 and 23.8, and 15.6 and 38.75 NTU during pre- and post-monsoon seasons.

Elevated post-monsoon values for these parameters can be linked to higher runoff from the catchment and higher turbulence during heavy rains. As per the Indian standard (IS:2296 1982), DO exceeding 4 mg/L indicates a healthy water body, but pre-monsoon DO levels were between 2.6 and 3.8 mg/L, while post-monsoon DO ranged between 3.6 and 5.8 mg/L. COD, an indirect proxy for potential pollutants, was between 14.5 and 17.6, and 18.2 and 25.6 mg/L in pre- and post-monsoon analyses, respectively. The additional anthropogenic influx through catchment runoff during the peak tourism seasons and post-monsoon months may result in higher post-monsoon concentrations.

The lake water's chlorine content has higher values in the pre-monsoon period (4.9–6.6 mg/L) than post-monsoon (4.3–5.6 mg/L). Soluble iron concentrations were between 0.15 and 1.2 mg/L during the pre-monsoon season, and 0.1 and 1.3 mg/L during the post-monsoon season, with little variation. Sulfate concentrations were higher (0.1–0.14 mg/L) during the pre-monsoon season and lower (0.08–0.12 mg/L) during the post-monsoon season, perhaps in the latter case due to dilution by rainfall.

Measurement of Chl-a, with TP and TN, provides a comprehensive picture of a water body's trophic condition, following the EPA National Eutrophication standards (Table 3). Low nutrient levels and Chl-a content result in low productivity in lake water systems – i.e., oligotrophic conditions. A mesotrophic condition may arise due to moderate nutrient content and Chl-a, while higher nutrient and Chl-a (>12 μg/L) concentrations indicate high

Table 3 | Classification of lake water by EPA National Eutrophication Survey (1974)

EPA National Eutrophication Standards (1974)	**Chlorophyll-a (μg/L)**	**Total phosphorus (μg/L)**	**Total nitrogen (μg/L)**	**Trophic condition**
	<7	<10	<400	Oligotrophic
	7–12	10–20	400–600	Mesotrophic
	>12	>20	>600	Eutrophic
Present study				
Season	**Chlorophyll-a (μg/L)**	**Total phosphorus (μg/L)**	**Total nitrogen (μg/L)**	**Lake's trophic state**
Pre-monsoon	67.5	75	1,130	Eutrophic
Post-monsoon	38	120	1,500	Eutrophic

productivity levels and are eutrophic. These parameters can also affect the level of phytoplankton in a lentic ecosystem, phytoplankton play an important role in nutrient-rich freshwater providing oxygen for aerobic organisms and degrading organic compounds (Phu 2014), an important regulating factor for maintaining lake ecosystem equilibrium. When a lake's productivity increases significantly, leading to higher phytoplankton biomass, the water becomes eutrophic, impacting the health of the lentic ecosystem and becoming a long-term matter of concern as constant unregulated eutrophic conditions can lead to the lentic system's ecological death. In this study, TP ranged between 60 and 90 μg/L (pre-monsoon), and 100 and 140 μg/L (post-monsoon), while TN was between 920 and 1,340 (pre-monsoon), and 1,200 and 1,800 μg/L (post-monsoon). Chl-a, which determines lake productivity directly, was between 52 and 83, and 27 and 49 mg/L during pre- and post-monsoon, respectively. The observations show that nutrient levels and algal abundance in the lake water are noticeably higher than the recommended eutrophication levels in both seasons – i.e., the water body is highly eutrophic.

3.2. Evaluation of nutrient enrichment, organic pollution, and classifying Aritar Lake water using NI, OPI, and WQI

NI was computed to elaborate the lake water's nutrient enrichment status. Wastewater discharges from surrounding settlements make a major contribution to the nutrient load, and, with runoff from settlements and agricultural zones, nutrient enrichment poses a severe threat. Because algae respond invariably to nutrient loading, excess algal biomass can affect habitat quality by altering DO concentrations, turbidity, biotic community structure, and the ecosystem's aesthetic value (Royer *et al.* 2008). Although nutrient loading and phytoplankton growth are essential for lentic ecosystems, high, above-optimal algal growth to algal blooms and eutrophication, ultimately degrading water quality and hindering aquatic life. If $\mathrm{NI} > 4$, eutrophic conditions are indicated. The lake's NI was between 4.61 and 7.31, and 2.75–4.69 during pre- and post-monsoon seasons, respectively (Figure 2), clearly suggesting significant nutrient enrichment and subsequent hyper-eutrophic conditions. This arises from prevailing environmental conditions including organic matter input from forest-dominated areas, wastewater discharged from human settlements, and the lake's shallow profile, which favors phytoplankton growth.

In this study, the OPI ranged from 0.93 to 1.35 (pre-monsoon) with an average of 1.15, and 1.34–2.06 – mean 1.65 (post-monsoon). Clearly the organic load has already begun to pollute the lake's water, with sampling station S4 classified as 'lightly polluted' during the post-monsoon season (Figure 3). A higher average post-monsoon might be linked to higher, peak tourist season discharges of wastewater from the lake's surroundings.

The relationship between Chl-a and nutrients is often influenced by factors such as flooding, grazing, and shading, making it difficult to distinguish between the effects of human disturbances and natural variations (Dodds & Welch 2000). Statistical study has shown significant correlations ($r = 0.797$) between NI and OPI during the pre-monsoon season, which could be due to similar spatial distribution of nutrient trends and organic pollutants coming from a common origin, i.e., anthropogenic sources. On the other hand, weak NI and OPI post-monsoon correlations ($r = 0.262$) can be explained due to nutrient and organic pollutant concentrations that are attributed to a variety of sources, including anthropogenic, geogenic, and runoff water, as well as being influenced by temporal factors.

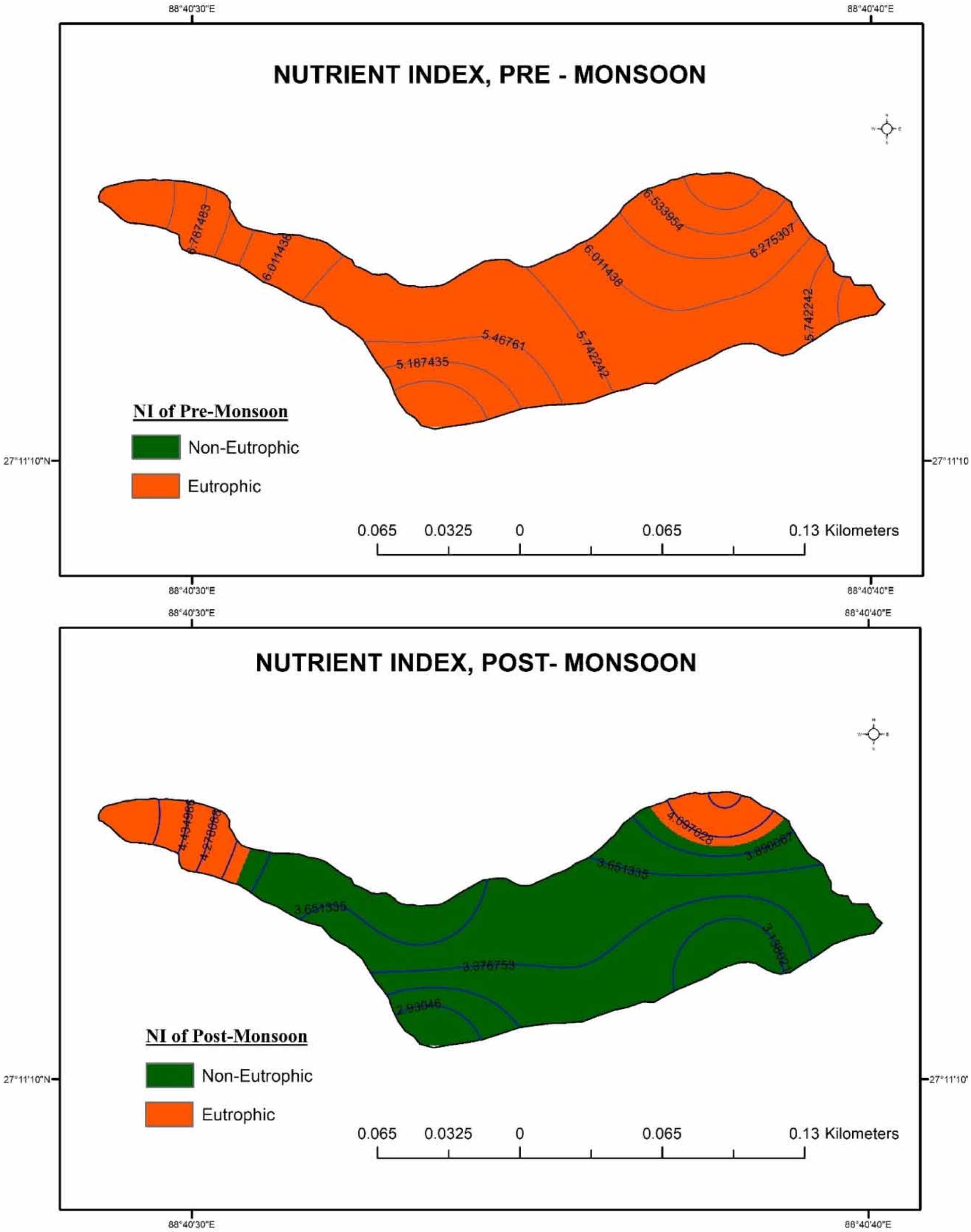

Figure 2 | Spatial distribution of the NI in Aritar Lake.

Based on cross-tabulation analysis, the result of the Pearson χ^2 test between OPI and NI is insignificant (0.224), indicating that the lake's nutrients and organic pollutants subjected to and influenced by diverse factors.

The WQI reflects a comprehensive view of significant physicochemical water quality parameters, and 11 parameters (Table 2) were considered in this study. The spatial distribution of Aritar Lake's WQI is explicated in Figure 4 for the pre- and post-monsoon seasons. Aritar Lake's WQIs ranged from 79 to 99.12 during the pre-monsoon season, indicating that the water is in the 'poor' category for drinking. Post-monsoon, the WQI range was

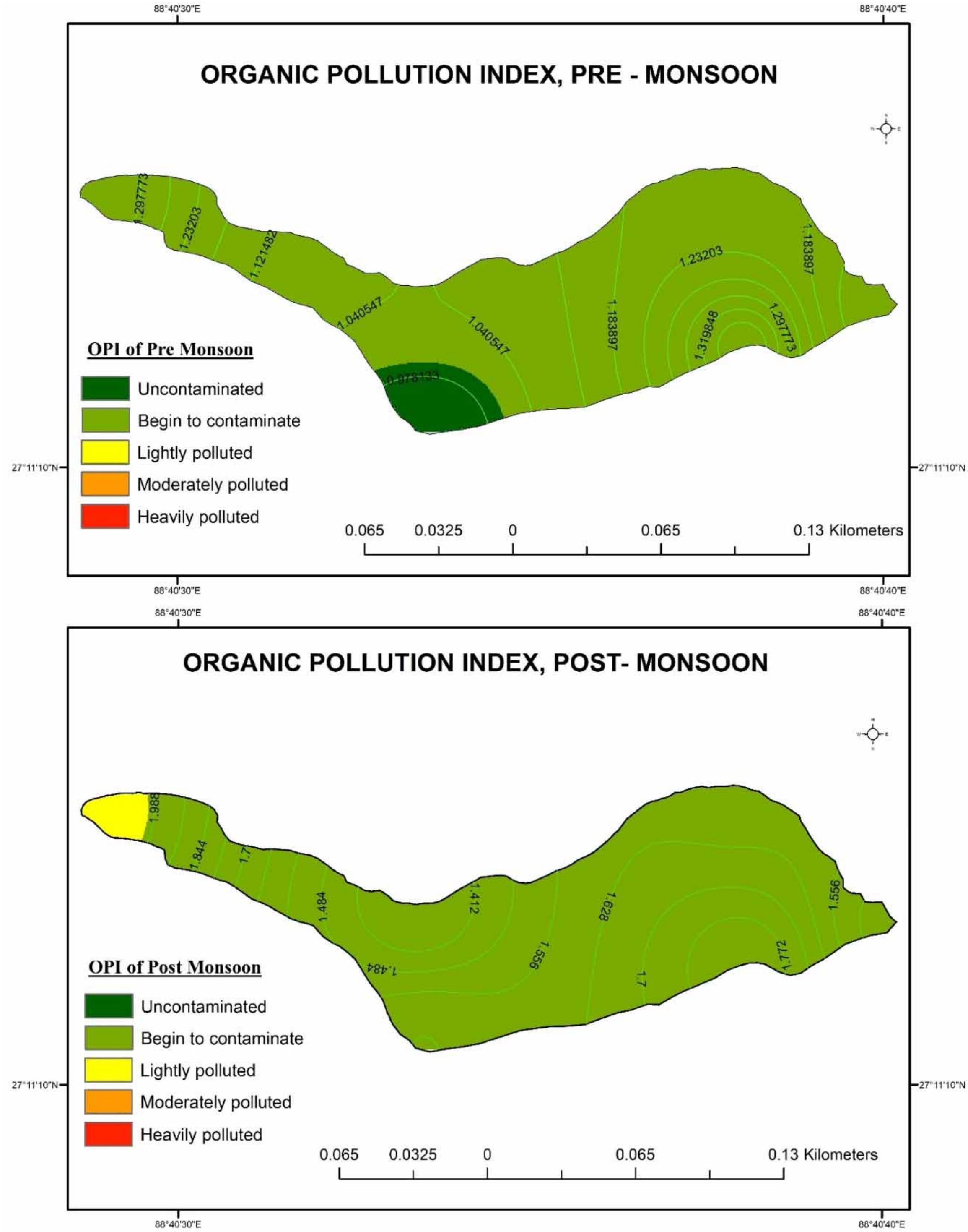

Figure 3 | Spatial distribution of the OPI in Aritar Lake.

between 75.25 and 109.55, the ‘moderate to very poor’ range. In general, the lake water does not seem to be of ‘good quality’ in either season and, therefore, cannot be considered for drinking purposes without proper treatment.

The study revealed a clear eutrophic condition and a pollution load that exceeded the lake’s natural biocapacity. Nutrient concentration management in aquatic systems is highly important since nutrient loads influence ecological processes other than algal growth, including heterotrophic respiration (Dodds 2006).

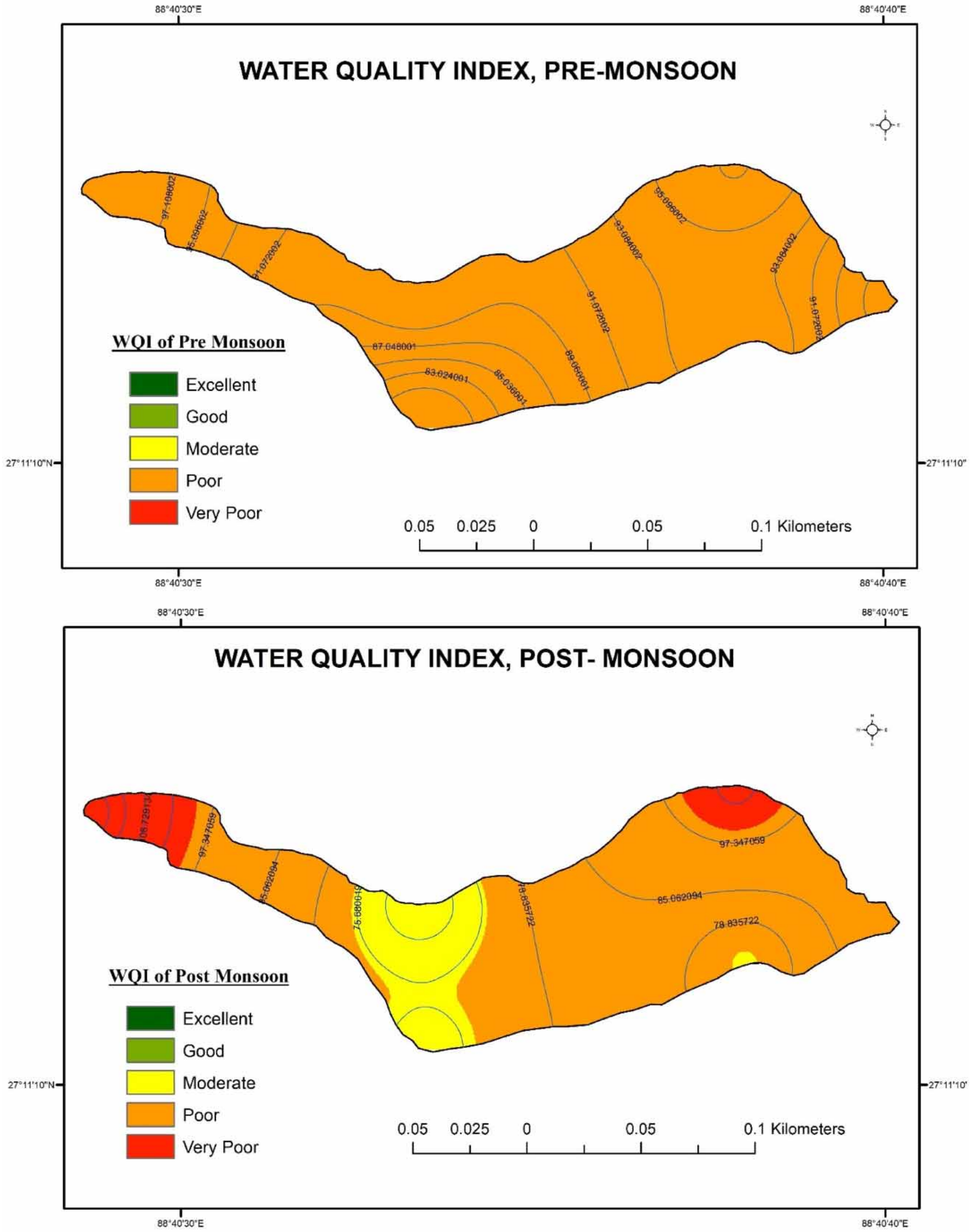

Figure 4 | Spatial distribution of the WQI in Aritar Lake.

4. MULTIVARIATE ANALYSIS AND STATISTICAL INTERPRETATIONS

4.1. Correlation of the variables analyzed

Correlation analysis is used to measure the strength of linear association between variables and calculate their relationship. In this study, Pearson's rank correlation method (two-tailed) was used. In the end, some water quality parameter correlations were significant at the 0.05 level (*) while some reflected significance at the 0.01 level (**).

During the pre-monsoon season (Table 4), temperature is statistically significant with TH (0.835*) and Cl^- (0.862*), and EC with TDS (0.971**) and turbidity (0.949**). TH is also statistically significant with DO (0.816*), COD (0.858*), TP (0.878*), and Cl^- (0.919**), while DO is statistically significant with Cl (0.867*), COD (0.894*), TP (0.886*), and TN (0.844*) respectively, and Cl^- with COD (0.891*) and TP (0.844*). COD is also statistically significant with TP (0.876*), as is TDS with turbidity (0.885*).

During the post-monsoon season (Table 4), temperature is statistically significant with pH (0.842*), turbidity (0.903*), TP (0.865*), TDS (0.990**), and Cl^- (0.966**). EC is statistically significant with TH (0.827*), turbidity (0.883*), and COD (0.838*), and TDS with turbidity (0.881*), TP (0.898*), and Cl^- (0.967**). TH is also statistically significant with DO (0.866*), TP (0.909*), and COD (0.962**), and turbidity with Cl^- (0.915*) and TP (0.838*), whereas COD is statistically significant with TP (0.858*) and TN (0.890*). Furthermore, DO is statistically significant with COD (0.874*), and Cl^- with TP (0.825*).

4.2. Cluster study

CA classifies sets of variables into groups so that those in the same group are more similar to each other than those in other groups. CA enabled identification of two distinct groups for the pre-monsoon season (Figure 5). Group 1 showed close association between COD and Cl^- (and TH), and Cl^- with TP and TN, which can be attributed to anthropogenic contributions and wastewater discharges from nearby settlements. In Group 2, the close alliance between EC and TDS is very obvious. On the other hand, the post-monsoon dendrogram showed a close relationship between EC, TDS, and TN, as the water's conductivity is primarily determined by dissolved ionic species.

4.3. Principal components analysis

PCA is used to minimize the dimensionality of a dataset. In this study, it was carried out in relation to the pre-and post-monsoon parameter values. The Eigen value is considered more than 1.

During the pre-monsoon season, component 1 (PC 1) shows the highest variation, about 65%. Subsequently, Component 2's (PC 2) variation is approximately 15%, and Component 3's (PC 3) around 10% (Table 5). The variations for the remaining components are insignificant.

PC 1 deals with temperature, EC, TDS, TH, turbidity, DO, Cl^-, COD, TP, TN, and Chl-a, and can be attributed to the combined influence of anthropogenic contributions and temporal factors. PC 2 demonstrates high EC, TDS, and turbidity loadings, which can be linked to geogenic and lithogenic sources. PC 3, which consists of pH, describes ongoing geo-physical and chemical mechanisms that determine the hydro-chemical nature of lake water systems.

Post-monsoon, PC-1 again shows the highest variation, at about 69%. PC 2's variation is approximately 16%, and PC 3's around 9% (Table 5). Again, the variations for the remaining components are insignificant. In the post-monsoon season, PC 1 showed high temperature, pH, EC, TDS, TH, turbidity, DO, Cl^-, COD, TP, and TN loadings, which can be linked to anthropogenic contributions and geo-climatic factors. PC 2, demonstrated for TN, can be attributed to agricultural runoff and cattle sheds, and PC 3 – essentially Chl-a –can be associated to algal components arising from nutrient enrichment in the lake system.

5. FACTORS AFFECTING ARITAR LAKE WATER AND CONSERVATION MEASURES AND MANAGEMENT POLICIES

Natural ecosystems maintain inert equilibrium through self-regulating energy flows, but are sensitive to external stimuli. Human activities to benefit socio-economic targets disrupt the natural equilibrium, degrading the ecosystem's long-term health. If ecosystem health is not controlled, this can lead to the system's death, having a domino effect on nature as well as the anticipated socio-economic goals.

Aritar Lake is an integral component of the local community, which depends on and benefits from lake-centric tourist activities. The large number of tourists means an elevated anthropogenic load into the lake, with direct impacts on its ecosystem. Apart from the anthropogenic contributions, rock weathering, soil erosion, and runoff from the catchment, as well as litter deposited in the lake are also accountable for changing the lake water's physicochemical characteristics. Local stakeholders have a significant role to play, therefore, they can take up cleaning and other conservative measures to reduce the lake's inorganic load. Revised environmental protection policies should also be implemented.

Table 4 | Aritar Lake correlation investigation during pre- and post-monsoon seasons

	Temp	**pH**	**EC**	**TDS**	**TH**	**Turbidity**	**DO**	**Cl^-**	**COD**	**TP**	**TN**	**Chl-a**
Pre-monsoon												
Temp	1	−0.026	0.511	0.643	0.835*	0.523	0.659	0.862*	0.662	0.536	0.508	0.313
pH		1	0.421	0.295	0.402	0.556	0.527	0.466	0.676	0.725	0.452	0.355
EC			1	0.971**	0.38	0.949**	0.396	0.683	0.520	0.369	0.640	0.150
TDS				1	0.447	0.885*	0.496	0.750	0.540	0.389	0.736	0.272
TH					1	0.53	0.816*	0.919**	0.858*	0.878*	0.501	0.491
Turbidity						1	0.414	0.742	0.604	0.521	0.531	0.130
DO							1	0.867*	0.894*	0.886*	0.844*	0.786
Cl^-								1	0.891*	0.844*	0.746	0.547
COD									1	0.876*	0.667	0.461
TP										1	0.647	0.706
TN											1	0.792
Chl-a												1
Post-monsoon												
Temp	1	0.842*	0.694	0.990**	0.618	0.903*	0.552	0.966**	0.560	0.865*	0.141	0.36
pH		1	0.753	0.799	0.531	0.77	0.644	0.713	0.535	0.674	0.192	0.198
EC			1	0.661	0.827*	0.883*	0.665	0.638	0.838*	0.770	0.669	0.537
TDS				1	0.648	0.881*	0.594	0.967**	0.603	0.898*	0.192	0.395
TH					1	0.704	0.866*	0.551	0.962**	0.909*	0.793	0.363
Turbidity						1	0.498	0.915*	0.693	0.838*	0.398	0.638
DO							1	0.405	0.874*	0.802	0.686	0.114
Cl^-								1	0.513	0.825*	0.129	0.528
COD									1	0.858*	0.890*	0.516
TP										1	0.542	0.408
TN											1	0.537
Chl-a												1

*Correlation is significant at the 0.05 level (two-tailed).

**Correlation is significant at the 0.01 level (two-tailed).

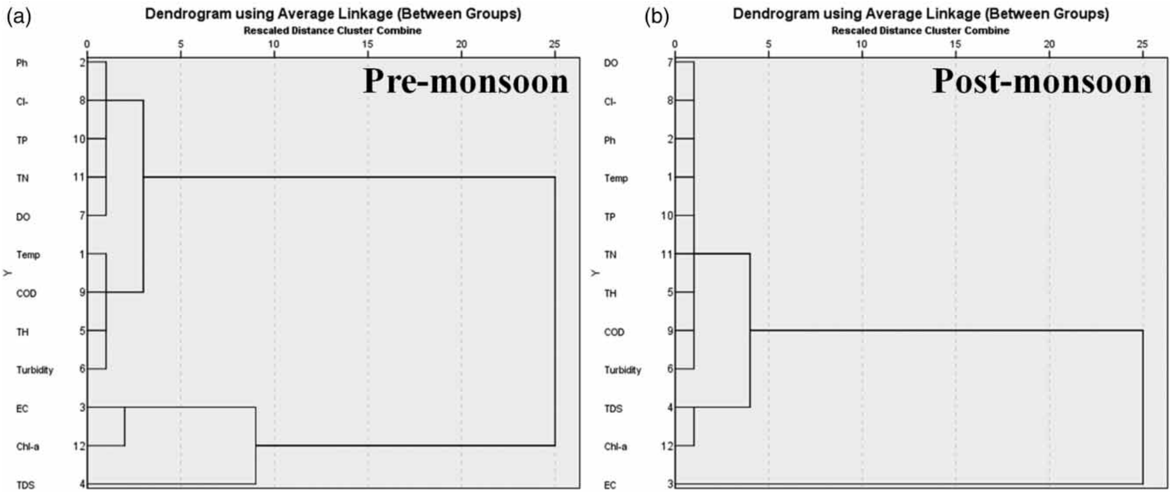

Figure 5 | Cluster study (dendrogram based on hierarchical clustering) of variables in Aritar Lake, during pre- and post-monsoon seasons.

Table 5 | PCA during pre- and post-monsoon seasons

	Component matrix					
	Pre-monsoon			**Post-monsoon**		
Variables	**PC 1**	**PC 2**	**PC 3**	**PC 1**	**PC 2**	**PC 3**
Temp.	**0.750**	0.114	−0.647	**0.877**	−0.472	−0.073
pH	0.598	−0.133	**0.741**	**0.789**	−0.327	−0.267
EC	**0.719**	**0.671**	0.149	**0.90**	0.148	0.091
TDS	**0.768**	**0.594**	−0.027	**0.888**	−0.418	−0.064
TH	**0.854**	−0.229	−0.306	**0.886**	0.378	−0.149
Turbidity	**0.761**	**0.579**	0.190	**0.926**	−0.24	0.235
DO	**0.902**	−0.38	−0.05	**0.782**	0.358	−0.469
Cl^-	**0.978**	0.024	−0.186	**0.837**	−0.498	0.161
COD	**0.909**	−0.162	0.041	**0.884**	0.464	−0.019
TP	**0.876**	−0.391	0.136	**0.958**	−0.004	−0.121
TN	**0.835**	−0.047	0.116	0.598	**0.786**	0.151
Chl-a	**0.623**	−0.546	0.075	0.538	0.108	**0.815**
Eigenvalue	7.785	1.845	1.197	8.289	1.948	1.115
Variability (%)	64.874	15.373	9.975	69.073	16.231	9.292
Cumulative %	64.874	80.247	90.222	69.073	85.304	94.596

Extraction method: PCA. Three components extracted.
The values highlighted in bold represent higher loading in particular extracted components.

6. CONCLUSIONS

The study showed distinct seasonal variations in the parameters measured, but they were within the desired limits for surface water. The concentrations of TP, TN, and Chl-a showed the lake's highly eutrophic nature. The NI was determined and showed highly eutrophic lentic ecosystems in both seasons. The higher post-monsoon NI can be associated with greater anthropogenic release during peak tourist seasons.

The OPI was also calculated and showed a similar pattern with 'contaminating starting' apparent in both the pre- and post-monsoon seasons.

The lake is an integral part of the Himalayas' fragile alpine ecosystem, as well as aiding the socio-economic life of a dependent local population. Hence, a sustainable approach is the only way to address environmental concerns quickly while acting strategically and effectively. For instance, *in situ* lake cleaning, including de-weeding, de-silting, bioremediation, bio-manipulation, nutrient reduction, etc., can be executed to address the issues. Catchment-related actions including silt traps, afforestation around the lake, lake fencing, shoreline development, low-cost sanitation, and other initiatives may also prove helpful in conserving this natural aquatic system.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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