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Trophic classification and assessment of lake health using indexing approach and geostatistical methods for sustainable management of water resources

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ABSTRACT

This study aims to analyse the spatio-temporal trends in water quality, trophic state, and organic contamination of an alpine lake in the Darjeeling Himalaya through field investigations and to portray a comprehensive picture using multivariate analysis. Analysed water parameters have shown notable seasonal variations and were within the acceptable range for inland surface water. Water quality index (WQI) and organic pollution index (OPI) values have displayed 'poor' to 'heavily polluted' status in the pre-monsoon season, with marginally better conditions during the post-monsoon studies. Trophic state indices (TSIs) values revealed 'eutrophic to highly eutrophic' conditions during the investigation period. The results of the PCA have depicted three major determining factors (i.e., anthropogenic contribution, geogenic or weathering, and seasonal/climatic factors) that control the overall pollution level in the lake water system. The current study can potentially be a benchmark for assessing and undertaking management and restoration measures for this nascent alpine ecosystem.

Key words: anthropogenic influence, eutrophication, mountain lake, organic pollution, water quality index (WQI), water resource management

HIGHLIGHTS

- Assessment of water quality and trophic state of the lake on a spatio-temporal scale.
- Geospatial appraisal of lake health using indexing approach, i.e., WQI, OPI, and NI.
- Application of multivariate statistics to delineate influencing factors and pollution sources.
- The findings will assist in the sustainable management of the lake water system.

1. INTRODUCTION

Lakes are an important natural resource present on earth's landscape. They are not only a source of water, but also provide ecological, social, and cultural benefits. Alpine lakes hold high significance in mountainous regions because they meet the household demand for water in remote areas. Due to their natural beauty and high ecological value, these lakes attract a lot of migratory species and lake-centric tourism cultures, thereby contributing significantly to local economic growth and ecological footprint. However, any lake ecosystem survives by maintaining a general level of health, and this largely depends upon the lake's exposure to various environmental factors and anthropogenic interventions. High nutrient interference from human activities, accelerated by disposing of wastes, greatly changes the natural background quality of lake water. The different anthropogenic problems associated with the lake environment include effluents/wastewater discharge, addition of diffused nutrients from adjacent crop fields, and over-exploitation of the lake for recreation activities that interfere with lake productivity and deteriorate its water quality (Sharma *et al.* 2010).

The trophic conditions in lake water are also greatly influenced by erosion, the influx of sediments, and nutrients from the lake watershed. Addition of nutrients in excess disturbs the natural balance of N/P (Redfield ratio of

N:P of 16:1), which results in algal blooms, fish kills, and many related problems (Davidson *et al.* 2012). The protection and preservation of the integrity of the lake water ecosystem are often considered a matter of priority due to the limited availability of fresh-water resources and the human interference that results in the degradation of the water quality (Parween & Ramanathan 2019). WQI is a very useful method for the overall assessment of water quality for its intended uses, such as drinking or domestic purposes, while multivariate statistical analysis suggests the influential sources of contamination (Singh *et al.* 2017). In order to conserve any lake ecosystem, it is highly important to have a complete overview of the lake's water quality at any particular time, so as to harness any necessary measures to improve the health of the lake and its water (Bhateria & Jain 2016).

The field investigation for the present study was conducted on Sumendhu lake, also known as Mirik lake, which is a renowned tourist destination in the Darjeeling hills, West Bengal, India. This lake provides the utmost touristic attraction to the area, and the other potential factors are integrally linked with tourism. The lake (geographical location: 26°53″163′N–26°53″620′N and 88°11″190′E–88°10″943′E) was developed in 1979 to facilitate tourism in the area (Figure 1). It has an average altitude of 1,767 m, covering an approximate area of 16.19 ha. The initial maximum depth of the lake was 7.92 m, and an arch-style bridge of around 24.38 m long runs across the lake. The lake is drained by the River Mechi, located at its' western frontier. Geographically, the location provides breathtaking views where glimpses of the hills with wildflowers appeal to the eyes of visitors. The farmlands spread across the valleys provide a spectacular view, which makes it way different from the other hill stations. Malley (1999) in his reports on the Darjeeling district talks about the beautiful streams, lakes, and lush green tea gardens, these were the main centres of attraction during the colonial period. Mirik is also marked with the trekking routes to Sandakphu, Phalut. Mirik is the largest supplier of oranges in the State of West Bengal. Mirik loads take the visitors to the nearest Bokar Ngedon Chokhor monastery, which provides a splendid view of the hills and the lake. It lies on the southern side of the lake and is the best place to inculcate

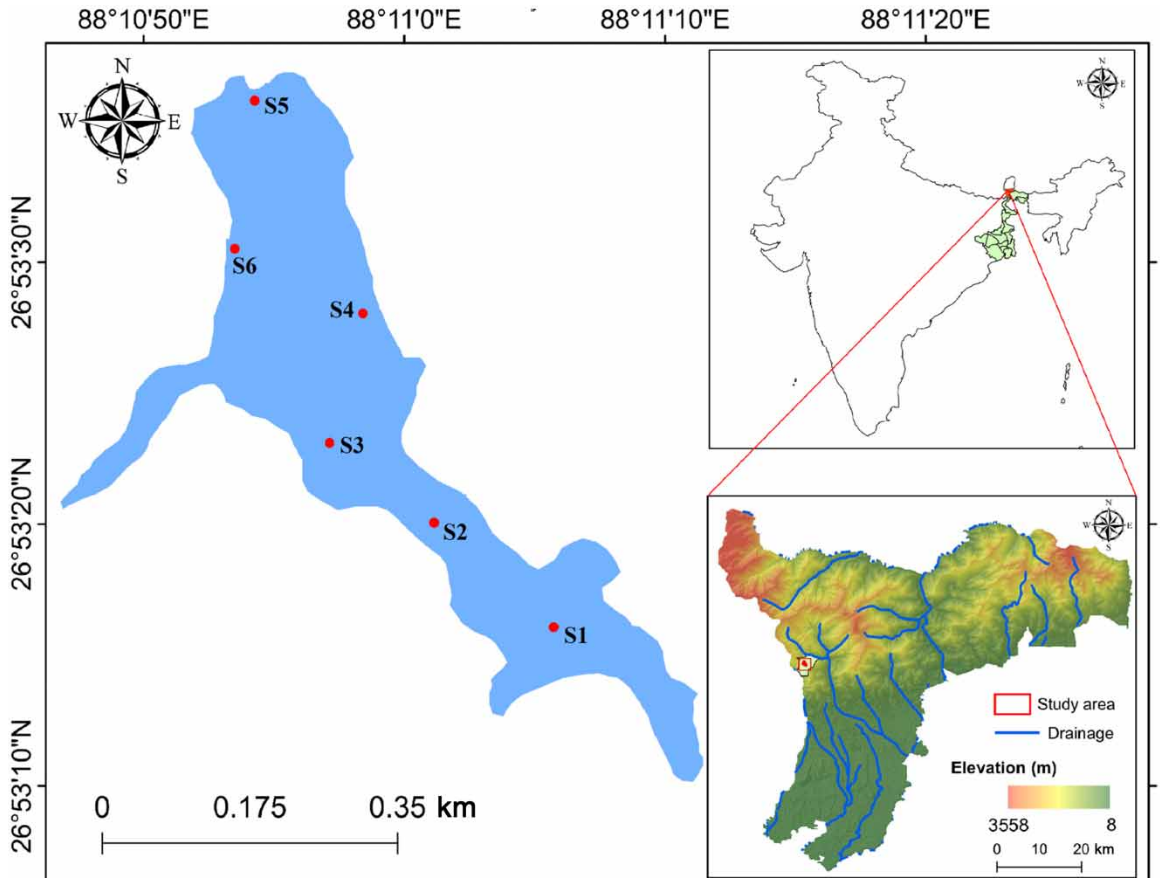

Figure 1 | Location of the study area.

the local art and culture of the region. The lake also witnesses certain rituals and acts of the local inhabitants which could be included as a part of inclusive tourism practices where the local communities could be engaged in the process of livelihood practices (Guha 2016). Of late, boating, fishing, and hosting picnics have been initiated as part of recreation. Picturesque valleys covered with dense trees line the western side of the lake, while the eastern bank is surrounded by a market which is directly dependent on the influx of tourists onto the lake site. Mirik, therefore, provides outstanding opportunities for tourism.

It was revealed in the recent study (Dutta *et al.* 2019) that most of the respondents strongly pointed out the fact that excessive human influence and the growing hotel industry had caused significant ecological degradation of the lake ecosystem. At the same time, contrastingly, they favoured the development of tourism businesses and hotel industries adjacent to the lake area, specifically for the socio-economic benefits of the region. The lake is an important part of the socio-economic structure of the locals residing nearby. It can be well assumed that the death of the lake will result in the crumbling of the local socio-economic structure.

Earlier, several studies evaluated the deuteriation of the water quality and biological diversity of Mirik lake due to direct discharges of sewage water and dumping of solid waste from nearby residential areas (Roy & Nandi 2012; Roy *et al.* 2017; Dutta *et al.* 2019). The present study evaluates the interdependency and interrelationship among the monitored water parameters by using multivariate statistical tools and also monitors the nutrient loading, trophic status, and water quality for drinking purposes of the Mirik lake water. The entire dataset used in this study is obtained from 3-year observation period (2018–2020) which is subjected to various statistical applications. Our current research will concentrate on (i) spatio-temporal variations in measured variables in lake water in relation to lake water quality, (ii) classification of lake water using indexing approaches such as the organic pollution index (OPI) and trophic state indices (TSIs), (iii) identifying the influence of geogenic and anthropogenic factors in the lake environment using geostatistical methods, and (iv) strategic steps for sustainable management of lake water resources.

2. MATERIALS AND METHODS

2.1. Field sampling and analytical procedure

The field investigation was conducted during 2017–2019, covering the pre-monsoon and pre-monsoon seasons. Six different sampling sites were selected for the purpose of water sample collection, of which two were located at the peripheral zone and four samples were collected in the middle of the lake. Water samples were collected in 1 L sterilized containers. pH, EC, TDS, and DO were measured on site using multi-parameter hand analysers (Eutech Instruments). Collected water samples were brought immediately to the laboratory for further physico-chemical characterization. Sample collection, preservation, and analysis were performed as per standard methods (APHA 2005). All laboratory glasswares were pre-treated with 2% HNO_3 solution, rinsed severally with ultrapure deionized water, and finally kept overnight at 40 °C in the oven to avoid further contamination. The reagents were used for the analysis of AR grade obtained from Merck, India. To ensure accuracy, every analysis of water parameters was run triplicated (the results were good agreement within $\pm$5%), and the mean values were considered for data presentation and interpretation. Multivariate statistical analysis such as Pearson's correlation, principal component analysis (PCA), and cluster analysis (CA) on the analytical results of water samples was performed using statistical software (SPSS, version 20.0) to find the possible sources of contamination, relative behaviour and the interdependency nature among the parameters.

3. RESULTS AND DISCUSSION

3.1. General characterization of lake water

The spatial and temporal results of monitored water parameters are summarized in Table 1. The recorded pH values of lake water samples were found to be within the neutral range (7.05 $\pm$ 0.44) during the post-monsoon and shifted marginally towards alkaline (8.25 $\pm$ 0.38) during the pre-monsoon season. Seasonal variations were noted for EC, TDS, and TSS contents in lake water, which revealed their higher values in the post-monsoon compared to pre-monsoon period (Table 1). This observation can be explained due to surface runoff influx and soil erosion during the rainy season in lake catchment areas, which result in an increase in suspended and dissolved solids in the lake water. The measured values for dissolved oxygen (DO) ranged between 4.90 and 8.40 mg/L in post-monsoon season with an average of 6.43 mg/L ($\pm$1.35) and between 3.40 and 6.20 mg/L during the pre-monsoon period with an average of 4.97 mg/L ($\pm$1.02).

Table 1 | Descriptive statistics of measured lake water parameters, along with standards of drinking water (BIS 2012) and surface water (IS:2296 1982)

Water parameters	Pre-monsoon				Post-monsoon				Indian standards for surface water (IS:2296)	BIS (2012), drinking water standards	
	Min	Max	Mean	SD	Min	Max	Mean	SD		Desirable	Permissible
pH	7.7	8.6	8.25	0.38	6.3	7.6	6.98	0.50	6.5–8.5	6.5–8.5	NX
EC (μS/cm at 25 °C)	228	490	333.33	103.67	274	560	429.00	95.22	–	–	–
TSS (mg/L)	16	29	21.62	4.89	28	46	36.40	6.91	–	–	–
TDS (mg/L)	153.24	325.6	223.69	68.72	185.4	378.5	289.47	64.71	500–1,500	500	2,000
TA (mg/L)	86	147	116.17	22.96	64	136	95.33	26.85	–	–	–
TH (mg/L)	28	52	37.68	8.54	16	24	19.97	2.74	300.00	–	–
DO (mg/L)	3.4	6.2	4.97	1.02	4.9	8.4	6.43	1.35	4.00	–	–
BOD (mg/L)	4.6	7.8	6.12	1.26	2.6	4.3	3.47	0.64	3.00	–	–
COD (mg/L)	27	38.5	32.58	4.50	16.5	27.5	21.33	4.05	–	–	–
Cl^- (mg/L)	16.5	24.5	20.87	3.30	9.8	17.2	13.72	3.03	250–600	250	1,000
SO_4^{2-} (mg/L)	1.7	2.6	2.20	0.35	0.9	1.8	1.42	0.35	400.00	200	400.00
Total PO_4^{3-} (mg/L)	0.08	2.1	1.29	0.74	0.02	1.4	0.44	0.61	–	–	–
Total NO_3^- (mg/L)	3.6	8.7	6.10	1.78	0.09	2.8	1.72	1.00	20–50	45	NX
Chl-a (μg/L)	46.5	78.4	61.70	11.87	22.9	43.8	35.12	8.50	–	–	–
Fe (mg/L)	0.64	0.9	0.78	0.09	0.52	0.76	0.65	0.09	0.3–50	0.3	NX

NX, no relaxation, i.e., values/concentrations within the desirable limit are only acceptable; no values/concentrations are permitted/acceptable beyond the recommended standards.

Increased DO levels in the post-monsoon season could be attributed to turbulence caused in lake water due to precipitation and the influx of runoff water into the lake system. Total hardness (TH) and chloride (Cl^-) showed marginally lower values in the post-monsoon season (Table 1) due to dilution effect caused by the infusion of rainwater. Increased DO levels in the post-monsoon season could be attributed to turbulence caused in lake water due to precipitation and the influx of runoff water into the lake system. Biological oxygen demand (BOD) is found to be a little higher than the inland surface water quality guideline during both seasons. The nutrient components (i.e., total nitrogen (TN) and total phosphorous (TP)) in lake water showed clear seasonal variations, of which notable variability was recorded in TN content. The measured values for nutrient components were recorded to be on the higher side during the pre-monsoon season in comparison to the post-monsoon (Table 1). This finding can be correlated to the higher rate of evaporation in the pre-monsoon season (i.e., summer), and also due to the dilution effect during the monsoon period. Likewise, elevated chlorophyll-a (Chl-a) content was recorded during the pre-monsoon and lower values were recorded during the post-monsoon season. This situation can be related to the higher level of nutrients, particularly TP in the lake water during the same period, which promotes algal growth and, therefore, chlorophyll-a content in a monitored lake. Findings of the present investigation on lake water system suggested that concentrations of measured water parameters are very much within the acceptable range for surface waters (IS:2296 1982), with few exceptions.

3.2. Computation of water quality index and OPI

3.2.1. Evaluation of water quality index

The water quality index (WQI) is a well-defined tool that replicates the composite influence of individual physico-chemical parameters on overall water quality (Sahu & Sikdar 2008; Gupta *et al.* 2016). To estimate the WQI, the assigned weightage (w_i), relative weightage (W_i) and recommended standards (WHO 2006; Bureau of Indian Standards (BIS) 2012) for drinking water quality parameters such as pH, EC, TDS, TA, TH, SO_4^{2-}, Cl^-, NO_3^-, PO_4^{3-} and Fe for both seasons are represented in Table 2. The assigned weightage on physico-chemical

Table 2 | Relative weight of physico-chemical parameters

Parameters	WHO standards (2006)	BIS standards (2012)		Weight (w_i)	Relative weight (W_i)
		Desirable value	Permissible value		
pH	6.5–8.5	6.5–8.5	NX	4	0.114
EC	2,000	2,000	NX	3	0.086
TDS	1,000	500	2,000	5	0.143
TA	200	200	600	2	0.057
TH	–	200	600	3	0.086
Cl^-	250	250	1,000	4	0.114
SO_4^{2-}	200	200	400	4	0.114
NO_3^-	45	45	NX	5	0.143
PO_4^{3-}	0.3	–	–	3	0.086
Fe	0.3	0.3	–	2	0.057
				$\sum w_i = 35$	$\sum W_i = 1$

parameters ranges from 1 to 5. Firstly, the relative weight (W_i) is formulated by the following equation.

$$W_r = \frac{w_i}{\sum_{i=1}^{n} w_i}$$

where W_r, w_i, and n represent the relative weight, weight of each physico-chemical parameter, and the number of parameters, respectively.

Secondly, a quality rating scale (q_i) for every parameter is calculated as the concentration of each parameter towards its recommended standard value laid by BIS (2012) and WHO (2006), and multiplied the result by 100:

$$q_i = \frac{C_i}{S_i} * 100$$

where q_i, C_i, and S_i are defined as the quality rating, the concentration of each water parameter (mg/L), and the standard for drinking water of each parameter (mg/L) according to the BIS (2012) and WHO (2006).

Finally, the sub-index (SI) is then determined for each water parameter, which is used to determine the WQI as per the following equation:

$$\mathrm{SI}_i = W_r * q_i$$

$$\mathrm{WQI} = \sum \mathrm{SI}_i$$

where SI_i and q_i are noted as the sub-index and the rating based on concentration of ith parameter, respectively.

The classification of WQI is: excellent (Class A) (WQI < 25), good (Class B) (WQI: 25–50), moderate (Class C) (WQI: 51–75), poor (Class D) (WQI: 76–100), and very poor (Class E) (WQI > 100).

WQI values give a clear representation of the utilisation of lake water for drinking and other purposes. Calculated results have revealed that WQI values range from 32.8 to 94.75 with a mean value of 72.91 and most of the samples fell under 'Poor' categories (except S1, 'Good') during the pre-monsoon (Table 3). While in post-monsoon, the WQI varies from 25.31 to 94.75 with an average of 44.47 and the majority of samples were of 'Good' water quality (except S5, 'Poor' and S6, 'Moderate'). WQI values of lake water demonstrate notable variations in the quality of water in various sampling locations (Figure 2). A maximum decline in water quality is observed at sampling point S5, due to the discharge of wastewater and raw sewage from nearby human settlements. The obtained results infer that the lake's water quality in some locations is at an alarming stage. Therefore, necessary initiatives and measures should be taken on an urgent basis for proper management of the lake and restoration of the lake ecosystem to achieve the desired water quality.

Table 3 | Lake water quality classification using WQI and organic pollution status (OPI)

WQI

	Pre-monsoon			Post-monsoon		
Sampling stations	**WOI**	**Class**	**Status**	**WOI**	**Class**	**Status**
S1	32.80	B	Good	25.31	B	Good
S2	69.09	C	Moderate	36.02	B	Good
S3	79.81	D	Poor	31.35	B	Good
S4	90.58	D	Poor	31.98	B	Good
S5	94.75	D	Poor	78.58	D	Poor
S6	70.41	D	Poor	63.59	C	Moderate
Mean ± SD	72.91 ± 22.21	C	Moderate	44.47 ± 21.43	B	Good

OPI

	Pre-monsoon			Post-monsoon		
Sampling stations	**OPI**	**Class**	**Status**	**OPI**	**Class**	**Status**
S1	1.02	II	Begin to contaminated	0.95	I	Good
S2	4.56	V	Heavily polluted	1.48	III	Begin to contaminated
S3	6.30	V	Heavily polluted	1.27	III	Begin to contaminated
S4	7.41	V	Heavily polluted	1.20	III	Begin to contaminated
S5	8.38	V	Heavily polluted	6.24	V	Heavily polluted
S6	4.69	V	Heavily polluted	4.78	V	Heavily polluted
Mean ± SD	5.39 ± 2.61	V	Heavily polluted	2.65 ± 2.27	III	Lightly polluted

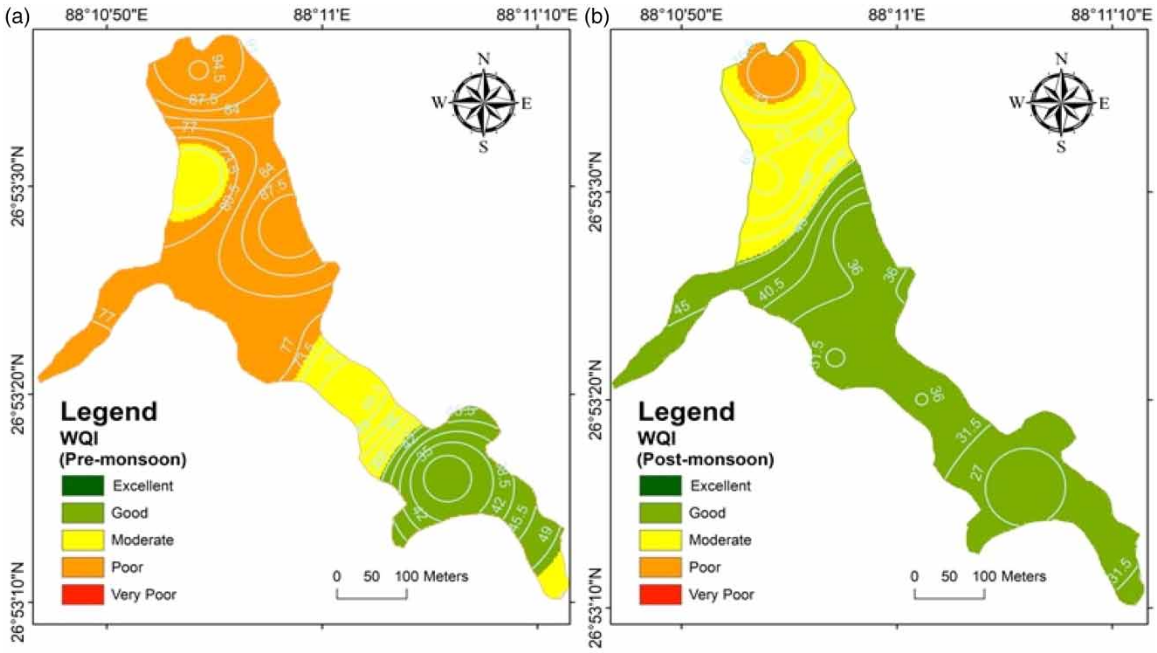

Figure 2 | WQI in lake water during pre-monsoon and post-monsoon seasons.

3.2.2. Development of OPI

The OPI is widely used to determine the comprehensive effects of COD, DIN, DIP, and DO on surface water quality (Saksena *et al.* 2008). The OPI value is computed by the following equation:

$$\mathrm{OPI} = \frac{\mathrm{COD}}{\mathrm{COD_S}} + \frac{\mathrm{DIN}}{\mathrm{DIN_S}} + \frac{\mathrm{DIP}}{\mathrm{DIP_S}} + \frac{\mathrm{DO}}{\mathrm{DO_S}}$$

where DIN, DIP, COD, and DO represent the dissolved inorganic nitrogen, dissolved inorganic phosphorus, chemical oxygen demand, and dissolved oxygen, respectively. DIN_S, DIP_S, COD_S, and DO_S are defined as the standard concentrations of the above parameters as mentioned in IS:2296. The OPI is classified as: <1 = uncontaminated (Class I), 1–2 = Begin to be contaminated (Class II), 2–3 = Lightly polluted (Class III), 3–4 = Moderately polluted (Class IV) and >4 = Heavily polluted (Class V).

The calculated OPI in the lake water was found to be within the range of 1.02–8.38 and 0.95–6.24 in the pre-monsoon and post-monsoon seasons, respectively. The highest OPI value was recorded for S5 which can be explained due to discharge of sewage and wastewater from adjacent human settlements, while the lowest OPI value in S1 can be correlated to the least anthropogenic interference at that location (Figure 3). Furthermore, the mean OPI in the pre-monsoon season is notably higher in comparison to post-monsoon season (Table 3). This observation can be linked to the dilution effect due to the additional water influx in the monsoon season.

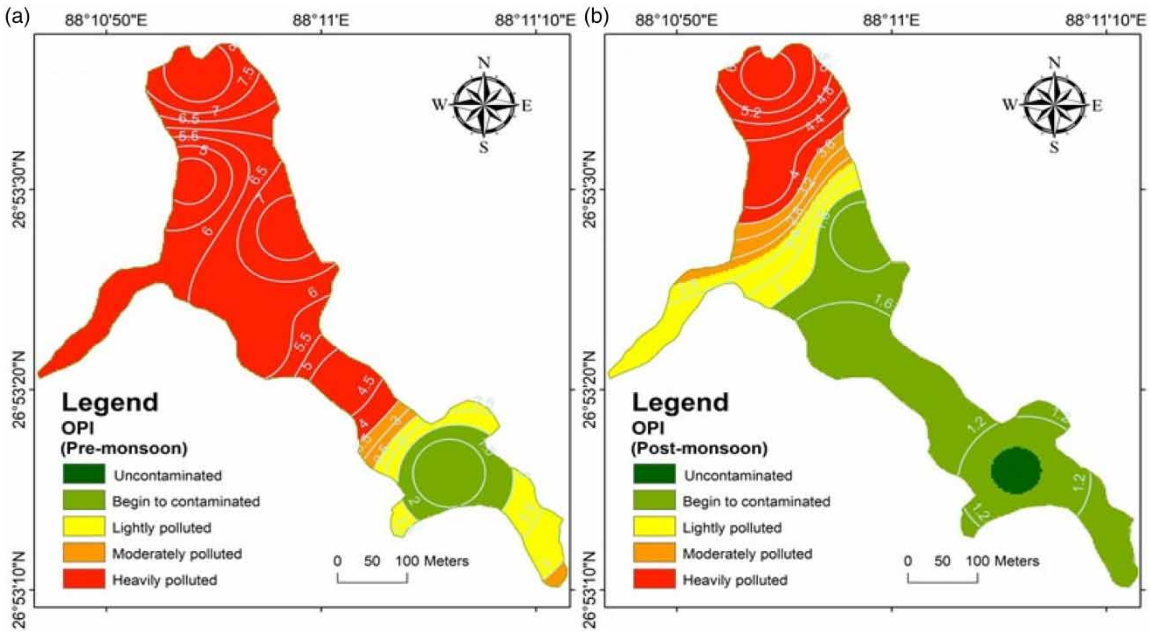

Figure 3 | OPI in lake water during pre-monsoon and post-monsoon seasons.

3.3. Nutrient index and TSIs for trophic classification of lake

Application of the nutrient index (NI) method and TSIs is very important as it helps to classify the lake water based on nutrient level and selected trophic-related water parameters individually, therefore initiating the preliminary steps towards lake management and conservation of aquatic ecosystem (Smith *et al.* 1999). High enrichment of nutrients is widely regarded as the major problem affecting the quality of water in any lentic ecosystem. Increased nutrients lead to high productivity thus facilitating algal bloom which greatly affects the water quality and also interferes with the overall ecological functions of the alpine lake.

NI is first introduced by the Chinese National Environmental Monitoring Center (Lin 1996) and formulated by the following equation:

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

where C_{COD}, C_{TN}, C_{TP}, and $C_{\mathrm{Chl\text{-}a}}$ are analysed values of concentrations of COD, TN, total phosphorus (all in mg/L), and chlorophyll-a (in μg/L) of lake water, respectively. S_{COD}, S_{TN}, S_{TP}, and $S_{\mathrm{Chl\text{-}a}}$ are the standard concentrations of COD (3.0 mg/L), TN (45 mg/L), total phosphorus (0.03 mg/L), and Chl-a (12 mg/L) in surface water, respectively (WHO 2006; BIS 2012). The value NI is >4, suggesting the water is classified as eutrophic. The dissolved nutrient content in the lake water showed distinct seasonal variations in different sampling stations during the observation period. The NI values of the lake water were found to be in the range of 4.33–13.88 and 2.04–8.49 during the pre- and post-monsoon season, respectively. However, the mean NI value in the pre-monsoon season is much higher than the post-monsoon season, which indicates that the lake is at high risk of eutrophication (Figure 4). The lower NI values in the post-monsoon season can be attributed to the dilution effect, which occurred as a result of precipitation and surface runoff influx.

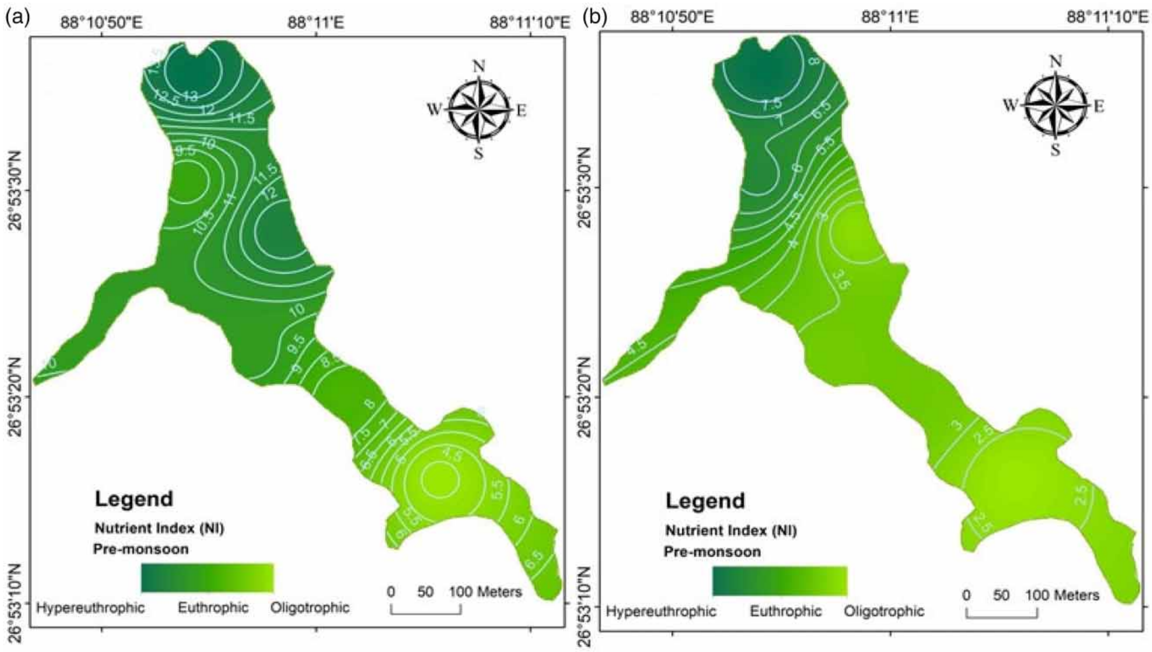

Figure 4 | Nutrient index (NI) values in lake water during pre-monsoon and post-monsoon seasons.

In the present study, the trophic state of lake water was assessed using selected trophic-related parameters such as Chl-a, TP, and TN, and evaluated by comparing them with the EPA National Eutrophication standards (Table 4). The results clearly indicated the levels of measured variables are notably higher than the EPA standards, which imply the eutrophic condition of lake water in both seasons (Table 5).

Table 4 | Trophic condition of Mirik lake based on concentrations of Chl-a, TP, TN in different seasons, along with EPA National Eutrophication Survey (1974)

Classification of trophic state of lakes based on EPA National Eutrophication Survey (1974)

Chl-a (μg/L)	Total phosphorous (μg/L)	Total nitrogen (μg/L)	Trophic condition	
<7	<10	<400	Oligotrophic	
7–12	10–20	400–600	Mesotrophic	
> 12	>20	>600	Eutrophic	
Chlorophyll-a (μg/L)				
Season	Min.	Max.	SD	Trophic condition
Pre-monsoon	46.50	78.40	11.87	Eutrophic
Post-monsoon	22.90	43.80	8.50	Eutrophic
Total phosphorous (μg/L)				
Season	Min.	Max.	SD	Trophic condition
Pre-monsoon	80	2,100	740	Eutrophic
Post-monsoon	20	1,200	550	Eutrophic
Total nitrogen (μg/L)				
Season	Min.	Max.	SD	Trophic condition
Pre-monsoon	3,600	7,200	1,320	Eutrophic
Post-monsoon	90	2,800	1,000	Eutrophic

Table 5 | Pearson correlation matrix for the Mirik lake water variables

Variables	pH	EC	TSS	TDS	TA	TH	DO	BOD	COD	Cl^-	SO_4^{2-}	PO_4^{3-}	NO_3^-	Chl-a	Fe
(a) Pre-monsoon															
pH	1	.891*	.454	.891*	.910*	.868*	.964**	.957**	.965**	.993**	.949**	.463	.601	.701	.965**
EC		1	.676	.999**	.682	.980**	.934**	.979**	.961**	.893*	.841*	.444	.611	.756	.919**
TSS			1	.679	.226	.732	.639	.581	.546	.415	.471	.674	.723	.598	.622
TDS				1	.680	.976**	.934**	.978**	.959**	.895*	.832*	.440	.595	.755	.917*
TA					1	.640	.785	.770	.789	.902*	.872*	.230	.515	.369	.806
TH						1	.939**	.964**	.956**	.848*	.874*	.581	.733	.824*	.940**
DO							1	.974**	.975**	.947**	.925**	.633	.685	.835*	.993**
BOD								1	.996**	.954**	.910*	.490	.615	.795	.966**
COD									1	.956**	.937**	.514	.639	.807	.975**
Cl^-										1	.909*	.381	.510	.667	.937**
SO_4^{2-}											1	.571	.782	.716	.962**
PO_4^{3-}												1	.768	.819*	.651
NO_3^-													1	.605	.749
Chl-a														1	.825*
Fe															1
(b) Post-monsoon															
pH	1	.940**	.545	.943**	.911*	.888*	.948**	.937**	.938**	.861*	.780	.691	.982**	.835*	.988**
EC		1	.767	1.000**	.938**	.962**	.932**	.954**	.950**	.902*	.882*	.763	.963**	.866*	.971**
TSS			1	.766	.735	.724	.668	.734	.720	.792	.884*	.687	.585	.493	.646
TDS				1	.945**	.962**	.940**	.961**	.956**	.911*	.885*	.771	.964**	.866*	.973**
TA					1	.954**	.992**	.982**	.997**	.936**	.833*	.916*	.885*	.860*	.914*
TH						1	.932**	.929**	.950**	.847*	.772	.877*	.901*	.941**	.900*
DO							1	.983**	.996**	.930**	.816*	.874*	.911*	.849*	.939**
BOD								1	.984**	.975**	.895*	.837*	.928**	.843*	.947**
COD									1	.934**	.838*	.886*	.910*	.851*	.940**
Cl^-										1	.951**	.786	.859*	.731	.890*
SO_4^{2-}											1	.639	.813*	.602	.851*
PO_4^{3-}												1	.647	.797	.682
NO_3^-													1	.863*	.988**
Chl-a														1	.815*
Fe															1

**Correlation is significant at the 0.01 level (two-tailed).
*Correlation is significant at the 0.05 level (two-tailed). Values highlighted in bold are indicate significant correlations.

The Trophic State Index (TSI) is a single quantitative index where numerical standardisation of selected variables is done. It is widely considered as a more realistic approach for classifying and evaluating the status of the lake;

TSI is calculated as

$TSI_{CHL} = 9.81ln(Chl - a) + 30.6$ (Carlson 1977)

$TSI_{SD} = 60 - 14.2ln(SD)$ (Carlson 1977)

$TPI_{TP} = 14.42ln(TP) + 4.15$ (Carlson 1977)

$TPI_{TN} = 54.45 + 14.43ln(TN)$ (Kratzer & Brezonik 1981)

Based on TSI Values, the lake can be distinguished as oligotrophic (TSI < 50), mesotrophic (TSI 50–60), eutrophic (TSI 60–70), and hypertrophic (TSI > 70). The temporal variations in TSIs ($TSI_{Chl\text{-}a}$, TSI_{TP}, TSI_{TN}, TSI_{SD}) of Mirik lake at different sampling locations are shown in Figure 5. The present investigation revealed that based on TSI_{chl} lake water was in eutrophic condition with a mean value of 65.25 in post-monsoon season and showed hypertrophic condition in pre-monsoon season having an average of 70.89. TSI_{TP} depicted hypertrophic conditions in both seasons with an average of 102.29 and 73.24 in pre- and post-monsoon, respectively. TSI_{TN} showed eutrophic conditions in post-monsoon season with a mean of 59.98 and hypertrophic conditions in pre-monsoon season with a mean of 80.00. Comparatively lower values are noted in post-monsoon season, and it can be corresponded to influx of rainwater, and surface runoff from lake catchment thus having a dilution effect onto lake water. TSI_{SD} had an average of 85.98 in post-monsoon and 78.50 in pre-monsoon season, SD transparency depicts higher value in the post-monsoon season. It can be clearly presumed that the primary productivity and nutrient level of the lake were very high throughout the study period.

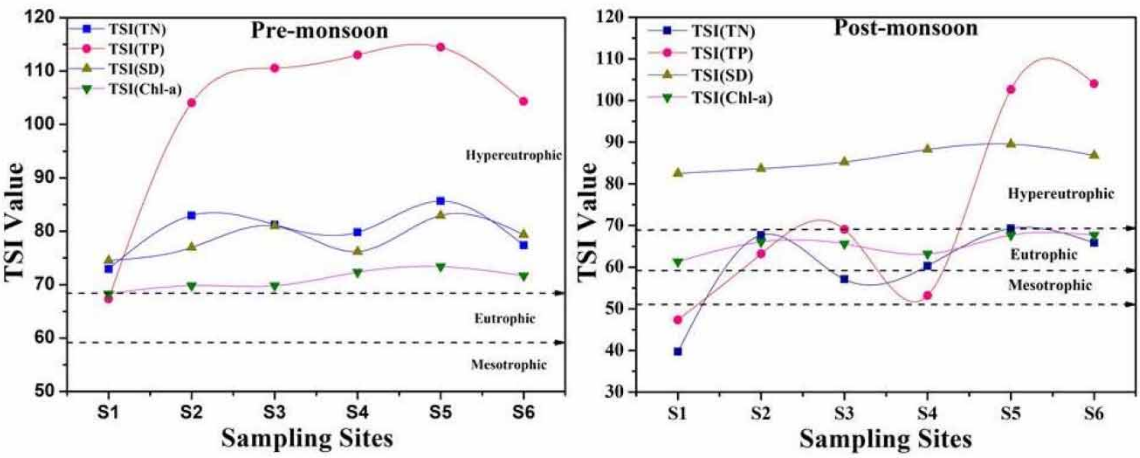

Figure 5 | Trophic condition of Mirik lake based on TSI_{Chl}-a, TSI_{TP}, TSI_{TN}, TSI_{SD} in different seasons during the study period.

3.4. Multivariate statistical approach

The multivariate analysis of the sample data has been carried out employing correlation analysis, PCA, and CA. The main objective behind performing the multivariate analysis is to identify the constituent sources and to distinguish factors associated with the natural and anthropogenic contributions to the lake ecosystem.

3.4.1. Correlation analysis

Correlation analysis is used to observe both interrelationship and interdependency among the analysed parameters and the correlation coefficient value nearer to +1 or −1 suggesting the strong or weak relationship among the examined parameters (Cengiz *et al.* 2017). In this study, the correlation analysis among the Mirik lake water parameter is represented in Table 5(a) and 5(b) for pre and post-monsoon season, respectively. A significant positive correlation is obtained among the variables such as pH vs EC, TDS, TA, COD, Cl^-, SO_4^{2-}, and Fe during the pre-monsoon, while in the post-monsoon significant correlation is obtained among pH with EC, TDS, TA, COD, Cl^-, NO_3^-, Chl-a, and Fe. These results suggest that the higher anthropogenic activities in vicinity of the lake surroundings. Strong positive correlation noted among EC-TDS, EC-TH, DO-BOD, BOD-COD, COD-Cl^-, and COD-SO_4^{2-} in both the season, i.e., in pre- and post-monsoon season, suggesting seasonal weathering of earth crust components and influx from nearby forest area. Particularly, strong positive correlation among COD vs NO_3^- and PO_4^{3-} and DO-Chl-a, TH-Chl-a, and PO_4^{3-}-Chl-a in post-monsoon and moderate positive correlation among TSS vs NO_3^- and PO_4^{3-} in pre-monsoon, suggesting seasonal effect highly influenced the tropic status of lake water.

3.4.2. Principal component analysis

PCA was used to extract the most important parameters explaining the quality of the water and determining the latent factors affecting the water quality. PCA (after varimax rotation) of analysed variables in the pre- and post-monsoon season extracts three principal components (PC1, PC2, and PC2), accounting for 97.759 and 99.123% of the cumulative variables of the dataset (eigen value >1), respectively and are shown in Table 6. In pre-monsoon season, the first principal component (PC1) exhibits higher loadings for pH, TA, DO, BOD, COD, Cl^-, SO_4^{2-}, Fe. This component can be linked to anthropogenic activity and exogenic contributions. The second principal component (PC2) accounts for EC, TDS, and TH; which can be attributed to geogenic factors such as soil erosion and mineral dissolution in the lake watershed. PC 3 shows higher loadings for TN, TP, and Chl-a, which infers lake water chemistry is influenced by trophic parameters due to excess nutrient loading in the lake water system. While during the post-monsoon season, the PC1 reveals higher loadings for pH, EC, TDS, TN, and Fe, which may occur due to the combined influence of anthropogenic contributions and temporal factors (such as precipitation and mineral dissolution). The PC2 accounts for TP and Chl-a; which is an indicative of eutrophic condition and excess nutrient in lake water. PC3 shows higher loadings for TSS, SO_4^{2-}, Cl^-, which can be linked with lithogenic and exogenic factors.

Table 6 | Varimax rotated PCA loadings matrix of Mirik lake water parameters

	Component (pre-monsoon)			Component (post-monsoon)		
Variables	PC1	PC2	PC3	PC1	PC2	PC3
pH	**.864**	.425	.252	**.873**	.373	.290
EC	.594	**.758**	.251	**.739**	.429	.496
TSS	.018	.642	.645	.197	.336	**.896**
TDS	.590	**.767**	.240	**.739**	.436	.498
TA	**.970**	.100	.099	.603	.637	.469
TH	.550	**.706**	.421	.628	.651	.381
DO	**.706**	.555	.421	.678	.583	.411
BOD	**.711**	.646	.273	.683	.504	.511
COD	**.742**	.589	.303	.654	.588	.458
Cl^-	**.861**	.469	.148	.591	.406	.655
SO_4^{2-}	**.837**	.295	.442	.549	.195	**.806**
PO_4^{3-}	.143	.198	**.934**	.277	**.871**	.395
NO_3^-	.403	.170	**.824**	**.887**	.320	.325
Chl-a	.336	.577	.602	.667	.679	.113
Fe	**.735**	.488	.468	**.849**	.324	.409

Extraction method: principal component analysis; Rotation method: Varimax with Kaiser normalization.
Rotation converged in nine iterations. Values highlighted in bold represent higher loading and show larger correlations with extracted PC.

3.4.3. Cluster analysis

Possible sources of contamination of the analysed parameters in lake water are evaluated by the hierarchical cluster analysis (HCA). This statistical tool is also explored the interdependency of multiple water quality parameters based on their chemical similarity and clustered them based on their strong interrelationship (Singh *et al.* 2005). The dendrogram from CA revealed the lake water parameters are into two and three statistically significant distinct clustered for pre- and post-monsoon season, respectively, and are shown in Figure 6(a) and 6(b). During pre-monsoon, Cluster 1 (C1) represents the higher influence of pH, EC, TDS, TA, TH, DO, BOD, COD, Cl^-, SO_4^{2-}, Fe, and Chl-a. Cluster 2 (C2) is included with TSS, NO_3^-, PO_4^{3-}, and Chl-a. This result of cluster 1 clearly revealed that

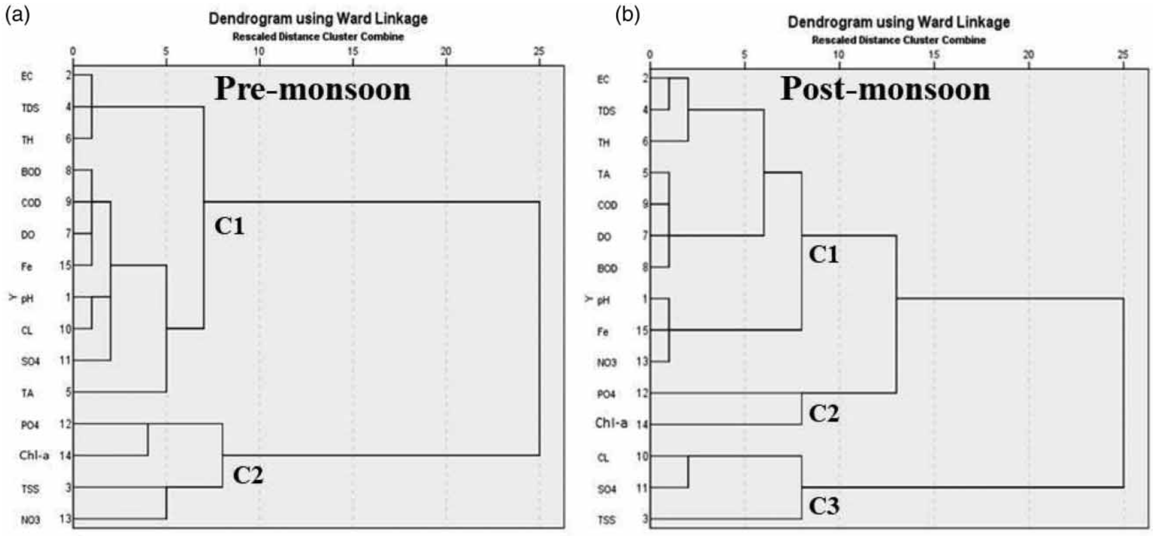

Figure 6 | Cluster analysis of measured variables in pre-monsoon and pre-monsoon seasons.

most of the ionic and anionic water parameters are mainly originated from anthropogenic activities in adjoining urban settlements. The result of CA is also in good agreement with correlation analysis. Whereas other clusters 2 is highly influenced by the lithogenic factor, i.e., seasonal weathering of the earth's crustal components and draining of soil minerals by surface runoff from the lake watershed. During post-monsoon, the first cluster (C1) is strongly associated with pH, EC, TDS, TH, TA, DO, BOD, COD, Fe, and NO_3^-, which describe their presence due to higher anthropogenic activities such effluents and sewerage discharges, along with temporal fluctuations. The second cluster C2 is strongly comprised with PO_4^{3-} and Chl-a (Figure 4(b)), that is contributed by the surface runoff from lake surroundings area and regulated nutrient loading of the lake water body. Cluster three (C3) is strongly associated with TSS, Cl^-, and SO_4^{2-}, and is contributed by the season affects and weathering of bed rocks of the lake watershed.

4. STRATEGIES FOR SUSTAINABLE MANAGEMENT OF LAKE WATER RESOURCES

Mirik lake, recognized as a popular tourist destination in West Bengal, is comprised of a pristine wetland with broad biodiversity and aesthetic exquisiteness. Therefore, many tourists frequently visit to ML every year. So, the local economy surrounding the ML area is significantly dependent on the tourism revenue. However, Mirik lake is experienced the severe deterioration in water quality over the years mainly due to manmade pollution. Subsequent to the development of Mirik lake as tourist attraction, Mirik town has been developed with unplanned human settlement. Insufficient drainage and lack of sewage system around the ML have practically transformed the lake into a sewage disposal reservoir. Discharge of wastewater into the lake water from nearby hotels and houses and throwing of garbage such as various types of plastics materials, pouches, packets, etc., into the lake water are observed as a common practice. In addition to that, local people have been using the ML for washing and bathing purposes. All these activities have triggered off the soil erosion and siltation in the lake system and aggravating the water pollution level of Mirik lake (Roy & Nandi 2012).

The present study revealed that the WQI is poor mainly in sampling stations S3, S4, S5, and S6 during the pre-monsoon season and in S5 during the post-monsoon season. The mean values of WQI of all six sampling stations highlight moderate and good during the pre and post-monsoon seasons, respectively. Similarly, the water classification based on OPI status has shown that the water is heavily polluted in sampling stations S2–S6, except S1 during the pre-monsoon season and in S5 and S6 during the post-monsoon season. The mean values of OPI of all six sampling stations reflect that the water is heavily polluted in pre-monsoon season and lightly polluted during post-monsoon season.

Based on observation and analytical results, some management strategies can be recommended on account of restricting the water pollution level as well as improving the ecological condition of Mirik lake. The government as well as local authority should take appropriate measures for ensuring a complete ban of sewage disposal into the lake water. Therefore, sewage treatment plants and proper sewerage system must be developed around the lake and simultaneously its proper maintenance should be taken care of. Similarly, littering with garbage at the Mirik lake adjacent areas must be banned. In addition, apt management related to the implementation of requisite security, sanitation facility, and lighting arrangement at night for tourists should be ensured at the ML surrounding areas. The daily monitoring and deweeding of the Mirik lake water must carry out as water quality (both biological and chemical) serves as a good eco-reflector. Additionally, cleaning of the overall lake surrounding area, desilting activities at frequent intervals, and afforestation programmes must be performed specifically to enhance Mirik lake's water capacity and at the same time minimising the chances of soil erosion nearby the lake. Also, it may be helpful to provide necessary alternate arrangements for washing and bathing for the local people. The efforts towards watershed management in ML catchment area can be useful. After all, the awareness campaigns regarding the importance of conserving lake water and the adjacent ecosystem must be carried out by the government, local authority, NGOs, etc., to educate the people more often (Roy *et al.* 2017).

5. CONCLUSION

To understand global environmental dynamics, it is essential to study remote and high-altitude alpine lakes, as these are important fresh-water resources for humans and living organisms in the hills and mountains. However, under the influence of tourism and anthropogenic interference, this lake can be considered as a model, portraying possible global degradation trends. The physico-chemical assessment of the lake water has shown notable seasonal variations, and higher values for EC, TDS, TSS, and DO were recorded in the post-monsoon season. Elevated levels of TDS and TSS are the result of not only anthropogenic contributions but also frequent landslides and soil erosion in the lake catchment area during the post-monsoon season. The turbidity and Cl^- can be well linked to sewage contributions and deposits through anthropogenic sources from surrounding human settlements and located nearby to the studied lake. The measured variables were within the permissible limits according to the Indian standards for surface water quality. However, the lake water was found to be highly eutrophic when concentrations of chlorophyll-a, TP, and TN were considered. The calculated values of $TSI_{chl\text{-}a}$ have shown the eutrophic state of lake water, while the results of TSI_{TP} and TSI_{TN} have depicted the hypertrophic condition of lake water during the investigation period. This observed trophic state in the lake water, from eutrophic to hypertrophic range, is a matter of serious concern, and it displays a steady sign of deterioration in the quality of lake water.

Correlation studies, CA, PCA have helped in establishing the relative interdependency of measured variables and possible source identification. Results from PCA have depicted the possible sources of pollution for the lake, which are both anthropogenic and natural, including recreational activities, municipal waste discharge, seasonal weathering, and soil erosion. CA has grouped the measured variables into three different clusters based on water quality characteristics and pollution levels. The study also revealed four distinctive pollution sources in the lake water system, such as suspended solids, nutrients, and natural organic and inorganic pollution and concluded that multivariate analysis is a useful and current tool for water quality monitoring and helps to suggest the future course of action for the restoration of the lake water ecosystem. Based on present observations, some relevant management strategies can be recommended on account of restricting the water pollution level as well as improving the ecological condition of the studied lake. However, further investigation into the sediment profile in the lake system, as well as a detailed survey on the socio-economic paradigm, may be necessary in the coming days to undertake restoration measures for the protection of the lake's water quality and health, as well as better management of the lake's surrounding areas.

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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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