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Ecological health assessment of a coastal ecosystem: Case study of the largest brackish water lagoon of Asia

Saroja Kumar Barik[1], Satya Narayan Bramha[2], Dibakar Behera[1], Tapan Kumar Bastia[1], Gregory Cooper[3], Prasanta Rath*[1]

[1] Dept. of Chemistry, School of Applied Sciences, KIIT University, Odisha, India-751024

[2] Radiological Safety Division, Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamil Nadu, India-603102

3 System Dynamics and Food Value Chains Centre for Development, Environment and Policy SOAS, University of London

Corresponding author: pr_kiit@yahoo.co.in; prathfch@gmail.com

Abstract

This study focuses on the ecological health assessment of Chilika, a shallow lagoon present in east coast of India, through nutrient stoichiometry and trophic state index (TSI). Multivariate statistical analysis such as ANOVA, Pearson's correlation, principal component analysis (PCA), and discriminant analysis (DA) were employed for data interpretation. Nutrient stoichiometry revealed that the Chilika Lagoon experiences phosphorus limitation with regard to nitrogen and silicate (N:P:Si=16:1:16) throughout the study period. As per the computed TSI values, the southern sector (SS), central sector (CS), and outer channel (OC) were assigned with a mesotrophic status, whereas the northern sector (NS) was assigned with the eutrophic status. From PCA, total nitrogen was found to be negatively correlated with salinity and positively correlated with silicate, thus indicating that the major source of nitrogen in the lagoon was freshwater ingress by rivers with high silicate content. DA indicated that it was successful in discriminating the groups as predicted.

Key words: Nutrient ratio, trophic state index, principal component analysis, discriminant analysis

Water quality has become an important feature in the description of aquatic biodiversity and execution of management strategies for the aquatic ecosystem (Crosa et al., 2006). The ecology of coastal waters is highly dynamic. Changes in salinity, increasing levels of organic matter and nutrients (Mitchell et al., 1997), amplified algal blooms, changes in bottom water condition such as hypoxia or anoxia (Cooper and Brush, 1991), and alterations in the phytoplankton community structure (Chang et al., 1996) occur due to the increased input of riverine inflow and domestic sewage effluent runoff from the periphery.

The stoichiometry of nutrients is attributed to the alteration in nutrient inputs, dilution, wind-driven upwelling, and seawater exchange (Hornbeck et al., 2011). The stoichiometric characteristics of nutrients can have noteworthy impacts on the growth of plankton and productivity of lagoon ecosystems (Ganguly et al., 2015). The limitation in the productivity of coastal waters has usually been controlled by nutrients such as nitrogen and phosphorus (Harrison et al., 1990; Oviatt et al., 1995; Redfield et al., 1963). Consequently, the nutrient stoichiometry, i.e., total nitrogen to total phosphorus (N:P), total nitrogen to silicate (N:Si), and silicate to total phosphorus (Si:P) ratios, are frequently used as an indicator to understand the nutrient dynamics in an estuarine ecosystem (Smith et al., 1984, 1991). The limitation of phosphorus in coastal ecosystems can be explained during the periods of heavy river water discharge with high N:P loading ratios (Harrison et al., 1990). It can also establish the nitrogen or phosphorus limitation during low river water discharge and high seawater flux having a Redfield N:P ratio (Fisher et al., 1992). The freshwater discharge brings a shift in the dominant siliceous species to nonsiliceous, which causes an increase in the N:Si ratio in an ecosystem (Fisher et al., 1992).

Trophic state classification of water bodies allows comparisons between ecosystems within and among different ecoregions in addition to developing an idea of the magnitude of cultural eutrophication suffered by a system (Dodds, 2002). The same is also useful to evaluate the relationships among several components of the ecosystem (Carlson, 1977). Therefore, such a classification can be used as an important management tool for assessing the health of the ecosystem under study.

Several researchers (Jeong et al., 2008; Nayak et al., 2004; Patra et al., 2010) have reported the spatiotemporal variation of water quality in the Chilika Lagoon. However, to date, no work has emphasized the spatial scenario of the trophic state index (TSI) and nutrient stoichiometry in the lagoonal system. Therefore, this study focuses on the ecological health assessment of the Chilika Lagoon based on the TSI and nutrient ratios.

Chilika, which is South Asia's largest shallow brackish water lagoon, is situated along the east coast of India between 19° 28'-19° 54'N and 85° 05'-85° 38' E (Fig. 1). It carries a unique combination of fresh, saline, and brackish water nature biodiversity. The lagoon is ecologically divided into southern sector (SS), northern sector (NS), and central sector (CS) and an outer channel (OS) depending on the range of salinity (Barik et al., 2017). The Mahanadi River system, made up of the Daya, Bhargavi, Nuna, and Makara rivers, contributes freshwater from the northern side, while the rivers Mandakini, Kansari, Salia, and other small streams contribute from the hills located to the west of Chilika (as part of Eastern Ghats). The 32 km long dredged channels of Chilika help to maintain salinity by connecting the lagoon to the sea mouth of the Bay of Bengal. The Palur Canal also contributes to the maintenance of salinity. Various researchers have reported the details of the surrounding environmental conditions and their significance to the lagoon's ecological characteristics (Barik et al., 2017; Panigrahi et al., 2009).

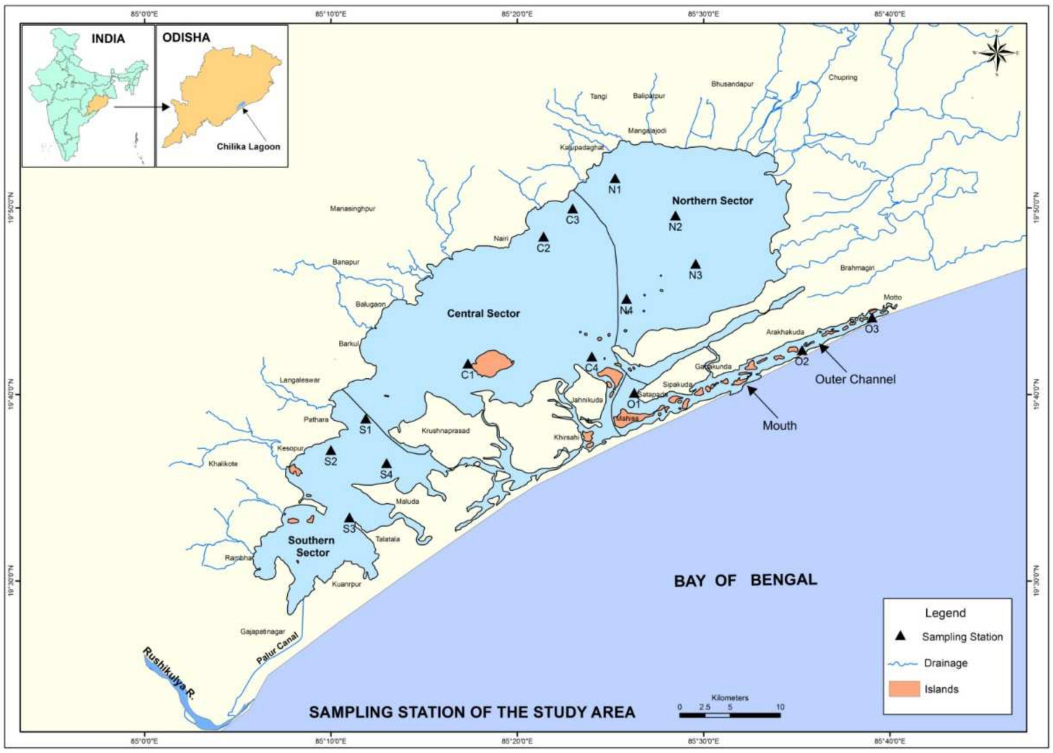


Fig. 1. Sampling locations and drainage pattern of the Chilika Lagoon

Sampling was carried out at 15 prefixed locations (Fig. 1) on a monthly basis from March 2013 to Feb 2015. The 12 months of the year have been classified into three seasons, that is, premonsoon (PRM): March-June; monsoon (MON): July-October; and postmonsoon (PSM): November-February). Subsurface (0.3 m) water samples were collected with a 5 liter Niskin sampler. Water temperature (WT), pH, ORP (Eh), and salinity were measured using a water quality checker (Aquaprobe AP-800). Depth and transparency were measured using a sechi disk. The parameters nitrite, nitrate, ammonia, phosphate, Chl-*a,* and silicate were measured using a UV–Vis spectrophotometer (AquaMate 8000, Thermo Fisher Scientific) with precisions of ±0.01, ±0.02, ±0.02, ±0.01, and ± 0.02 μM, respectively. In addition, total nitrogen (TN) and total phosphorus (TP) were measured in a similar manner after acid digestion (Grasshoff et al., 1999). DO was measured following the modified Winkler's method (Carrit and Carpenter, 1966). Biochemical oxygen demand (BOD) of the collected samples was measured after 5 days of incubation. Total alkalinity (TA) was measured by the titration method (APHA, 2005). All samples were analyzed for respective parameters within 12 h in the analytical laboratory.

A correlation matrix was constructed by calculating the coefficients (r) of different pairs of parameters, with the significance of individual parameter combinations tested by the p-value. PCA was used to understand the mode of behavior of principal factors acting on the aquatic ecosystem (Bengraine and Mahaba, 2003). Standardization is done through z-scale transformation to avoid misclassification due to wide differences in data dimensionality (Liu et al., 2003). Discriminant Analysis (DA) is derivation of linear combinations of two or more variables. It works on taking variables as raw data and constructs a discriminate function for each group (Shrestha and Kazama, 2007). One-way ANOVA tests were performed to determine spatiotemporal variation between various water quality parameters in the lagoon. As per standard practice, TN, TP, and Chl-*a* are usually used to determine the trophic status of a lagoon (Carlson, 1977). In addition to this, light penetration level is also an important factor for the establishment of the trophic status of the shallow ecosystems (Carlson, 1977). The following mathematical equation was used to calculate TSI:

$$TSI_{Trans} = 60 - 14.42 \ln (SD)$$

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

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

$$TSI_{CHL} = 9.81 \ln (Chl\text{-}a) + 30.6$$

where SD is expressed in meters and TP and TN are expressed in mg l^{-1}. Chl-*a* was expressed in mg m^{-3}. The waters with TSI < 40 are categorized as the oligotrophic state, and the waters with TSI ranging from 40 to 50 are categorized as the mesotrophic state, while those in the range of 50-70 as eutrophic state and a value higher than 70 suggests hypertrophic state (Kratzer and Brezonik, 1981). TSI was also used to abstract the health condition of the lagoon. All mathematical, graphs, and multivariate statistical data analyses were made using Microsoft Excel, Surfer (ver. 8), and SPSS (ver. 20).

The average seasonal values as well as the spatial distribution of the physicochemical properties and their correlation matrix are depicted in Tables 1 and 2. The contour maps depicted in Fig. 2 (1-6) show the spatial distribution of salinity and DO in the Chilika Lagoon.

The depth and morphometry of the lagoon are important factors affecting the hydrodynamic processes occurring in the water column (Wetzel, 2001). The NS was shallowest (1.16 ± 0.33 m) because of the occurrence of sediment deposition from the Mahanadi River catchment and OC was deepest (2.68 ± 0.78 m) because of the tidal cycle of seawater and the current of seawater passing through the sector (Table 1). During

MON, the higher depth experienced by the lagoon could be due to the heavy river water that flows from the river to the sea (Panigrahi, 2006). The one-way ANOVA test revealed that depth significantly varied for both sectors and seasons ($p < 0.05$, $n = 360$). Depth was positively correlated with salinity and transparency, meaning that the high river water discharge suppresses the rate of photosynthesis. Negative correlation with PO_4^{3-}, TN, SiO_4^{4-}, and TSS could be due to the formation of salinity wave in a higher depth area as the surface water rises and nutrients also form vertical stratification (Table 2). In Table 1, NS showed the lowest transparency (0.39 ± 0.27 m), perhaps because of the deposition of silt-borne run-off (Ganguly et al., 2015; Fouilland et al., 2012) and the resuspension of bottom sediments by wind-driven forces (Ramanadhan et al., 1964). The SS is the most undisturbed region and maintains the highest transparency of 1.04±0.47 m, in agreement with earlier observations (Panigrahi et al., 2007). Transparency was significantly and negatively correlated with NO_2^-, TSS, and TP, showing that nitrification processes will be affected in high turbid water in the lagoon system (Nixon, 1988), (Table 2).

The TSS significantly contributes to the turbidity and population density of phytoplankton in coastal ecosystems. The lowest (62.93 ± 32.54 mgl^{-1}) and highest (97.87 ± 47.08 mgl^{-1}) TSS was in the PSM and MON seasons, respectively (Table 1). The spatial distribution of TSS showed that the lowest (33.20 ± 14.78 mg l^{-1}) and highest (105.40 ± 35.88 mg l^{-1}) TSS were observed in SS and NS, respectively (Table 1). The one-way ANOVA test revealed that TSS significantly varies among both sectors and seasons ($p < 0.05$, $n = 360$). TSS was strongly positively correlated with PO_4^{3-} and SiO_4^{4-} and negatively correlated with salinity and TA (Table 2). This finding could be due to the effect of lower saline water causing the desorption of phosphate and silicate from suspended particulate matter (Yu and Wang, 1999).

WT variation of surface water depends on a number of factors such as air temperature, solar radiation, wind speed, cloudiness, salinity variation, and freshwater discharge. The lowest (27.52 ± 2.15 °C) and highest (28.27 ± 2.58 °C) values of WT were observed in CS and SS of the Chilika Lagoon, respectively (Table 1). The seasonal variation of the WT was observed in between PSM (25.19 ± 0.65 °C) and PRM (29.94 ± 0.89 °C). The lowest WT during PSM could be due to the frost cooling effect of the surface water and highest WT during PRM could be due to the intensive solar radiation, which humidified up the surface water (Bramha et al., 2008; Shenoi et al., 2009). The one-way ANOVA test revealed that the variation of WT was significant ($p < 0.05$, $n = 360$) among sectors and seasons. The other tropical ecosystems experience similar patterns of variation in water temperature (Garg et al., 2009). The surface water temperature of the lagoon demonstrated direct proportionality to PO_4^{3-} and SiO_4^{4-} (Table 2), while showing lower solubility of nutrients in the warm water, whereas an inverse relationship with DO (Table 2) shows higher solubility of oxygen in cold water (Weiss et al., 1970) and also the evidence of less release of oxygen through photosynthesis with decreasing water temperature (Manasrah et al., 2006).

Table 1 Spatiotemporal variation in water quality parameters with units in the Chilika Lagoon.

Parameters	Seasons			Sectors			
	PRM	**MON**	**PSM**	**SS**	**NS**	**CS**	**OC**
Depth (m)	1.89±0.80	1.94±0.83	1.56±0.86	2.35±0.37	1.16±0.33	1.18±0.37	2.68±0.78
Trans (m)	0.67±0.34	0.80±0.54	0.63±0.36	1.04±0.47	0.39±0.27	0.65±0.36	0.74±0.29
WT (◦C)	29.94±0.89	28.52±1.07	25.19±0.65	28.27±2.58	27.96±2.30	27.52±2.15	27.77±1.78
TSS (mgl-1)	67.70±35.10	97.87±47.08	62.93±32.54	33.20±14.78	105.40±35.88	90.90±40.36	74.90±23.29
Salinity (psu)	20.35±8.95	6.07±5.86	10.09±8.96	14.03±5.58	5.61±.78	9.51±9.46	21.99±9.14
DO (mgl-1)	5.62±1.08	6.55±1.00	7.89±1.80	6.30±0.86	7.08±2.59	6.44±1.49	7.02±0.61
BOD (mgl-1)	3.64±1.65	2.87±1.58	2.40±1.26	2.62±0.59	3.31±1.78	3.10±1.84	2.81±1.85
TA (mgl-1)	163.79±18.32	106.48±20.34	176.24±.09	155.37±23.48	135.12±41.78	156.60±38.52	148.07±31.33
pH	7.99±0.37	8.64±0.24	8.75±0.30	8.45±0.24	8.43±0.62	8.63±0.53	8.29±0.28
Eh (mV)	34.53±34.85	76.27±50.04	120.93±58.45	105.08±63.08	62.00±44.14	55.58±68.98	85.38±45.95
NO_2 −(μM)	0.68±0.47	0.41±0.44	0.80±0.46	0.29±0.20	0.79±0.32	0.74±0.50	0.73±0.69
NO_3 -(μM)	1.49±1.50	1.29±1.32	1.11±1.20	0.37±0.22	1.28±0.93	1.68±1.77	2.04±1.39
PO_4 3- (μM)	0.91±0.29	1.13±0.71	0.42±0.12	0.64±0.35	1.29±0.79	0.90±0.44	0.65±0.35
NH_4 +(μM)	18.29±9.01	47.60±24.40	21.93±11.63	26.94±16.64	26.96±26.08	31.25±24.12	26.85±15.02
SiO_4 4- (μM)	42.55±24.19	107.95±34.31	40.01±13.44	65.48±28.34	70.93±45.60	68.09±47.46	44.85±37.29
TN (μM)	51.42±21.07	39.37±8.63	36.09±17.88	35.93±2.99	50.78±24.34	48.45±17.59	31.26±9.86
TP (μM)	2.09±1.60	1.31±0.98	2.32±1.49	1.26±0.70	3.07±1.98	1.77±1.21	1.39±0.33
Chl-*a* (μgl-1)	27.40±13.01	3.61±7.19	6.14±1.80	13.63±15.12	12.05±10.90	11.75±11.00	7.95±9.51

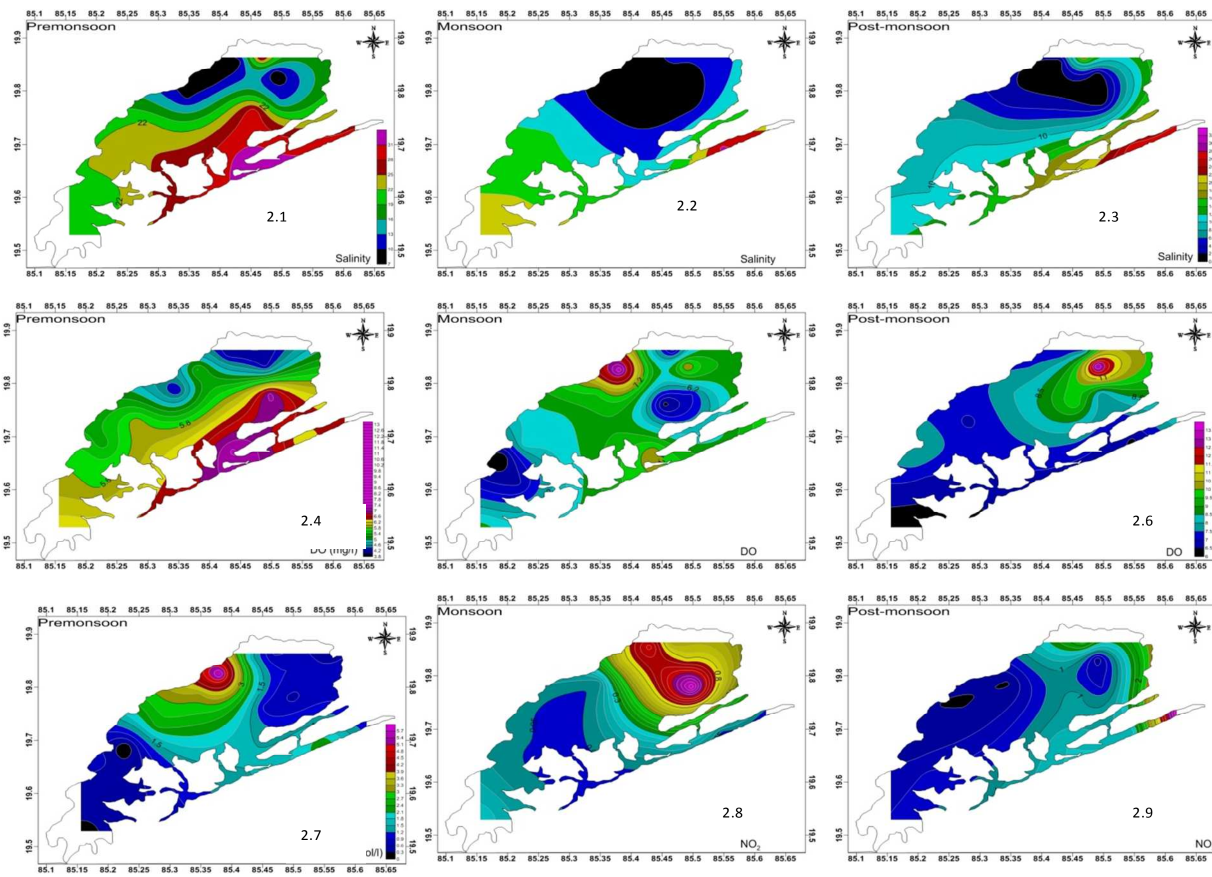
Table 2 Pearson's correlation matrix of water quality parameters for the study period

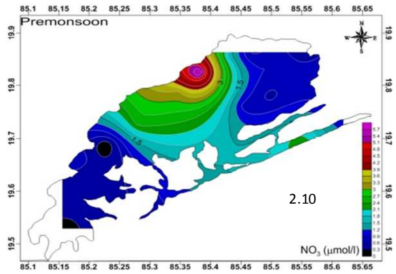
	Depth	Trans	TSS	WT	Salinity	DO	BOD	TA	pH	Eh	NO_2^-	NO_3^-	PO_4^{3-}	SiO_4^{4-}	NH_4^+	TN	TP	Chl-*a*
Depth	1																	
Trans	0.478**	1																
TSS	-0.481**	-0.318*	1															
WT	0.16	0.236	0.337*	1														
Salinity	0.576**	0.214	-0.448**	-0.072	1													
DO	-0.204	-0.159	0.198	-0.378*	-0.256	1												
BOD	0.052	-0.143	0.031	0.114	0.195	-0.299*	1											
TA	-0.043	0.096	-0.449**	-0.692**	0.361*	0.098	-0.069	1										
pH	-0.283	0.019	0.257	-0.220	-0.540**	0.599**	-0.21	-0.137	1									
Eh	0.235	0.182	-0.282	-.323*	-0.071	0.299*	-.346*	0.085	0.291	1								
NO_2^-	-0.320*	-0.520**	0.092	-0.342*	0.084	0.091	0.133	0.241	-0.133	-0.19	1							
NO_3^-	-0.091	-0.278	0.098	0.052	0.021	-0.168	-0.091	-0.029	-0.219	-0.317*	0.549**	1						
PO_4^{3-}	-0.195	-0.238	0.493**	0.563**	-0.320*	-0.25	0.423**	-0.655**	-0.097	-0.324*	0.12	0.124	1					
SiO_4^{4-}	-0.148	-0.004	0.348*	0.597**	-0.585**	-0.163	0.036	-0.784**	0.19	0.011	-0.202	0.041	0.588**	1				
NH_4^+	0.133	0.094	0.145	0.271	-0.282	-0.22	-0.154	-0.530**	0.077	0.105	-0.198	0.032	0.238	0.559**	1			
TN	-0.407**	-0.275	0.244	0.165	-0.311*	-0.278	0.222	0.014	-0.215	-0.502**	0.046	0.136	0.255	0.081	-0.046	1		
TP	-0.402**	-0.347*	0.106	-0.243	-0.14	0.214	0.061	0.074	-0.029	-0.17	0.156	-0.12	-0.009	-0.203	-0.206	0.499**	1	
Chl-*a*	-0.050	-0.025	-0.152	0.109	0.462**	-0.360*	0.077	0.275	-0.088	-0.284	-0.03	-0.106	-0.075	-0.307*	-0.242	0.237	0.091	1

*p<0.05, **p<0.01

The spatiotemporal variation in salinity in the Chilika Lagoon is largely governed by seawater intrusion through sea mouth and river water discharge (Barik et al., 2017). The variation in salinity is a proxy for its impact on the biodiversity of the lagoon. Variations in salinity in the lagoon according to seasons and sectors are shown in Fig 2 (1-3). The lagoon was polyhaline in nature during PRM and maintained a mesohaline nature during both MON and PSM; however, the individual sectors registered different classifications: SS and CS – mesohaline, NS – oligohaline, and OC – polyhaline. Palmer et al. (2011) also observed these results for the Chilika Lagoon. The one-way ANOVA test revealed that the variation in salinity was significant ($p < 0.05$, $n = 360$) with regard to sectors as well as seasons. The lowest salinity (5.61 ± 0.78 psu) was observed in NS. This finding could be due to the freshwater discharge (~80% of annual) from major rivers (Daya, Bhargavi, and Nuna); the highest (21.99 ± 9.14 psu) salinity was recorded in OC of the lagoon, potentially due to seawater intrusion through the sea mouth (Table 1, Mohanty and Mohanty, 2002). A similar spatial variation in the Chilika Lagoon was also recorded by earlier studies (Jeong et al., 2008; Mohanty et al., 2009; Ramandham et al., 1964; Tripathy, 1995). The correlation metrics indicated that salinity showed a negative relationship with pH, PO_4^{3-}, SiO_4^{4-}, NH_4^+, and TN, thus indicating that lower saline regions of the Chilika Lagoon contained higher nutrient concentrations, which generally support plankton growth. The negative relationship of salinity with TA and Chl-*a* showed that input of nutrients was from the surrounding catchment area and the major rivers and dilution of nutrients by seawater and enrichment with freshwater discharge (Table 2).

The average concentration of DO showed a minor variation over space (Fig. 2 4-6). The average DO (5.62 ± 1.08 mg l^{-1}) was lowest during PRM, which could be due to the churning of sediments, which declines the transparency level and increases oxygen consumption for the decomposition of organic matter generated from densely covered macrophytes (Panigrahi, 2006). The highest average DO concentration (7.89 ± 1.80 mg l^{-1}) was also observed during PSM (Table 1), which could be attributed to the higher rate of photosynthesis by submerged macrophytes and plankton communities, which require light intensity and transparency (Nayak et al., 2004; Panigrahi, 2006; Rath et al., 2004). The higher range of DO in the present study could be an indication of improved ecosystem health in terms of oxygen saturation. Similar observations were also reported for other estuarine environments (Ramesh, 2000). DO was positively correlated with pH and negatively correlated with NH4+. During the study period, the BOD ranged between 0.06 and 7.52 mg l^{-1} with an avg. of 3.07 mg l^{-1}. Sectorial variation followed the order: NS (3.56 ± 2.03 mg l^{-1}) > OC (3.06 ± 1.74 mg l^{-1}) > CS (3 ± 1.79 mg l^{-1}) > SS (2.79 ± 1.58 mg l^{-1}). The lowest BOD values (2.42 ± 0.31 mg l^{-1}) were recorded in the OC during PSM, as this region was disturbed with tidal flux of seawater through the open sea mouth. The highest BOD (4.26 ± 0.69 mg l^{-1}) was recorded in the NS during PRM; this could be due to the decomposition of weeds and macrophytes by elevated salinity and the mixing of released decomposed organic matter from the benthic compartment to the water column. The positive correlation between BOD and PO_4^{3-} represents the contribution of nonpoint pollution and the physicochemistry of the estuary. The major nonpoint sources for phosphorus and nitrogen compounds comprise soil erosion, sewage from settlements, geologic deposits, natural organic matter decomposition, and agricultural runoff (Madramootoo et al., 1997).




Premonsoon
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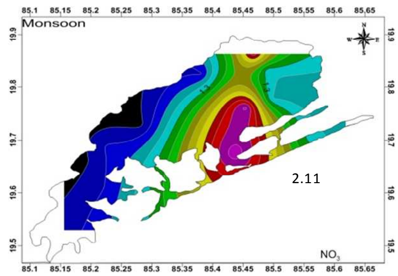
NO3 (µmol/l)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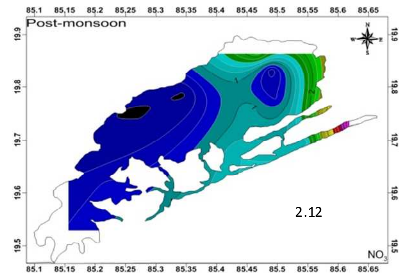
NO3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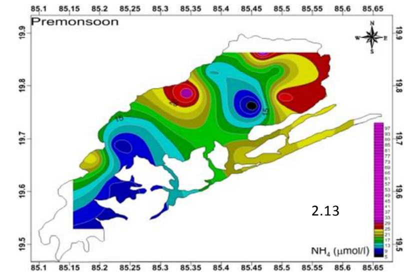
NO3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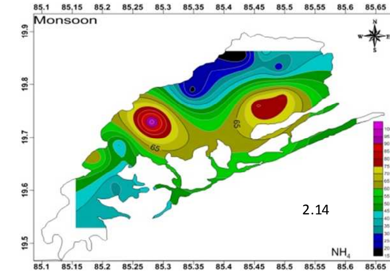
NH4 (µmol/l)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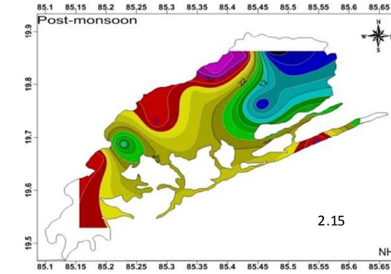
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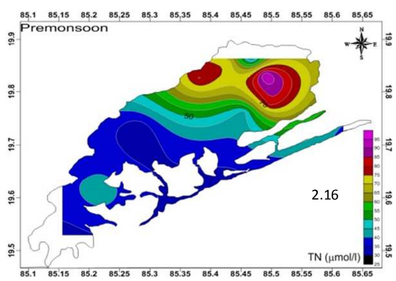
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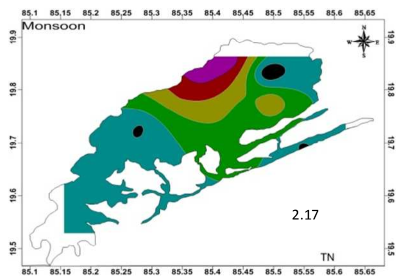
TN (µmol/l)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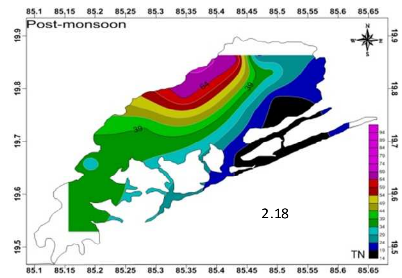
TN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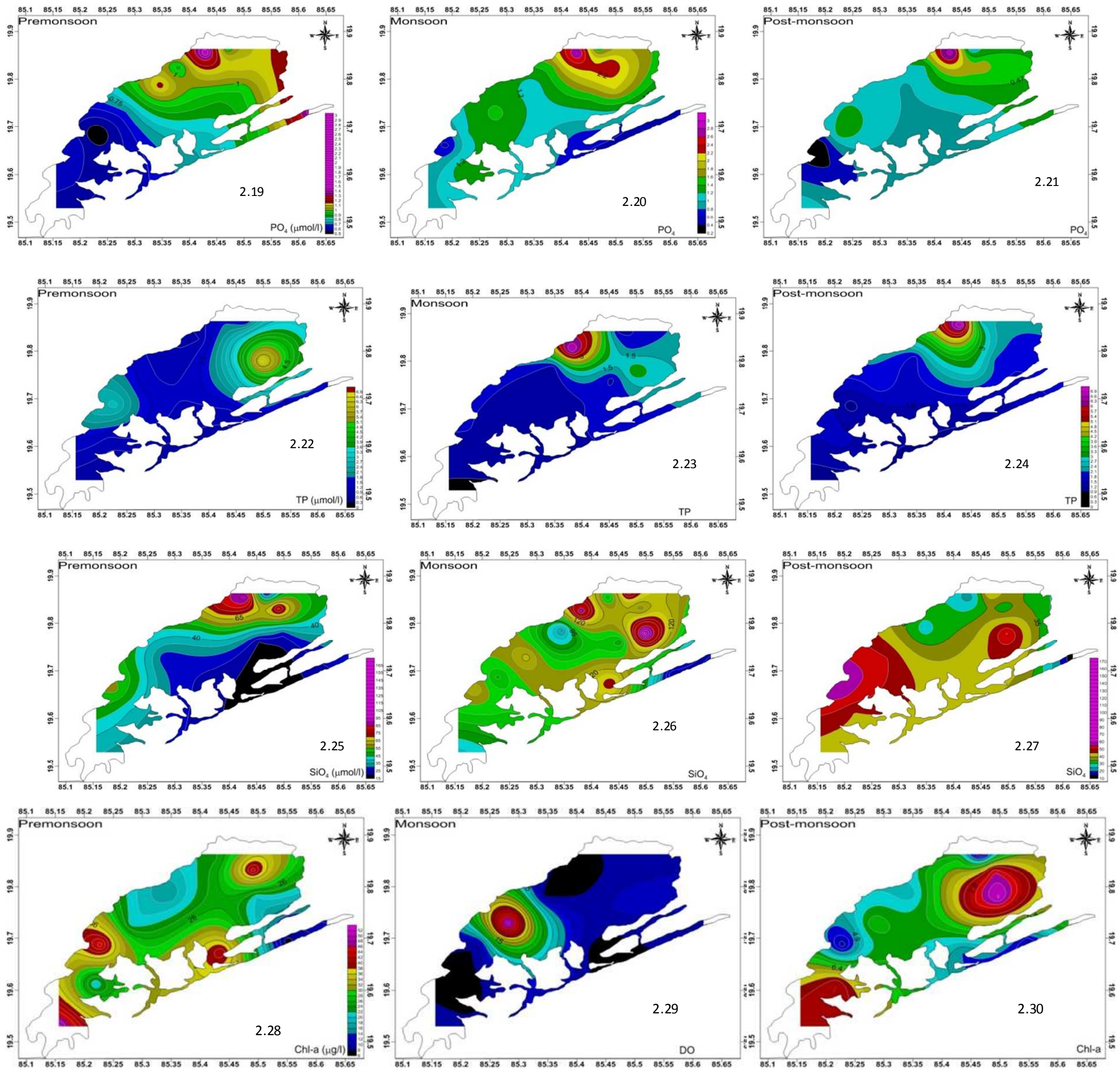

Fig. 2. Contour maps showing the spatiotemporal distribution of important water quality parameters of the Chilika Lagoon during 2013-2015.

TA is mostly controlled by the interplay between climatic and geological factors (Gorham et al., 1983), which changes the type and volume of ions transported from the drainage basin. The lowest (106.48 ± 20.34 mg l^{-1}) concentration of TA was measured during the MON (Table 1); this could be due to the low carbonate and bicarbonate contents in the river-discharged freshwater (Siddiqi and Rao, 1995) and higher CO_2 saturation (Gupta et al., 2008). The highest (176.24 ± 8.10 mg l^{-1}) TA values were observed during the PSM, which could be attributed to the intrusion of seawater through the dredged channel to the lagoon (Fig. 1); this reflects the fact that freshwater influxes from river discharge and seawater from the mouth are the controlling factors for TA variations in the Chilika Lagoon. TA shows strong negative correlations with PO_4^{3-}, SiO_4^{4-}, and NH_4^+.

The higher residence time of water in the Lagoon increases the rate of release of CO_2 by dominating respiration over production during PRM. This could be the reason for the lowest pH value (7.99 ± 0.37) observed during the said period (Gupta et al., 2008; Rajasegar et al., 2003). The highest pH of 8.75 ± 0.30 observed during PSM may be due to the higher productivity in the lagoon (Saravanakumar et al., 2008) (Table 1). The one-way ANOVA test revealed that the pH varied significantly ($n = 360$ and $p < 0.05$) among seasons.

High Eh values were observed in PSM (120.93 ± 58.45 mV) and SS (105.08 ± 63.08 mV) (Table 1). The one-way ANOVA test revealed that the Eh value significantly varied among seasons ($p < 0.05$, $n = 360$). Throughout the study, all the seasons showed a reducing environment, but the seasons in PSM demonstrated more reducing environment than the lowest during the seasons in PRM. Eh negatively correlates with NO_3^-, PO_4^{3-}, and TN, thus showing the reducing conditions that support the denitrification process in the lagoon environment (Table 2).

Nutrients are the most important parameters in the costal environment influencing the growth, reproduction, and metabolic activities of living beings. The distribution of nutrients mainly depends on seasons, tidal conditions, and freshwater flow from land sources and rivers.

Nitrite is the intermediate oxidation state between ammonia and nitrate. Nitrate can appear as transient species by the oxidation of ammonia or the reduction of nitrate and is often released into the water as an extracellular product of planktonic organisms (Chandran and Ramamurthy, 1984; Santsehi et al., 1990). The lowest average nitrite (0.29 ± 0.20 µM) observed in SS could be due to the mixing of lagoon water with the Rushikulya estuary (through the Palur Canal) with lower nitrite concentrations and less mixing of freshwater from river influx than those in other sectors (Table 1, Fig. 2.7-2.9). The highest (0.79 ± 0.32 µM) concentration observed in NS could be from freshwater discharge as evident from correlation matrix in Table 2 ($r = 0.056$, $p < 0.05$) and *in situ* production through extracellular release (Kanuri et al., 2013). The one-way ANOVA test revealed that variation in nitrite was significant between sectors ($p < 0.05$, $n = 360$).

Nitrate is the final oxidation product of nitrogen compounds in freshwater as well as marine water. Quick assimilation by phytoplankton and enhancement by surface runoff results in large-scale spatiotemporal variation in nitrate in the coastal environment (De Souza, 1983; Qasim, 1977; Zepp, 1997). The lowest (0.37 ± 0.22 µM) and highest (2.04 ± 1.39 µM) concentrations were observed in SS and OC (Table 1, Fig 2.10-2.12). The one-way ANOVA test revealed that variation in NO_3^- concentration was significant ($p > 0.05$, $n = 360$) between the sectors of the Chilika Lagoon. However, the trend indicated that the region with seawater influence (SS and OC) maintained lower concentration, which could be due to dilution with seawater containing lower nutrient concentration. NS, with influence of riverine discharge, and, among seasons, PRM (high residence time, Muduli et al., 2013) recorded high nutrient content, which could be attributed to the mineralization process, which releases nutrients to the ecosystem (Panigrahi, 2006). This observation supports findings of Gupta et al. (2008) who revealed the active mineralization process in NS of the lagoon. Some trophic estuaries recorded highest NO_3^- levels during monsoon (Patil and Anil, 2008; Pednekar et al., 2014), and the difference could be attributed to relatively lower residence time in NS of the lagoon (Muduli et al., 2013), which helped the nutrients to flush out. A significant positive relationship with NO_2^- and a negative relationship with Eh indicated that the major source of NO_3^- was from the oxidation process (Touriner et al., 1981). The lowest (18.29 ± 9.01 µM) and highest (47.60 ± 24.40 µM) concentrations of ammonia were observed during PRM and MON seasons, respectively (Fig 2.13 - 2.15). The one-way ANOVA test reveals that ammonia significantly varies among seasons ($p < 0.05$, $n = 360$) but not significantly between sectors.

The lowest (36.09 ± 17.88 µM) and highest (51.42 ± 21.07 µM) concentrations of TN were observed during PSM and PRM seasons, respectively (Table 1).The one-way ANOVA test revealed that TN varies significantly among sectors as well as seasons ($P < 0.05$, $n = 360$), potentially from higher dilution because of more intense precipitation. Regarding spatial variation, the lowest (31.26 ± 9.86 µM) and highest (50.78 ± 24.34 µM) values were recorded in OC and NS of the lagoon, respectively (Fig 2.16-2.18). TN was negatively correlated with salinity and positively correlated with SiO_4^{4-}, thus indicating that the major sources of nitrogen are from freshwater inputs with high silicate contents (Table 2).

Phosphate is an important inorganic nutrient for the growth of autotrophic phytoplankton, algae, and macrophytes. The lowest and highest concentrations of phosphate were observed during PSM (0.42 ± 0.12 µM) and MON (1.13 ± 0.71 µM) seasons, respectively (Table 1, Fig 2.19-2.21). The one-way ANOVA test revealed that phosphate significantly varied for both seasons ($p < 0.05$, $n = 360$) and sectors ($p < 0.05$, $n = 360$). The observed trend (NS > CS > OC > SS) indicated that the source of phosphorus in NS could be from freshwater runoff from major Mahanadi catchments, which propagate through the lead channel toward mouth and OC. Further, the release of phosphate could be from sediments due to the churning of water by winds (Chandran and Ramamurthy, 1984). The lower concentrations of phosphate observed in SS followed by OC could be due to less discharge of river water and also due to uptake by macrophytes, phytoplankton, (Cole cv and Sanford, 1989) or the sea grasses observed. During PRM, phosphate was positively correlated with BOD and negatively correlated with pH, thus indicating active mineralization of organic compounds in summer demands oxygen from the pelagic compartment; such phenomenon decreased the pH level in the Chilika Lagoon (Panigrahi, 2006). Phosphate positively correlated with TSS, WT, and BOD but negatively correlated with TA, Eh, and salinity (Table 2). These findings could be due to the higher salinity of water responsible for the desorption of phosphate from suspended particulate matter. The lowest (1.31 ± 0.98 µM) and highest (2.32 ± 1.49 µM) concentrations of TP were observed during MON and PSM seasons, respectively (Table 1).The spatial distribution showed that the lowest (1.26 ± 0.70 µM) and highest (3.07 ± 1.98 µM) concentrations of TP were observed in SS and NS of the lagoon, respectively (Fig. 2.22-2.24). The one-way ANOVA test revealed that TP significantly varied among sectors ($p < 0.05$, $n = 360$), but no significant variation was found among seasons. TP strongly and positively correlated with TN but negatively with depth and transparency (Table 2), thus indicating that the mineralization process is affected by depth (Jalali M et al., 2014).

The concentration of silicate is often considered to determine the growth rate of diatoms (Wassmann et al., 1999), as required for the production of silica frustules. The lowest (40.01 ± 13.44 µM) and highest (107.95 ± 34.31 µM) concentrations of silicate were observed during PSM and MON seasons, respectively (Table 1, Fig. 2.25-2.27). The former finding could be attributed to the uptake of silicates by phytoplankton (especially diatoms and silico flagellates) for their biological activity (Mishra et al., 1993) together with adsorption into suspended sedimentary particles, chemical interaction with clay minerals, and coprecipitation of soluble silicon with humic compounds and iron (Rajasegar et al., 2003). The one-way ANOVA test revealed that silicate concentrations in the Chilika Lagoon vary significantly between seasons ($p < 0.05$, $n = 360$). The source of silicate from freshwater discharge is also revealed by the correlation matrix, thus showing a significant negative correlation with salinity and positive correlation with WT (Table 2). Higher silicate in freshwater could be due to the weathered silicate material that occurs in the river, which subsequently is discharged into the lagoon (Lal D et al., 1978).

Seasonal changes and biogeochemical process can have a strong potential to regulate the nutrient stoichiometry in the lagoons and coastal waters. Such change in nutrient stoichiometry may result to shifts in the plant population and diversity (Loureiro et al., 2006). Alternatively, N and P have been reported as limiting nutrients for primary production in the coastal waters (Oviatt et al., 1995). Some studies have shown that P can be a limiting nutrient in coastal areas associated with periods of high river runoff with high N/P loading ratios (Harrison et al., 1990; Xu et al., 2008). Fig. 3 (a, b, c) shows the seasonal variation of potential nutrient limitation trends during the study period. Potential nitrogen limitation follows the order: PSM (53.5%) > MON (50%) > PRM (23.5%). Potential phosphorus limitation follows the order MON (97%) > PRM (73.33%) > PSM (53.33%) and silicate limitation remains in the order PRM (50%) > MON (0%) = PSM (33.33%) (Fig. 6). The N:P > 16 and Si:P > 16 values for all the seasons revealed that the Chilika Lagoon experiences phosphorus limitation with regard to nitrogen and silicate (N:P:Si = 16:1:16) throughout the study period, which favored the growth of diatoms. However, during PRM, when the Si concentration is found to have decreased, the species diversity shifted from siliceous-based to nonsiliceous-based phytoplankton community (Domingues et al., 2005; Rocha et al., 2002; Srichandan et al., 2015b). The N/P and N/Si ratios indicated that OC is propagated with nitrogen limitation during PSM only. This finding could be due to the dominance of nutrient-poor seawater. N limitation at high saline regions also has been reported for coastal waters impacted by the Mississippi River plume (Lohrenz et al., 1999). The SS, CS, and

NS showed phosphorus limitation as a common trend during the seasons PRM and MON. The silicate limitation maintained at OC and NS during MON and PSM, respectively. During MON, the water quality characteristics of OC were completely dominated with freshwater because of freshwater discharge from the major rivers completely overwhelming tidal water flux through the sea mouth. During PSM, NS was maintained with completely freshwater (salinity, 1.75 psu), which is another possible reason for the above observation. Nitrogen limitation is observed in many coastal waters and lagoons by different workers (Ault et al., 2000; Fong et al., 1993;Nixon,1982).

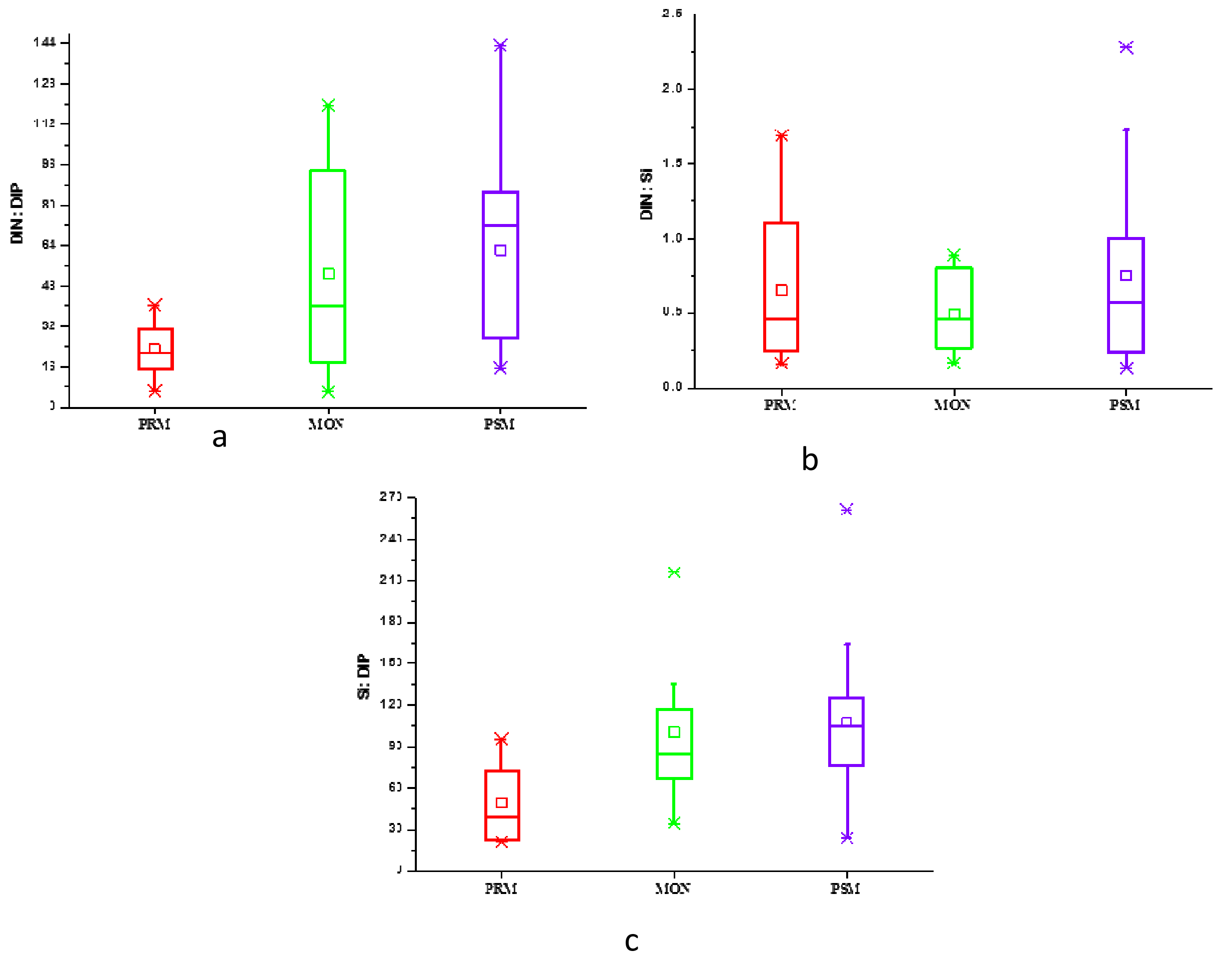

Fig. 3 (a, b, c). Seasonal variation in nutrient ratios for the Chilika Lagoon during the study period.

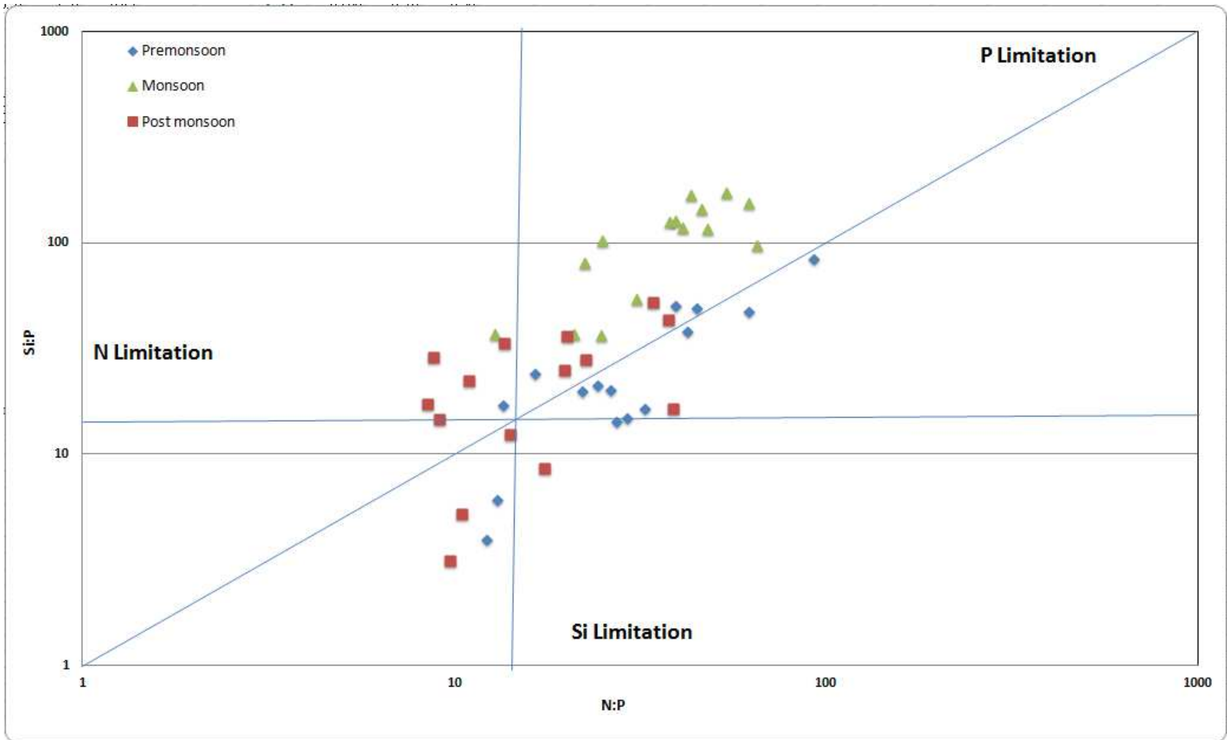

Fig. 6. Scatter plot showing the nutrient limitation for water quality parameters during the seasons (premonsoon, monsoon, and postmonsoon).

Chl-*a* is the most important variable to accelerate the growth of phytoplankton in coastal lagoons. Its concentration is a good indicator of the luxurious growth of algae in waters (Räike et al., 2003). The lowest (3.61 ± 7.19 µg l^{-1}) and highest (27.40 ± 13.01 µg l^{-1}) concentrations of Chl-*a* were recorded in the Chilika Lagoon during the MON and PRM seasons, respectively, while the SS shows a high concentration of Chl-*a* (Table1, Fig. 2.28-2.30). The highest concentration during PRM could be due to the increase in nitrate concentration. Chl-*a* also strongly positively correlated with salinity and negatively correlated with pH, DO, and PO_4^{3-} (Table 2).Whenever salinity in coastal ecosystems increases, the possible phytoplankton blooming causes a decline in pH, nutrients, and oxygen content of the ecosystems. The one-way ANOVA test revealed that the variation in Chl-*a* was significant ($p < 0.05$, n = 360) between seasons. Chl-*a* was positively correlated with salinity (Table 2) and negatively correlated with DO, pH, and SiO_4^{4-}. This could be due to the seasonal effect and higher concentration of Chl-*a* observed during the dry season.

Urbanization, agricultural runoff, local sewage, prawn processing units, and catchment runoff are the main sources of nutrient discharge and organic matter loading. Ultimately, these factors influence the trophic status of the Chilika Lagoon (Ganguly et al., 2015). As per practice, TN, TP, and Chl-*a* are usually used to determine the trophic status of a lagoon. In addition to this, light penetration level is also an important factor for the establishment of the trophic status of shallow ecosystems (Carlson, 1977). Therefore, in the present study, for evaluation of TSI, sechi disk transparency was also considered. TSI was used to abstract the health condition of the lagoon. As per the computed TSI, SS, CS, and OC are placed in mesotrophic status, whereas NS is in eutrophic status (Fig. 4). This could be attributed to the fact that a substantial area in NS is dominated with macrophytes with a reduced transparency.

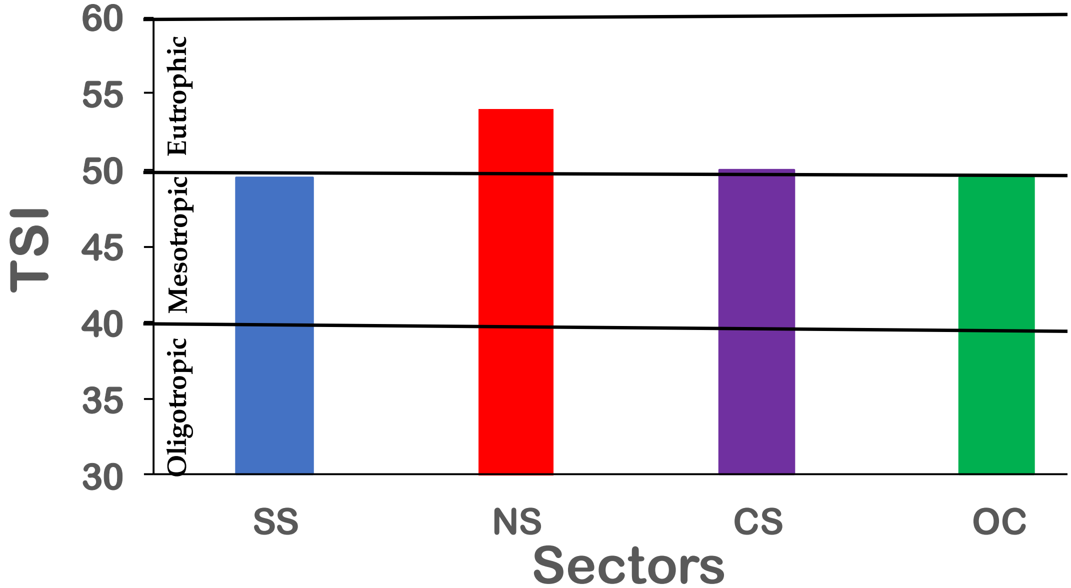

Fig. 4. Trophic state index (TSI) status of the different sectors of the Chilika Lagoon

The water quality dataset was subject to PCA for clarification of their interrelationships. A varimax rotation of principal components was used for simpler and relatively more meaningful representation of the underlying factors, as it lowers the contribution to principal components of variables with minor significance and increases the more significant relationships. Five principal components with Eigenvalues > 1 were extracted with a variance of 72.96% from the total variance (Table 3). The PC1 accounted for 22.05% of the total variance, which is strong positively loaded with SiO_4^{4-}, WT, and PO_4^{3-} in addition to moderate positive loading of NH_4^+ and TSS. This component was also strong negatively loaded with TA and moderate negatively loaded with salinity, potentially due to the river water ingress into the lagoon carrying particulate-bound nutrients. This factor may be considered as "fresh water factor." The PC2 accounted for 15.84% of total variance. This component is moderately positively loaded with Chl-*a*, while weak positively loaded with TN and salinity. In addition, this component is also strongly negatively loaded with pH and DO and weakly negatively loaded with Eh. This suggests that the decrease in pH, DO, and Eh may be attributed to the higher salinity and Chl-*a* content of water with a higher rate of respiration of phytoplankton. The PC3 accounted for 15.47% of total variance with a strong positive loading of TN and TP with a negative loading of depth. A weak-positive loading of TSS along with moderate negative loading of salinity is also noticed in this component. This suggests that the lagoon zone with lower salinity and depth, that is, river ingress area, has higher nutrients, which may be due to the river water having suspended solids enriched with nutrients. The PC4 accounted for 11.38% of total variance and strong positively loaded with NO_2^- and NO_3^-, with a weak-negative loading of transparency. This observation may be attributed to the fact that, in low-depth areas of the lagoon with high saline phases, decomposition of the freshwater weeds results in an increase in nitrate and nitrite concentrations. The PC5 accounted for 8.22% of total variance and strong positively loaded with BOD and weak positively loaded with PO_4^{3-}, thus showing that the lagoon is loaded with organic matter.

Table 3 Rotated varimax principal component analysis of water quality parameters for the Chilika Lagoon.

	Component				
	PC1	PC2	PC3	PC4	PC5
SiO44-	0.900				
TA	-0.892				
WT	0.751				
PO_4^{3-}	0.727				0.469
NH_4^+	0.638				
TSS	0.512		0.470		
pH		-0.818			
DO		-0.797			
Chl-*a*		0.678			
Eh		-0.528			
Depth			-0.811		
TN		0.442	0.753		
TP			0.712		
Salinity	-0.508	0.469	-0.531		
NO_2^-				0.858	
NO_3^-				0.842	
Transparency			-0.480	-0.570	
BOD					0.860
Eigen value	3.969	2.851	2.784	2.048	1.480
% of variance	22.051	15.839	15.468	11.379	8.221
Cumm.% of variance	22.051	37.89	53.359	64.738	72.959

Stepwise DA using Wilks' method was carried out by entering individual sampling station and seasons as grouping variables, with the physicochemical parameters nutrients and Chl-*a* as independent variables. The module was executed by entering the most correlated variable in the beginning and then the second until an additional variable adds no significant change. The first canonical discriminate function (F1) accounted for 65.9%, while the second function (F2) accounted for 30% of the discriminating ability of the discriminating variables. The standardized canonical coefficients indicated that TSS, NO_3^-, and TP contributed significantly to the first discriminating score, while depth, TSS, and nitrate contributed to the second discriminating function among other variables. A high canonical correlation indicated that there exists significant difference between group variation of variables, and the functions discriminate appreciably well. A lower value of Wilks' lambda (0.083) for the first discriminating function indicated its success in discriminating the groups. The plot of first and second canonical discriminant functions demonstrated the distinctive groupings (Fig. 5).

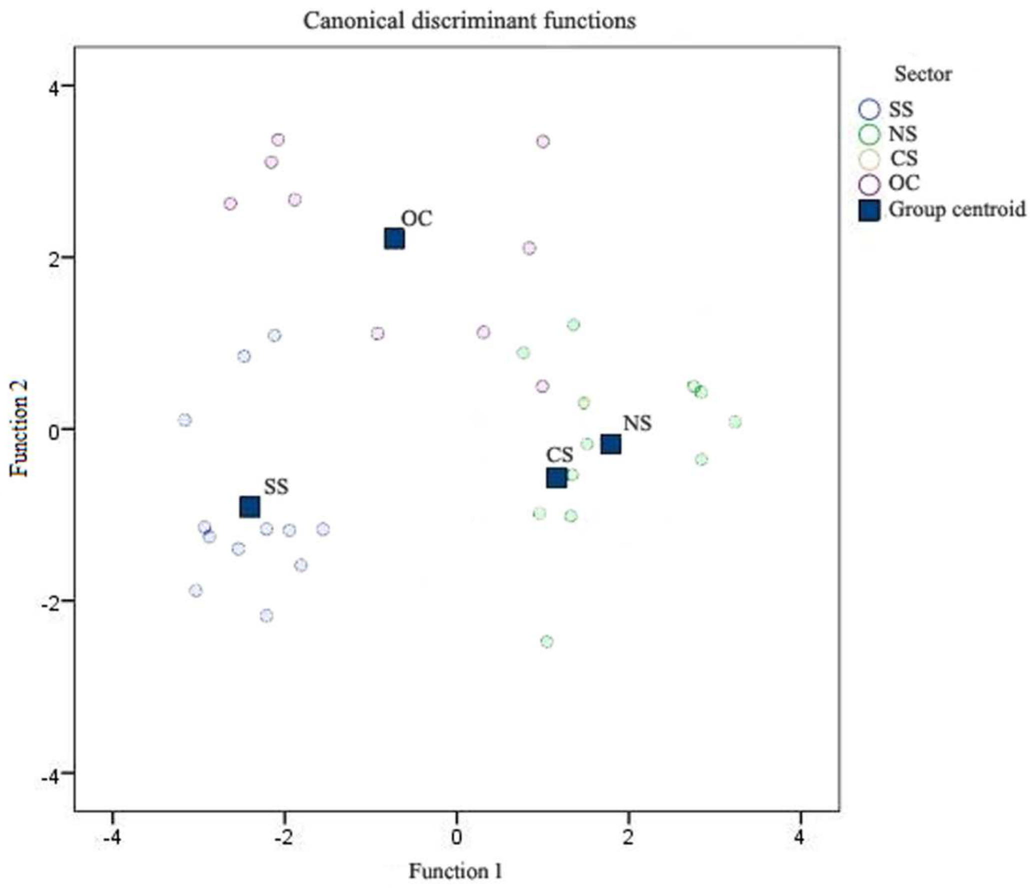

Fig. 5. Biplot display of discriminate analysis for the Chilika Lagoon

Chilika is the important hotspot for the biodiversity of South Asia. The multivariate statistical tools were helpful for assessing the spatiotemporal scenario of water quality, as well as for establishing the ecological health status of the lagoon. The ANOVA tests revealed that all the studied water quality parameters show significant difference ($p < 0.05$, $n = 360$) with regard to seasons and sectors, except TA, ammonia, and Eh. The lagoon is categorized into individual sectors on the basis of variations in salinity: SS and CS: mesohaline, NS: oligohaline, and OC: polyhaline zone. The ecological health assessment of the lagoon with regard to TSI showed that NS is categorized as the eutrophication zone, which could be due to the high sedimentation and decomposition of aquatic macrophytes. It is alarming for the lake manager to emphasize on special monitoring for this particular sector at regular time intervals. In the future, these findings may be the baseline reference for the lake scientist to determine the source of nutrient load to the NS.

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