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ORIGINAL RESEARCH PAPER

Physicochemical characteristics and trophic state evaluation of post glacial mountain lake using multivariate analysis

S. Nayek[1,*], *S. Gupta*[2], *K.K. Pobi*[3]

[1]*Department of Environmental Science, Amity Institute of Applied Sciences, Amity University, Kolkata, India*

[2]*Department of Environmental Science, The University of Burdwan, Golapbag, Bardhaman, West Bengal, India*

[3]*Department of Chemistry, Asansol Engineering College, Asansol, West Bengal, India*

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ABSTRACT: The current study deals with the physicochemical characterization, temporal variability and trophic state evaluation of a post glacial mountain lake in eastern Himalaya during the period of 2014-2016. Notable seasonal variations are recorded for physicochemical parameters of lake water. The values for electrical conductivity, total suspended solids, total dissolved solids, total alkalinity and Chloride are higher during the rainy season. Concentrations of total phosphorous (136.78±29.14 µg/L), total nitrogen (7177.78±1346.70 µg/L) and Chlorophyll-a (38.54±21.67 µg/L) in lake water are distinctly higher than the recommended standards for eutrophic condition of lake/surface water. Application of multivariate tools such as cluster analysis and principal component analysis reveals that ionic constituents of lake water are majorly associated to the geogenic and exogenic factors, with minor seasonal influences. Trophic state indices based on water transparency (3.15±1.57), total phosphorous (74.72±3.39), total nitrogen (82.64±2.83) exhibit hypertrophic nature of lake water; while trophic state index for chlorophyll-a indicate eutrophic condition. Deviations between Trophic state indices (TSI_{CHLa}-TSI_{SD}: -14±7.88, TSI_{CHLa}-TSI_{TP}: -9.17±3.33, and TSI_{CHLa}-TSI_{TN}: -17.56±5.29) infer that the nutrients (phosphorus and nitrogen) are not limiting factors for the algal biomass, and non-algal components such as suspended solids soil/sediment particles affects the light attenuation in the monitored lake. The observations reveal that trophic condition of monitored lake is in alarming stage. Therefore, measures should be taken on urgent basis in order to intercept the increasing trend in eutrophication, and for the restoration of water quality and integrated lake ecosystem.

KEYWORDS: *Limiting factors; Mountain Lake; Multivariate analysis; Physicochemical characterization; Temporal variations; Trophic state index (TSI).*

INTRODUCTION

A lake is a large body of water surrounded by land, inhabited by various forms of life. Each lake can be considered as a complex system formed in a particular geological period under specific environmental conditions, and functions based on the existing stable links between its components. Such systems are characterized by a set of internal properties and features, and the balance of which is primarily determined by the external influences. Lakes are subjected to various natural processes taking places in the environment like hydrologic cycle, weathering process, with unprecedented developmental activities. The important water parameters influencing the aquatic ecosystem are temperature, pH, total solids,

*Corresponding Author Email: *sumanta.nayek@gmail.com*
Tel.: +91 9474112075 Fax: +91 33 7102 0346

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dissolved oxygen and nutrient content; and these parameters are the limiting factors for the survival of aquatic organisms (Lawson, 2011). Eutrophication is one of the most ubiquitous environmental problems in inland surface waters, which is primarily subjected to enrichment with two nutrients, phosphorus and nitrogen added from anthropogenic sources (Davidson *et al.,* 2014). Evaluation of trophic status of aquatic ecosystems is an important scientific basis for sustainable water resource management and to preserve the integrity and ecosystem function (Ndungu *et al.,* 2013). Nutrients supplement from the lake watershed may influence the water quality and trophic status of lake water. Excessive inputs of nutrients (compounds of nitrogen and phosphorous) to the water body leads to the increased growth of algal biomass, and therefore causes many issues such as reduction in dissolved oxygen, water transparency, resulting in decline in water quality and subsequent adverse effects on human and lake ecosystem (Kane *et al.,* 2014; Wilkinson, 2017). Study of water quality and trophic state of inland surface waters has been the topic of interests for the researchers worldwide (Kane *et al.*, 2014; Doan *et al.*, 2015; Ali and Khairy, 2016; Sivakumar, 2016; Wilkinson *et al.*, 2017; Zhang *et al.*, 2017). Different water parameters were used for the evaluation of trophic state which includes Secchi disk depth, chlorophyll-a, total phosphorous and total nitrogen. Computation of Trophic state index (TSI) has been considered as a reasonable method for the assessment of trophic conditions (Carlson, 1977), and often used for classifying lakes. In India, several studies has been performed in recent past to analyze the trophic condition and eutrofication level of inland surface waters (Sheela *et al.*, 2011, Mishra and Garg, 2011; Gupta, 2014; Ganguly *et al.*, 2015; Saluja and Garg, 2017), but no such focus has been given to investigate the trophic conditions of mountain lakes. Sustainable management of the lake and preservation of its water resources require reliable information regarding the water quality and trophic conditions of lake water. Sikkim Himalayan region has been bestowed with some of the outstanding geological features with variety of natural resources. Water resources in this segment are available in the form glaciers, lakes, rivers and streams and natural springs. However, an increase in the rate of human development and urbanisation poses a significant threat to the lake ecosystem and water resources. Khacheopalri Lake is considered as one of the most sacred lakes in Sikkim and a popular pilgrimage sites for both Buddhists and Hindus. As a Holi Lake, its water is only used for rites and rituals, common human, household and agricultural uses are strictly prohibited. The influx of tourists and pilgrims are high throughout the season, which causes visible impacts on lake water and surrounding ecosystem Jain *et al.,* 1999; 2004. Previous investigations on this lake were majorly focused on hydrology, plankton diversity, hydro-ecological linkage, and land use/land cover changes in the lake catchment area (Jain *et al.,* 1999; 2000; 2004). The main objective of this study is to i) assess the limnological characteristics, seasonal variations in water parameters and trophic condition of lake, ii) relative contribution of selected variables to the trophic condition, and classify possible sources using multivariate approach, iii) identification of limiting factors controlling lake productivity. The study has been carried out in Khacheopalri Lake of India during the period of 2014-2016.

MATERIALS AND METHODS

Description of the study area

The Khacheopalri Lake is situated at an altitude of 1,700 m in the midst of pristine forest with Lat: 27°22′24″N Long: 88°12′30″E, near Khacheopalri village in the West district of Sikkim in India (Fig. 1).The lake represents the original 'neve' region of an ancient hanging glacier at the southern bank of the Lethang valley; the depression was formed due to the scooping action of glacier (Jain *et al.,* 1999; Chakrabarti, 2016). The lake is situated within Raman watershed on the southern boundary of the Khangchendzonga Biosphere Reserve. It has a drainage area of 12 sq.km, which includes broad leaved mixed forests, some agricultural lands with two villages, and bog area of approximately 70,100 sqm. The surface water spread area of the lake is 3.79 hectares, sparsely surrounded by boggy area. The dimension of lake has reduced significantly in compare to its original form due to encroachment of peripheral vegetation and eutrophication. Inflow into the lake is through two perennial streams, while the outflow is from one major outlet (Jain *et al.,* 1999; 2000). The lake catchment area mainly comprises of Kanchendzonga gneiss and sandy loam soil (Chakrabarti, 2016). The study area is characterized by three distinct season - rainy season (June – October) and winter season (November – March), with short summer season (April – May) in an

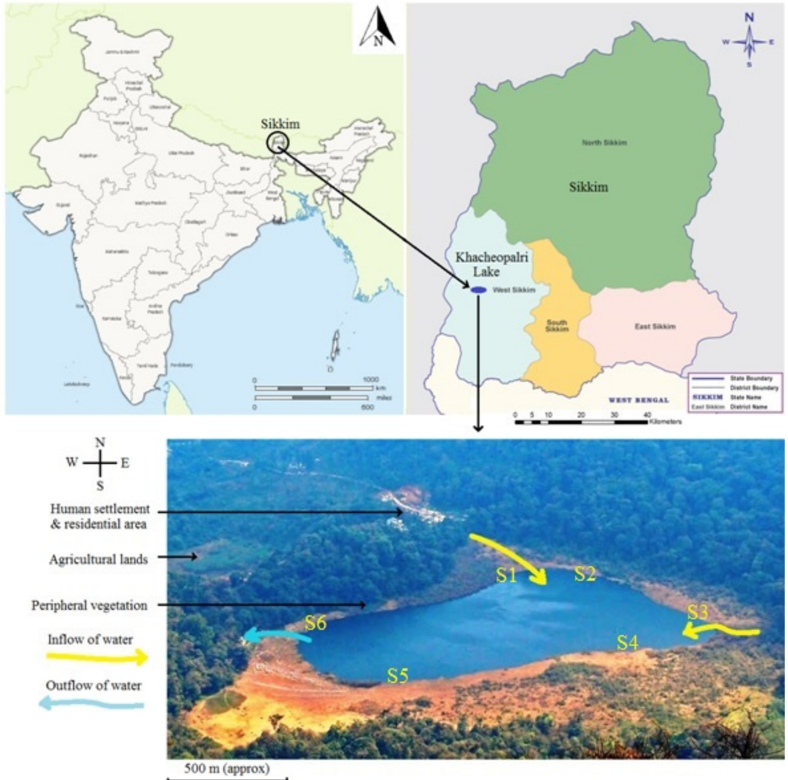

Fig. 1: Geographic location of the study area in eastern Himalaya

annual cycle. Temperature ranges from 3^0C (in winter) to 22^0C (in summer); with an estimated annual rainfall of approximate ≥ 3500 mm (Choudhury, 2006).

Collection of water samples

Six different sampling sites (S1-S6) were selected systematically (considering potential pollutant sources, water inlets, outlets, and geologically influenced areas) along the peripheral region of the studied lake for the purpose of lake water sample collection (Fig. 1). Water samples were collected at regular intervals (bi-monthly) from each sampling point during the period of 2014-16 covering all three season viz. summer (pre-monsoon), rainy (monsoon) and winter (post monsoon). For every sampling, three representative samples were collected from each sampling sites, and the mean values were considered. Water samples were collected at 1ft depth approximately from the surface level in pre acid washed 1L polythene containers, rinsed well with the sample water before fill it up to capacity, and taken to the laboratory for further physicochemical investigation.

Analysis of collected water samples

Temperature, pH, EC, TDS, DO were measured on field by using multi-parameter water quality analyzer (WQC-24). Rest, all other water parameters such as free CO_2, alkalinity, total hardness (TH), total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), chlorophyll-a (CHLa) were analysed in laboratory conditions following the standard methods (APHA, 2005). TSS was determined after filtered by GF/C filter papers. TP was determined in the unfiltered water by ascorbic acid method after persulfate oxidation. TN was measured in UV spectrophotometer after a potassium sulfate digestion. CHLa concentration was measured by using a spectrophotometer after extraction in ethanol. Secchi transparency (i.e. Secchi depth: SD) was determined from the empirical equation of total suspended solids $[\mathrm{Log}_{10}(\mathrm{SD}) = 0.76 - \mathrm{Log}_{10}(\mathrm{TSS})]$. Computation of light attenuation coefficient (K_{na}) is useful tool in order to assess the underwater light availability, and mechanism controlling light attenuation. K_{na} is calculated using Eq. 1 (Walker, 1982).

$$K_{na} = \frac{1}{SD} - (0.025 * CHLa) \quad (1)$$

Quality control assurance

Collection of water samples and its preservation were performed according to the standard methods (APHA, 2005). Mark reagents (AR grade) and standard solutions (suprapure grade) were used for routine laboratory analysis. All working and intermediate standard solutions were prepared using ultrapure water (resistivity=18.2/MΩcm) (Sartorius stedim biotech, arium®61316). Each parameter for collected water samples were analysed in three times replication to ensure the accuracy of analytical results. Blanks were also determined and used for background correction.All experimental results/calculations were standardized within 2% standard error (SE) level.

Statistical approach

The variations in selected water parameters and measured variables was determined and standardized by statistical techniques, and recorded as mean ± standard deviation (St.dev). Conventional graphical methods were used to furnish the nature of lake water. Bi-variate and multivariate statistical analysis i.e. Pearson correlations, Hierarchical Cluster analysis (HCA), and Principal component analysis (PCA), were performed to assess the relative influence/ interdependency of measured variables on each other, and to identify their possible sources.

RESULTS AND DISCUSSION

Physicochemical characterization of lake water and seasonal variations

The results obtained by physicochemical analysis of collected lake water samples are represented in Table 1. Noticeable variations are observed in measured water parameters due to temporal changes and exogenous factors. Temperature is considered as one of the prime factors in an aquatic environment as it affects various reactions in aqueous system. The temperature of lake water samples recorded as 18.7–19.4 ℃ during summer (post monsoon), 11.2–12.7 in rainy season (monsoon), and 6.9–8.6 during winter (post monsoon). The pH of water is a numeric expression of acidic or alkaline nature, which affects the solubility of ionic components and controls their fate in aqueous environment. The pH lake water samples varies from 5.2–6.7, with a mean value of 6.08±0.44 which is marginally lower than the Indian standards (IS: 2296, 1982) for surface waters (Table 1). The slightly acidic nature of Khacheopalri Lake can be explained by high organic load and subsequent release of organic acids (Jain *et al.,* 2000). EC in water is a function of its dissolved ions, largely dependent on the concentrations of inorganic salts and organic components in the water (Radojevic and Baskin, 1999). The EC value of lake water samples varies between 27.4–96.4 µS/cm, showing higher values during monsoon 86.4–96.4±25.89 µS/cm. The elevated EC values in monsoon is an indicative enrichment of dissolved salts which can be linked to dissolution of mineral and influx of dissolved ions/ salts through precipitation and surface runoff. TSS and TDS originate from weathering of rocks and soils, dissolution of minerals and slowly dissolved soil minerals (Chandra *et al.,* 2012). The suspended solids and dissolved solids content in lake water samples varies from 11.5–37.6 mg/L and 18.4-86.4 mg/L respectively, and showing their maximum values during rainy season. This observation can be linked to greater soil erosion in lake catchment areas, and influx of turbid water from adjoining agricultural fields and

Table 1: Physicochemical characteristics and temporal variations in Khacheopalri Lake water parameters (Min-Max ± St. Dev, n=18)*

Water parameters	Pre-monsoon (Summer)	Monsoon (Rainy)	Post-monsoon (Winter)	Indian standards (IS: 2296) for inland surface water
Temperature (°C)	18.7-19.4±0.31	11.2-11.7±0.21	6.9-8.6±0.13	-
pH	6.1-5.8±0.13	6.7-6.3±0.17	5.4-6.2±0.17	6.5-8.5
EC (mS at 25°C)	43.62-52.6±3.80	86.4-96.4±4.26	27.4-38.5±4.77	1000
TDS	25.4-37.2±5.11	72.4-86.4±6.04	18.4-24.6±2.89	500-1500
TSS	18.4-25.3±2.96	28.5-37.6±4.04	11.5-18.8±3.02	-
DO	4.2-4.5±0.13	4.6-5.2±0.25	2.8-3.4±0.26	4
CO_2	6.6-7.6±0.44	4.6-5.2±0.25	7.4-7.8±0.17	-
Total alkalinity	38.2-30.5±1.73	49.4-36.6±2.28	42.8-35.4±2.17	-
Total hardness	26.5-19.5±1.62	18.4-12.5±1.28	29.8-23.2±1.4	300
Cl^-	5.2-5.7±0.22	6-6.4±0.17	3.6-4.2±0.25	250-600

*Except pH, EC, Temperature, all other physicochemical parameters are in mg/L human settlement (Kane *et al.,* 2014). The level of TDS in sampled lake water are well under the recommended IS standards. DO is an important parameter to assess the waste assimilative capacity of water, and it fluctuate seasonally with variation in water temperature (Rao and Rao, 2010). For inland surface water, DO level of 3-5 mg/L is considered as a sign of healthy water body. The DO content in lake water ranges from 2.8–5.2 mg/L (with mean value of 4.11±0.80 mg/L). Maximum values for DO in lake water samples are recorded during the rainy season, which can be explained due to intense mixing of rain water, surface runoff and greater turbulence rate. Minimum DO level is observed during the winter season, which falls marginally below the surface water standards (Table 1). The low DO suggest the poor quality of water indicating the slow rate of photosynthesis by phytoplankton present in the lake water (Saluja and Garg, 2017). Free CO_2 in aquatic environment may arrive due to elevated CO_2 pressure at submerged soil zone as a result of root respiration and organic decomposition. The level of free CO_2 in surface water is normally less than 10 mg/L. In this study, free CO_2 values in sampled lake water ranges from 4.6–7.8 mg/L which imply that and its minimum values recorded during the rainy season (monsoon). The hardness of water is mainly free CO_2 level in studied lake are very much within normal range,due to presence of alkaline earths such as Ca^{2+} and Mg^{2+}. Total hardness of lake water varies from 12.5–29.8 mg/L, and found to be on higher side during the post monsoon (winter season). Alkalinity of water can be expressed as the strength of water to neutralize acids. The total alkalinity (TA) of lake water ranged between 30.5–49.4 mg/L, and higher values recorded during winter season (i.e. post monsoon). The chloride in groundwater may be from diverse sources such as weathering, leaching of sedimentary rocks and soil, domestic and municipal effluents (Sarath Prasanth *et al.,* 2012). In this study, Cl^- content of lake water ranged between 3.6–5.7 mg/L, and their higher values recorded during winter season (i.e. post monsoon). Chlorophyll-a content in surface waters is considered as indicator of algal biomass, and thus often used as a trophic state indicator of any water body (Carlson, 1977). The concentrations of chlorophyll-a varied substantially in different seasons, with mean concentrations varies from 18.4 to 74.4 μg/L (Fig. 2). Noticeably increase in chlorophyll concentration is recorded during the summer season, which can be linked with reduction in water level due to evaporation and higher algal growth. Niswander and Mitsch (1995) stated that addition of inorganic and/or organic phosphorous to water brings about eutrophication by increase in oxygen demand and increase in production of growth factors for algae, thus resulting in increased algal growth. The concentrations of phosphorous in lakes and streams are extremely variable. Hutchinson (1957) stated that in natural surface and relatively uncontaminated lakes, the level of phosphorous ranging from 2 -1600 μg/L. In current study, the level of total phosphorous in lake water samples ranges from 80–180 μg/L showing highest values during the summer (Fig. 3). This situation may be associated

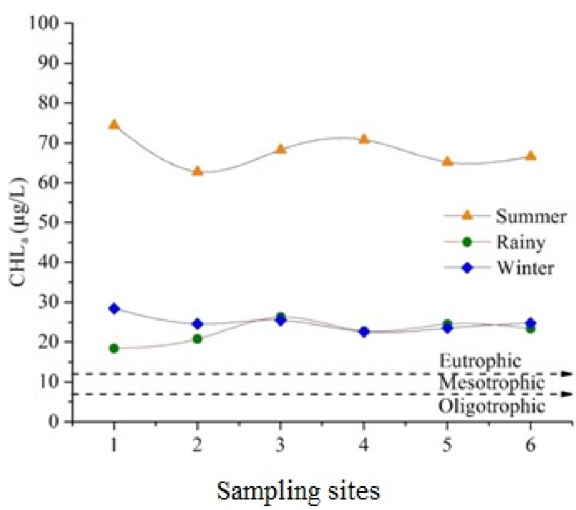

Fig. 2: Seasonal deviations in chlorophyll-a concentrations

with reduction in water level and higher abundance of biogenic components. Nitrogen compounds are most wide-spread contaminants in the environment, and mostly derived from anthropogenic souses such as agricultural lands, runoff containing human and animal wastes (Pang *et al.,* 2013). Total nitrogen content in the lake water samples varies from 5200–9000 μg/L, with higher values during post monsoon (i.e. winter) (Fig. 4). Higher concentrations of nutrients (e.g.TP and TN) in Khacheopalri lake can be linked to higher abundance vegetal coverage along the peripheral zone, and subsequent litter fall and decomposition of organic matter. Influx of surface runoff from surrounding cultivated lands and sparsely populated areas within lake-watershed also contribute nutrient enrichment in lake water. Reduction in TP content during rainy season (i.e. monsoon) can be corresponded to the dilution effect due to atmospheric precipitation and influx of surface runoff. In monsoon, the majority of cations and anions are influenced by atmospheric precipitation, but in winter and summer, they are the consequence of watershed erosion and chemical weathering processes (Anshumali and Ramanathan, 2007). The investigation reveals that the measured values of most of the parameters of lake water samples are very much within the recommended limits of Indian standard for inland

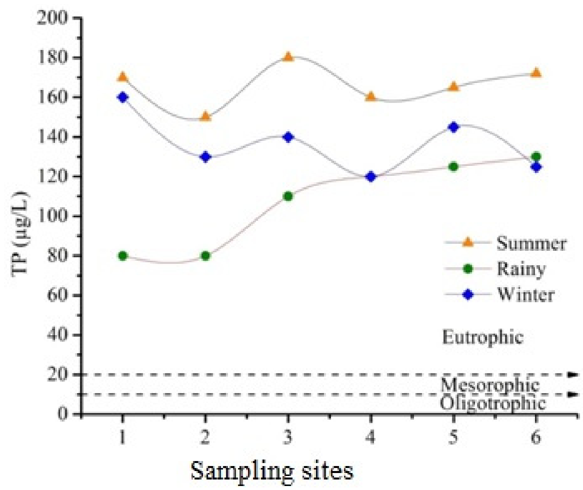

Fig. 3: Seasonal deviations in total phosphate concentrations

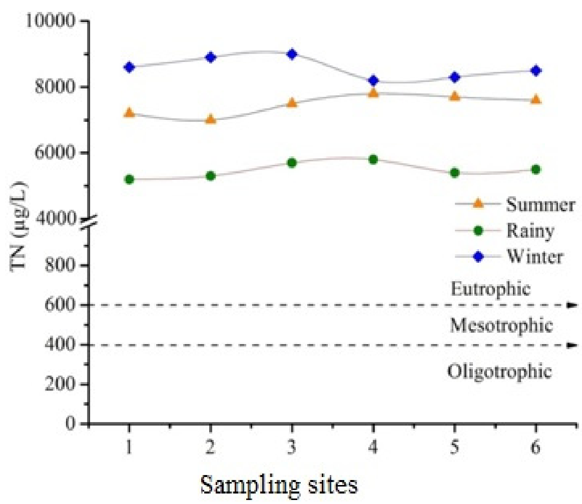

Fig. 4: Seasonal deviations in total nitrogen concentration

surface water (IS-2296, 1982) throughout the study period, with some minor exceptions such as DO during the winter season. The higher values for pH, EC, TDS, TSS, DO, total alkalinity in rainy season (i.e. monsoon) can be attributed to dissolution, soil erosion and influx of surface runoff from surrounding cultivated lands and forest dominated catchment areas. The concentrations of CO_2, total hardness, total alkalinity, Cl^- and TN are higher in post monsoon (summer season). This observation can be explained due to post monsoon effects i.e. to the high rate of mineralization and surface runoff from human settlements and agricultural sources. The results obtained from physicochemical analysis of lake water are very much consistent with earlier reports (Jain *et al.,* 1999, 2000, 2004).

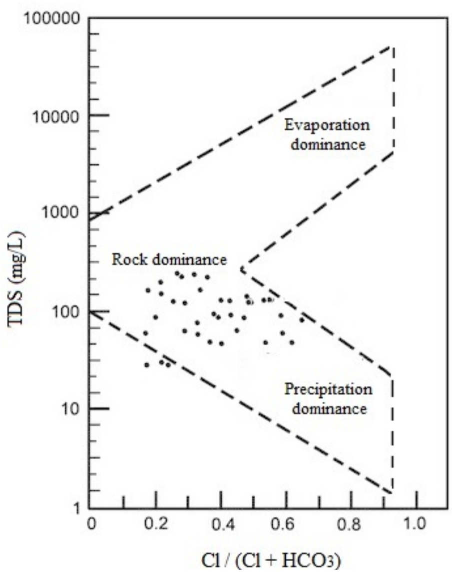

Fig. 5: Gibbs's diagram representing the ratio of $Cl^-/(Cl^-/HCO_3^-)$ as a function of TDS

Solute composition in the lake water can originate from a variety of physical, chemical and biological processes in the drainage basin. In the absence of any significant contribution from atmospheric precipitation and pollution sources, the chemistry of the lake is influenced mostly by the lithology of the basin (Das and Kaur, 2001). Gibbs's (1970) diagram is widely used to establish the relationship of water composition and lithological characteristics. A simple plot of TDS against $Na^+/(Na^+ + Ca^{2+})$ and/or $Cl^-/(Cl^- + HCO_3^+)$ can be very useful to identify the major natural mechanisms controlling lake water chemistry: i) atmospheric precipitation, ii) rock weathering and iii) evaporation and crystallization. The plotted diagram (Fig. 5) of TDS against $Cl^-/(Cl^- + HCO_3^+)$ infers that geochemical weathering of rock is the major factor which control lake water composition, with very minor influences due to precipitation.

Multivariate analysis

Descriptive statistics and multivariate analyses can be very useful in context to hydrochemical characterization, and identifying of possible sources of contribution in surface waters (Belkhiri *et al.,* 2010; Grace *et al.,* 2008). The correlation between two variables reflects the degree to which the measured parameters are related. The correlation analysis of measured water parameters (Table 2) execute strong positive correlations between Temp – CHLa, pH – EC, EC – TDS, CO_2 – Cl^-, CO_2 – TN, CO_2 – TP, Cl^- – TN, TN – TP and CHLa –TP. Positive association between the components can be explained due to homogenecity in their distribution pattern or they are sourced from common origin. Strong negative correlations between water pH with TH and Cl^-, can be explained due to slight acidic nature of lake water. Significant negative

Table 2: Pearson's correlation matrix for physic chemical parameters of lake water samples

Variables	Temp	pH	EC	TDS	TSS	DO	CO_2	TA	TH	Cl^-	TN	TP	CHLa
Temp	1												
pH	0.099	1											
EC	0.021	0.925**	1										
TDS	-0.317	0.846	0.939**	1									
TSS	0.198	0.891	0.899	0.776	1								
DO	0.464	0.842	0.880	0.677	0.867	1							
CO_2	-0.045	-0.802	-0.894	-0.824	-0.886	-0.982**	1						
TA	-0.526	0.285	0.469	0.651	0.183	0.184	-0.494	1					
TH	-0.148	-0.905**	-0.901	-0.785	-0.947**	-0.839	0.877	-0.074	1				
Cl^-	-0.084	-0.961**	-0.971**	-0.892	-0.814	-0.883	0.964**	-0.423	0.885	1			
TN	-0.060	-0.814	-0.973**	-0.811	-0.892	-0.870	0.977**	-0.528	0.841	0.966**	1		
TP	0.474	-0.605	-0.760	-0.896*	-0.520	-0.451	0.751*	-0.735	0.558	0.665	0.756*	1	
CHLa	0.925**	-0.234	-0.327	-0.629	-0.128	0.134	0.305	-0.697	0.154	0.268	0.311	0.746*	1

*Significance level of 0.05, and ** significance level of 0.01

correlations between EC – Cl^- , EC – TN, TDS – TP, TSS – TH and DO – CO_2 can be associated with dissimilar distribution pattern and origin, or may be due their contrast behavior and seasonal response.

Hierarchical cluster analysis (HCA) is another important statistical tool which is employed to sort out the homogeneity or dissimilarities, and view the association among the measured variables using dendrogram. HCA (Agglomerative method using Euclidean distance) of water parameters executed two distinct clusters as shown in Fig. 6. Cluster 1 (C1) comprises of two sub-cluster. First group (Sub-cluster 1) showed a closed association between pH, EC, TSS, DO and Temperature, while second group (sub-cluster 2) executed close association between TA and TDS. The cluster 1 (consisted of sub-cluster 1 and sub-cluster 2) may be associated to the temporal and geogenic factors i.e. mineral dissolution and weathering process in lake catchment area. Cluster 3 (C2) includes CO_2, TH, Cl^-, TN, TP and CHL_a, which can be attributed to the anthropogenic contribution (such as agricultural runoff and biogenic waste/wastewater). The outcome of HCA conform the results from correlation analysis, and the notable difference between the clusters in terms of Euclidean distance imply different sources.

PCA is commonly employed for source/patterns identification of measured parameters in a composite dataset. In this method, the original variables are converted into independent variables called principal components, which execute linear combinations of original variables (Sarbu and Pop, 2005). PCA analysis (after varimax rotation) of measured water parameters extracts two principal components (PC1 and PC2), account for 92.18 % of the cumulative variation of the dataset, having eigen value greater than one. The PC matrix (after varimax rotation) with factor loading for each parameter is described in Table 3. The PC1 explained 69.36 % of the total variance in the dataset and exhibited higher loadings for pH, EC, TDS, TSS, CO_2, TH, Cl^-, TN, and TP. This component can be linked to geological weathering, coupled with exogenic contribution (such as surface runoff influx, soil erosion) in the lake watershed. The PC2 accounts for 22.82 % of the total variance in the dataset, and shows higher loadings for temperature, DO, TA and CHLa. This observation can be explained by the fact that lake water chemistry is influenced by seasonal and temporal variations, such as change in temperature, precipitation rate and diffusion of atmospheric O_2.

Assessment of trophic state and seasonal trends in trophic conditions

Evaluation of trophic state of water is and is useful to determine health of lake, and is essential to mitigate adverse environmental impacts. Trophic condition of lakes may be influenced by a variety of factors such as nutrients, light, suspended/dissolved solids, mixed regime and hydrodynamic condition (Havens, 2000;

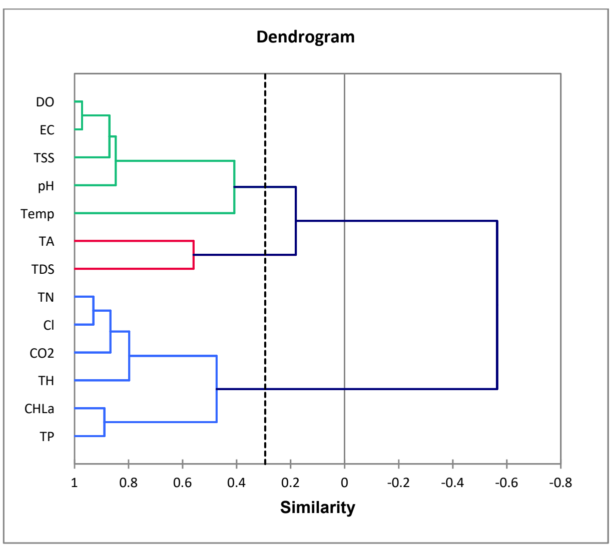

Fig. 6: Dendrogram with clustering results for the physicochemical parameters in Khacheopalri lake water

Table 3: Factor loading matrix (after varimax rotation), eigen values and variances for lake waters

Variables	PC1	PC2
Temperature	-0.037	0.953
pH	0.934	0.181
EC	0.994	0.057
TDS	0.956	-0.281
TSS	0.902	0.299
DO	0.477	0.848
CO2	-0.986	-0.064
TA	0.503	0.675
TH	0.891	-0.286
Cl^-	0.975	-0.129
TN	0.982	-0.055
TP	0.790	0.513
CHL-a	-0.390	0.895
Eigen value	9.017	2.967
Variability (%)	69.361	22.823
Cumulative %	69.361	92.185

*Values in bold correspond for each variable to the factor for which the squared cosine is the largest

Table 4. Classification of trothic state of lakes based on EPA National Eutrophication Survey (1974)

Chlorophyll-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

Matthews *et al.,* 2002). Dodds and Cole (2007) reported that anthropogenic contributions have major influence on trophic state through alterations of nutrients and light entering aquatic system. Trophic condition of aquatic system implies a multidimensional complex mechanism, which may vary for different system based on the performance and dynamics of each parameter (Donia and Hussein, 2004). Trophic state of water body is evaluated based on some selected parameters such as chlorophyll-a (CHLa), total phosphorous and total nitrogen, and compared with the recommended standards of EPA National Eutrophication Survey (Table 4).

Priority is given to the biological parameters such as Chlorophyll-a content, which is considered to be the most relevant to the algal biomass. The concentrations level of these trophic parameters (i.e. CHLa, TP, TN) and their seasonal variations in accordance to recommend standards are graphically represented in Figs. 2, 3, and 4 respectively. The investigation shows elevated concentration of CHLa, TP and TN in lake water samples in all the season, which imply substantial nutrient enrichment in lake during the study period. The measured concentrations for chlorophyll-a in lake water are notably higher as compare to the recommended eutrophication standards during the rainy and winter season, and reaches to the maximum level (almost three times greater) during summer indicating upper eutrophic condition (Fig. 2). The elevated level of chlorophyll-a is a clear reflection of higher algal biomass during the pre-monsoon period, which can be correlated to elevated TP content and favourably warm water temperature in lake water consistent with earlier reports on Asian lakes and reservoirs (An and Park, 2003; Xu *et al.,* 2010). Nutrient availability (i.e. TN and TP) and their concentrations level have been found to be the prime factors influencing algal growth and biotic productivity of aquatic system (Okech *et al.,* 2018). TN concentrations in lake water are extensively high with compare to recommended eutrophication standards (Fig. 3) indicating highly eutrophic state of lake water throughout the study period. TN content in lake water can be attributed to the anthropogenic sources such as runoff from nearby villages/human settlements. The levels of TP in lake water are also distinctly beyond the eutrophication standards, and exhibits upper eutrophic condition in all three seasons (Fig. 4). Higher level of TP in lake water can be associated with dissolution and leaching of phosphatic rocks and influx of water from agricultural fields. The observations infer that the lake water is highly rich in nutrients, and may face algal growth, macrophyte problem and poor health of the lake ecosystem. The observation based on obtained results (Figs. 2, 3 and 4) suggest that the different level of selected parameters (i.e. CHLa, TP, TN) results in different classes of trophic state in different sampling sites which should be considered for the classification of lakes (Kane *et al.,* 2014). The results also shows that the seasonal trends for CHLa and TN content are very comparable at each sampling stations, while TP shows drastic fluctuations in seasonal trends for each sampling sites. Computation of trophic state index (TSI) is more realistic approach for classifying lake. This method includes numerical standardization of selected variables (i.e. water transparency, CHLa, TP and TN); and often used for the purpose of classifying and evaluating the trophic status of various regional water bodies and lentic systems (Carlson, 1977; Kratzer and Brezonik, 1981; Matthews *et al.,* 2002). The equations are as Eqs. 2 to 5.

$$TSI_{SD} = 60 - 14.2 \ln(SD) \quad (2)$$

$$TSI_{TN} = 54.45 + 14.43 \ln(TN) \quad (3)$$

$$TSI_{TP} = 14.42 \ln(TP) + 4.15 \quad (4)$$

$$TSI_{CHLa} = 9.81 \ln(CHLa) + 30.6 \quad (5)$$

Lakes with TSI < 40: recognised as oligotrophic, TSI of 40- 50: as mesotrophic, TSI of 50 - 70: as eutrophic, and TSI > 70 suggesting hypertrophic condition. The statistical summary TSI values based on SD, TN, TP and CHLa in different seasons are furnished in Table 5.

Secchi disk (SD) transparency, an indicator of light availability in the water column, provides an indirect measure of the concentrations of suspended solids as well as algal component in the water (Sheela *et al.,* 2011). In the present study, TSI_{SD} of lake water varies from 69.83 to 86.65, indicating the hypertrophic nature of lake. The highest values for TSI_{SD} recorded in rainy season, and the lowest values observed during the winter (Fig. 7). According to the results TSI_{TN} are categorized as hypertrophic in all three season (Table 5), and its maximum and minimum values are recorded during winter and rainy season respectively (Fig. 7). The recorded values for TSI_{TP} represents hypertrophic nature of lake during the dry seasons (i.e. summer and winter), but fall down to eutrophic state during rainy season (i.e. monsoon) (Fig. 7). Decreasing trend of TSI_{TN} and TSI_{TP} during monsoon can be attributed to the dilution effect because of higher rainfall and influx of

Table 5. Descriptive statistics for Trophic state indices (TSIs) in studied lake

Trophic state indices (TSIs)	Summer (Min–Max ±St.dev)	Rainy (Min–Max ±St.dev)	Winter (Min–Max ±St.dev)
TSI_{SD}	76.51-81.03±1.60	82.72.86.6±1.44	69.83-76.81±2.33
TSI_{TN}	82.53-84.09±0.60	78.24-79.82±0.61	84.81-86.16±0.53
TSI_{TP}	76.40-79.03±0.91	67.34-74.34±3.18	73.19-77.33±1.58
TSI_{CHLa}	71.21-72.88±0.59	59.17-62.67±1.24	61.19-63.43±0.77

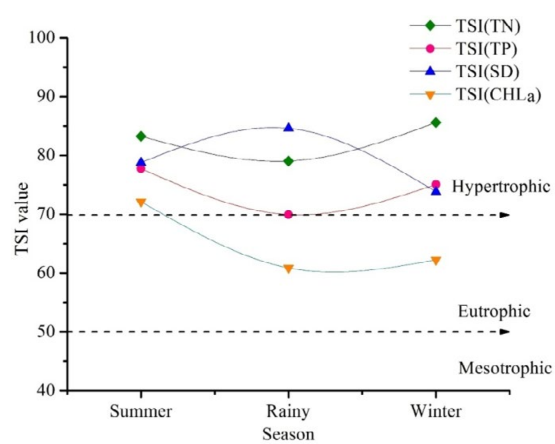

Fig. 7: Seasonal variations in trophic state indices

runoff water. TSI_{CHLa} of the lake water is in hypertrophic state during the summer (i.e. pre monsoon) and descend to eutrophic condition in rainy (monsoon) and winter (post monsoon) season (Fig. 7). Elevated TSI_{CHLa} of the studied lake in summer can be corresponded to higher TP content in the lake water during this period which favours algal growth thus chlorophyll content in lake water. The investigation also reveals that seasonal changes have some influences on lake water due to variations in temperature, precipitation rate and other natural process such as algal productivity, biological decomposition rate etc.

The deviations of TSI_{SD}, TSI_{TP}, and TSI_{TN} from TSI_{CHLa} are used to describe abiotic and biotic relationships, gain insight about lake trophic structure, and infer additional information about the functioning of the lake (Carlson, 1991; Havens, 2000; Matthews *et al.,* 2002; An and Park, 2003). Therefore, the TSIs and their deviations can be employed to access the state of lake ecosystems. Phosphorus limitation is occurred when $TSI_{CHLa}–TSI_{TP}>0$, whereas nitrogen limitation is indicated when $TSI_{CHLa}–TSI_{TN}>0$. Non-algal turbidity become restraining factor when $TSI_{CHLa}<TSI_{SD}$ and $TSI_{CHLa}<TSI_{TP}$ and TSI_{TN} (Matthews *et al.,* 2002). In this present study, calculated TSI_{CHLa} shows substantially lower values than TSI_{SD} throughout the study period including all three season (Table 6).

These clearly indicate that something other than algal components may be suspended solids, sediment particle and particulate components are contributing to the light attenuation. The results obtained from TSI_{CHLa}-TSI_{TN} and TSI_{CHLa}-TSI_{TP} represents values less than zero (< 0) in all the season (Table 6). This observation infers that nutrients (TN or TP) are not key factors which limit biological productivity of lake, rather it may be non-algal turbidity, which restricts the phytoplankton growth in lake water. Correlation study between TSIs shows significant positive correlation between TSI_{TP} -TSI_{CHLa} (Table 7), which conforms that TP content in lake water favours algal growth in studied lake. TSI_{SD} is insignificantly correlated with TSI_{TN}, TSI_{TP} and TSI_{CHLa} (Table 7) which infers that water transparency (SD) of monitored lake is not affected by dissolved/particulate nutrients or by algal components.

Further statistical analysis between measured variables of lake water reveal that SD is significantly associated (0.938) with TSS, and weakly correlated (0.012) with CHLa, which confirms that the decrease in water transparency is mainly subjected to the suspended solids and sediment particles rather than algal particles in studied lake water in all the season. The results obtained from the current study are reasonably consistent with An and Park (2003), Xu *et al.,* (2010), who also reported that non-algal particles affect light attenuation in Asian lakes and reservoirs. The ecological integrity of the lake ecosystem can be influenced by its physical components, water quality and prevailing environmental conditions. Determination of light attenuation coefficient (K_{na}) is a useful tool to measure underwater light condition, and can be linked to water clearity/turbidity (Larson *et al.,* 2007). The coefficient (K_{na}) majorly depends on the depth of water, algal components, non-algal particles (i.e. suspended solids, sediment particles), and colored dissolved organic/ inorganic matter (Ganju *et al.,* 2014). The mean light attenuation coefficient (K_{na}) for studied lake water found to be 3.15±1.6. Correlation analysis showed significant negative correlation (r = -0.628) between CHLa and $K_{na,}$ which infers that algal components/ biomass should not be consider as interfering factor

Table 6. Deviations in TSI_s values in different season with annual average

Trophic state indices deviation	Summer (Mean±St. dev)	Rainy (Mean±St. dev)	Winter (Mean±St. dev)	Annual average
TSI_{CHLa} - TSI_{SD}	-6.67±2.23	-23.75±1.96	-11.58±3.54	-14.00
TSI_{CHLa}- TSI_{TN}	-11.14±0.74	-18.16±0.93	-23.36±0.87	-17.56
TSI_{CHLa}- TSI_{TP}	-5.62±0.93	-9.08±2.11	-12.82±0.85	-9.17

Table 7. Correlation analysis between TSIs

	TSI_{SD}	TSI_{TN}	TSI_{TP}	TSI_{CHLa}
TSI_{SD}	1			
TSI_{TN}	-0.443	1		
TSI_{TP}	-0.234	0.618	1	
TSI_{CHLa}	-0.154	0.287	0.783*	1

* Significance level of $p < 0.05$

for the light attenuation and biotic productivity of the lake (An and Park, 2003; Ganju *et al.,* 2014). The strong negative correlations between K_{na}-TP (r = -0.747) and K_{na}-TN (r = -0.806) signify that nutrients (TP and TN) have minimal or no influence on light attenuation in the studied lake system. These clearly suggest that non-algal particulates dominate light attenuation, and act as limiting factor which controls biotic productivity of the lake. Non-algal particles/components in studied lake can be linked to surface runoff and turbid water influx from nearby agricultural field and human settlements; and also due to the mineral dissolution and soil erosion in lake catchment area.

CONCLUSION

The results obtained from the current investigation revealed clear temporal and inter-seasonal variations in physicochemical parameters of lake water. Multivariate analysis confirms that the qualitative and compositional variations in lake water are majorly subjected to the geological weathering and soil erosion in lake watershed, exogenic contribution such as inputs of turbid water and agricultural runoff and drainage from nearby human settlement. The level of Chlorophyll-a, TP and TN in studied lake are many folds higher than established critical values for the eutrophic conditions of lake/water body throughout the season, which clearly signify decline in water quality. TSI values for SD, TN and TP in lake water reveal hypertrophic condition in all three season, except TSI_{TP} which descend to eutrophic state during the monsoon. TSI with respect to CHLa content in lake water categorised as hypertrophic state during the summer (i.e. pre monsoon), and changes to eutrophic state for the remaining part of the annual cycle. The results of deviation in trophic state clearly suggest dominance of non-algal turbidity; and reduction in water transparency is mainly due to the dissolved solids and sediment particles which affect light attenuation and limit the biological productivity. The observations from present research work provide valid scientific reasons for further in-depth study on quantification of nutrients enrichment in water-sediments for the purpose of restoration of water quality and to restrict the increasing trend of eutrophication. Considering the religious, socio-cultural and ecological importance of Khacheopalri Lake, it is an essential need to address the eutrophication problems; including the participation of locals and State/National responses to conserve this sacred lake and health of lake ecosystem.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript.

ABBREVIATIONS

°C	Degree Centigrade
CA	Cluster analysis
CHLa	Chlorophyll-*a*
CO_2	Carbon dioxide
Cl^-	Chloride
Cm	Centimeter
DO	Dissolved oxygen
°E	East degree
EC	Electrical conductivity
Eq.	Equation
Km	Kilometer
Ft	Feet
HCA	Hierarchical cluster analysis
IS	Indian Standards
K_{na}	Light attenuation coefficient
L	Liter
Lat.	Latitude
Long	Longitude
mg	Milligram
mg/L	Milligram per liter
µg/L	Microgram per liter
ml	Milliliter
mm	Millimeter
ms	Millisiemens
MΩ	Mega Ohms
N	Nitrogen
°N	North degree
P	Phosphorus
PCA	Principal component analysis
PC	Principal component
r	Correlation coefficient
Sq	Square
sqm	Square meter
sq.km	Square kilometer

SD	Secchi disk
SD (St. dev)	Standard deviation
SE	Standard error
TA	The total alkalinity
TDS	Total dissolved solids
TH	Total hardness
TN	Total nitrogen
TP	Total phosphorus
TSI	Trophic state index
TSI_{TN}	Trophic state index for total nitrogen
TSI_{TP}	Trophic state index for total phosphorus
TSI_{SD}	Trophic state index for secchi disk
TSI_{CHLa}	Trophic state index for chlorophyll-*a*
TSI_{s}	Trophic state indices
TSS	Total suspended solids
°W	West degree
%	Percentage
µg	Microgram
µS	Microsiemens

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AUTHOR (S) BIOSKETCHES

Nayek, S., Ph.D., Assistant Professor, Department of Environmental Science, Amity Institute of Applied Sciences, Amity University, Kolkata, India. Email: *sumanta.nayek@gmail.com*

Gupta, S., Ph.D., Assistant Professor, Department of Environmental Science, The University of Burdwan, Golapbag, Bardhaman, West Bengal, India. Email: *srimantagupta@yahoo.co.in*

Pobi, K.K., Ph.D. Candidate, Department of Chemistry, Asansol Engineering College, Asansol, West Bengal, India.
Email: *krishnendupobi@gmail.com*

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