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Spatio-Temporal Distribution of Physico-Chemical Parameters and Chlorophyll-*a* in Chilika Lagoon, East Coast of India

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Present study contains the current status of Chilika Lagoon water quality during pre-monsoon, monsoon and post-monsoon seasons of the year 2012. Spatial and seasonal distributions of water quality parameters *viz.* WT, pH, Salinity, DO, TSM, Chl-*a* and inorganic nutrients (NO_2^-, NO_3^-, NH_4^+, PO_4^{3-}, SiO_4^{4-}) were examined in this study. Twenty locations were selected covering all the ecological sectors of the lagoon. Study reveals significant spatio-temporal variation in water quality parameters. The pH of the lagoon was found to be slightly alkaline. DO concentration was controlled by photosynthetic activities of autotrophs. Results of one-way ANOVA indicated spatio-temporal variation in the nutrients especially NH_4^+ and SiO_4^{4-} ($p<0.01$). Concentration of PO_4^{3-} was found below the pollution limit for aquatic lives. Among the nutrients, SiO_4^{4-} was the most influencing factor regulating phytoplankton production of the lagoon throughout the year. However, NH_4^+ was found as the second influencing factor for distribution of Chl-*a*.

[**Keywords:** Chilika Lagoon, Nutrients, Salinity, Water quality, Chl-*a*]

Introduction

Dredging of channels and tidal inlets in coastal lagoons is common and frequent for maintaining the quality of water, preserving biodiversity and for safe navigation[1]. Because of such human alteration together with the natural environmental changes, water quality of the lagoon is altered. Chilika Lagoon is a shallow brackish water coastal ecosystem located in the east coast of India. From the past 80-85 years, it is experienced that the physico-chemical parameters of Chilika Lagoon have undergone several alterations due to variation in climatic condition, and desilting action of mouth of the lagoon[2]. Water characteristics of the lagoon are strongly influenced by both fresh (river influx, terrestrial runoff from catchment area during rain) and marine water influx (inlet of Bay of Bengal). In addition, enhanced anthropogenic input can lead to eutrophication in estuarine and marine environment[3-6]. Human and natural pressures are constantly changing the biogeochemical processes operative in the lagoon. The lagoon water characteristics especially the nutrient distribution are strongly influenced by exchange of both fresh (including anthropogenic inputs *viz*. urban, industrial and agricultural wastes) and marine water[7,8]. Seasonal variability of water quality parameters in Chilka lagoon was resulted due to the superposition of seasonal cycles of light, temperature and river dynamics. Macrophyte abundance was decreased after opening of new mouth and its subsequent influence on the nutrient dynamics [9,1].

However, dredging of artificial mouth (September 2000), shift and closure of old mouth (2003), opening of new mouth near Gabakunda (August, 2008) are some of the drivers that led to change in sediment budget and biogeochemistry, increase in macrophytes, impact on fish yield, change in species composition, eutrophication etc. Chilika Development Authority has carried out some key activities for the lagoon restoration such as lake basin treatment, desiltation of lead channels, improvement of Nalabana ecosystems, fishery resource potential and management etc.

Apart from these some measures are to be taken periodically for restoration of the ecological stability such as catchment area treatment, water management, biodiversity conservation, sustainable resources development and management etc.[10]. It is therefore imperative to give attention for regular and constant water quality monitoring in assessing the health of the lagoon.

Materials and Methods

Chilika Lagoon located along east coast of India lies between latitude 19˚ 28′ - 19˚ 54′ N and longitude 85˚05′-85˚38′ E (Fig.1). Lagoon experiences a tropical climate with average temperatures between 39 ºC and 14 ºC. Rainfall is concentrated during southwest monsoon period (July-September). Average annual rainfall is over 1,200 mm (www.chilika.com). The lagoon is broadly divided into four ecological sectors based on salinity and depth. Those are the Northern Sector (NS), the Central Sector (CS), the Southern Sector (SS) and the Outer Channel (OC)[11,12]. Total water spread area of the lagoon is 906 sq. km during the summer and 1165 sq. km during south west monsoon[13].

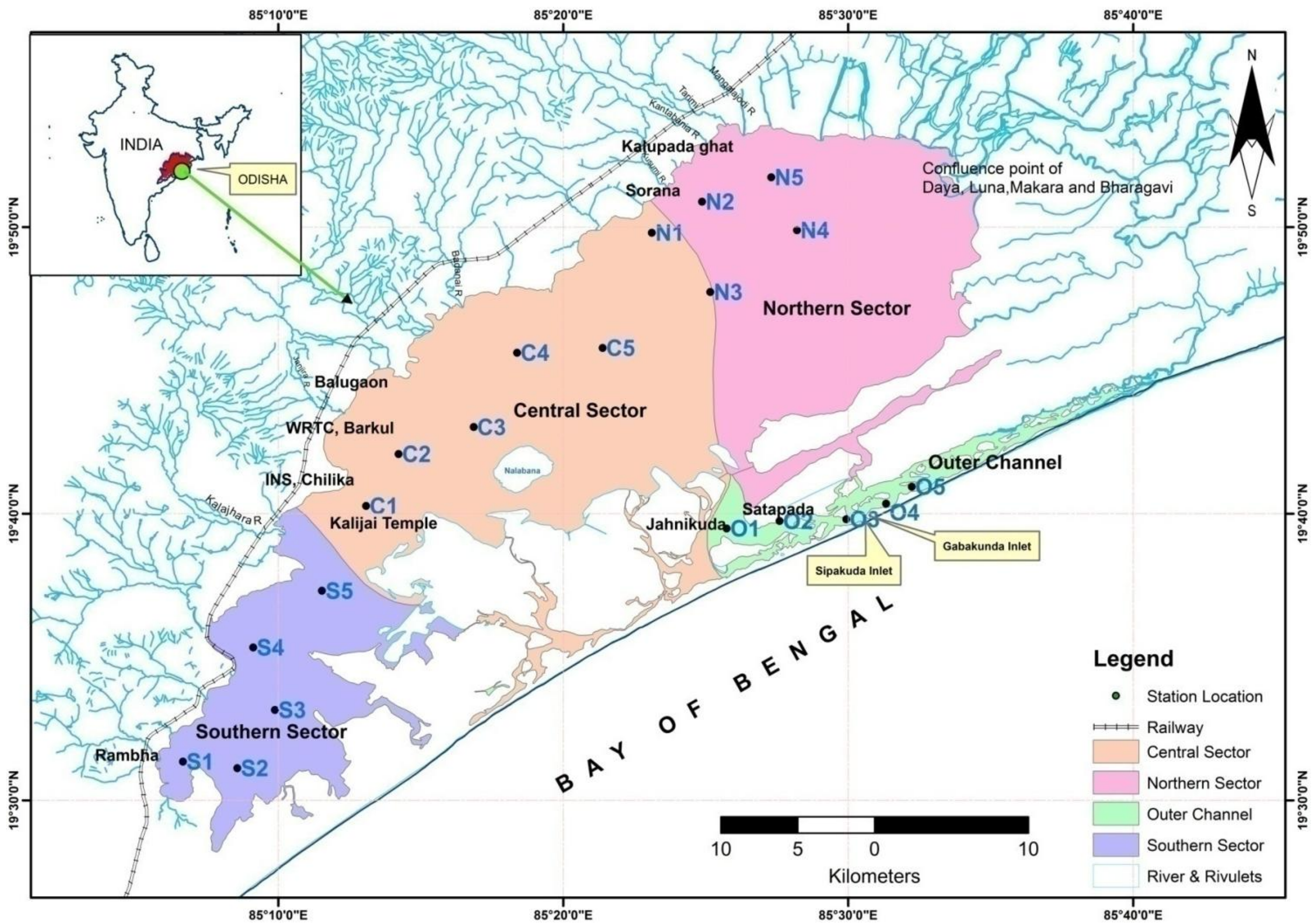

Fig. 1— map showing sampling locations (numerical digits corresponding to station code) in different sectors in Chilika Lagoon [CS: Central Sector, NS: Northern Sector, SS: Southern Sector, OC: Outer Channel]

Average depth of the lagoon is 2 m and longitudinal stretch is about 65 km. Lagoon spreads from northeast to southwest parallel to the coastline with a variable width of 20.1 km. A sand bar separates the lagoon from the Bay of Bengal. Main lagoon is connected through OC with the Bay of Bengal. The outstanding problem of the system is choking of the OC and the northward shifting of the inlet mouth. Rapid growth of aquatic weeds resulted due to siltation and reduction of salinity in the lagoon restricts free movement of fishes[14]. Different types of aquatic weeds such as emergent, floating and submerged are present in the lagoon and more enrichment in NS[15]. Biological sedimentation resulting from cyclic growth, spread and disintegration of macrophytes are considered as one of the dominant processes for modification of lagoon environment[7]. Growth of aquatic weeds and macrophytes breach the free exchange of water and sediment between the lagoon and the bay[16]. High evaporation from the lagoon during the summer and a large fresh water inflow from number of rivers and rivulets at the northern end during the monsoon and post-monsoon significantly influence the area of the lagoon[17]. The fresh water inflow into the lagoon is mainly from the western catchment and from the Mahanadi river system. Around 47 rivers and rivulets drain into the lagoon from western catchment. As an approximate 1362 million Cubic M. of water (42%) is discharged into the lagoon from the western catchment and 1888 million Cu. M. of water (58%) is discharged from the Mahanadi[15].

Surface water samples were collected from 20 stations (5 stations from each sector) covering all the four sectors of the lagoon (Fig. 1). A clean plastic bucket was used to collect the surface water. For each parameter duplicate samples were collected to ensure the result. Field surveys were carried out during the pre-monsoon (PRM; March-June), monsoon (MON; July-October) and post-monsoon (POM; November-December) seasons[18]. Sampling was carried out during the morning hours between 9:00 A.M-2:00 P.M. Water Temperature (WT) and pH were recorded onboard using mercury filled centigrade thermometer (accuracy ±0.1ºC) and a pH meter (EUTECH, accuracy ±0.01) respectively. Water transparency in terms of Secchi Disk Depth (SDD) was measured by means of Secchi Disk. SDD observations were made thrice and the mean was considered as the result. DO was estimated following Winkler's method[19]. Salinity was estimated by Knudsen's titrometric method[20]. For Chl-*a* and nutrient analysis, 1 liter of water samples were collected separately from each station and kept in an ice box and transported to laboratory for further analysis. Chl-*a* was determined spectrophotometrically using well calibrated UV–Visible double beam spectrophotometer (JASCO, Model: V-650) according to Strickland and Parsons [21]. One liter of water samples were collected for determination of TSM and subsequently analysed gravimetrically according to Strickland and Parsons (1972)[21]. After vacuum filtration of the water samples, nutrients [NO_2^- (nitrite), NO_3^- (nitrate), NH_4^+ (ammonia), PO_4^{3-} (phosphate), SiO_4^{4-} (silicate)] followed by standard methods [19]. One-way ANOVA was applied to evaluate statistical differences in water quality parameters among four different sectors of the lagoon. The "p" values resulted from ANOVA test stands for "probability value" which implies significant variation in the parameter when less than a threshold (generally 0.01 or 0.05). F value is a ratio of two mean squares. Significant variation in parameter results when the F value exceeds the critical value. In addition to ANOVA, correlation coefficient matrix was computed among the observed parameters for each season to explore their interrelations. Graphical software Surfer (Version-8) was used to prepare the interpolated plots wherein the latitudes (ordinates) and longitudes (abscissa) are presented in degree decimal units.

Results and Discussion

Table.1 shows the average and range of water quality parameters determined during the study period.

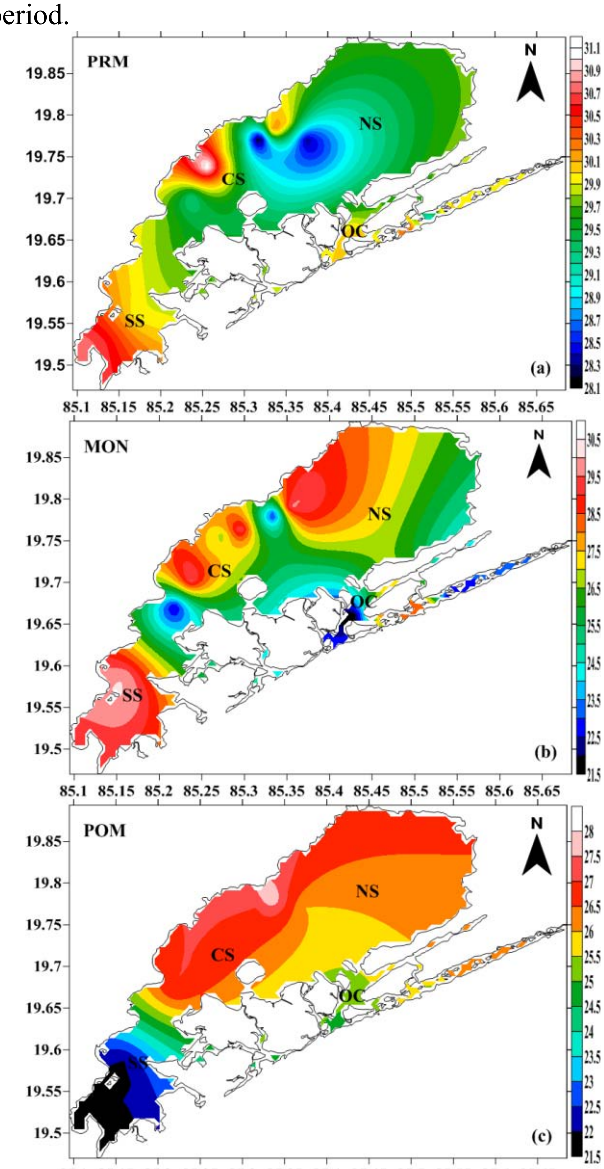

Fig. 2—spatial distribution of WT (°C) in Chilika Lagoon during PRM, MON & POM

Table 1 Seasonal variation in water quality parameters of Chilika Lagoon

Seasons	PRM				MON				POM			
Parameters	NS	CS	SS	OC	NS	CS	SS	OC	NS	CS	SS	OC
WT (°C)	28-30.25	29.25-31.17	29.95-30.78	28.8-30.4	22.4-29.73	22.2-29.6	29.3-29.96	21.3-28.5	26-28	27	21.5-22	25-26
Depth(m)	1.3-1.85	1.24-2.9	1.8-3.15	1.14-3.18	1.6-2.24	2.73-3.1	1.7-3.46	1.85-3.75	1.6-2	1.5-3.3	1.9-3.4	1.17-3.3
SDD(m)	0.43-0.75	0.72-0.88	0.89-1.5	0.36-0.98	0.23-0.8	0.13-0.95	0.75-1.07	0.35-0.6	0.44-0.8	0.6-0.94	0.72-1.2	0.5-0.84
pH	7.8-8.6	7.8-8.9	7.87-8.74	8.53-8.85	8.15-8.72	7.85-8.04	7.47-7.8	6.96-8.02	7.54-8.82	7.63-7.77	6.78-7.3	7.3-7.68
DO (mg/l)	6.71-8.25	5.97-7.36	5.54-6.74	6.25-7.74	7.36-8.22	6.45-6.98	6.59-7.58	5.96-7.09	7.25-8.22	7.25-7.90	3.23-8.54	6.29-8.22
Salinity(PSU)	5.75-9.05	16.4-19	15.35-16.56	21.65-32.42	1.57-6.96	10.1-12.86	12.09-14.28	13.76-18.97	2.9-7.9	8.25-11.15	11.63-15.34	13.41-20.29
SiO_4^{4-} (µg/l)	17.45-43.04	16.42-25.1	14.82-29.02	25.01-37.98	6.55-13.91	7.36-16.02	6.79-30.86	7.1-18.92	19.99-32.44	15.66-38.98	11.22-36.09	12.03-40.38
PO_4^{3-} (µg/l)	0.48-1.2	0.46-0.69	0.41-1.57	0.12-1.06	0.46-0.57	0.3-0.66	0.3-1.22	0.042-0.76	0.56-0.98	0.36-1	0.32-1.35	0.57-0.99
NO_2^- (µg/l)	0.45-1.35	0.42-4.96	0.33-0.54	0.55-0.79	0.35-0.62	1.4-3.76	0.32-0.58	0.33-0.61	0.15-0.45	0.17-1.21	0.21-0.44	0.35-0.79
NO_3^- (µg/l)	4.65-10.56	4.36-27.33	3.43-6.72	1.04-8.8	3.55-4.43	2.34-24.27	0.042-8.22	0.49-6.02	4.36-7.98	2.83-7.61	2.81-6.34	4.38-7.55
NH_4^+ (µg/l)	9.11-22.47	8.57-23.56	7.74-15.15	1.18-19.83	8.14-12.56	1.17-10.75	4.55-12.18	1.04-12.36	13.64-24.01	8.82-24.38	7.96-43.88	2.83-24.21
TSM (mg/l)	2.5-9.54	3.58-11.54	9.5-28.42	10.18-30.15	10.52-71.29	48.8-105.6	53.04-76.2	14-25.4	4.59-11.6	3.8-9.40	10-32.6	18.2-35
Chl-*a* (mg/m^3)	9.09-22.92	8.55-12.82	7.72-15.12	2.33-19.79	15.04-18.75	9.93-21.6	9.1-34.815	2.1-25.51	12.76-22.46	8.25-22.81	4.28-19.02	2.65-22.64

WT is recognized as an important water quality parameter since it directly influences biological activity of lagoon organisms. During the period of study, water temperature varied from 28.00 to 31.17 °C, 21.30 to 29.96 °C and 21.5 to 28.0 °C during PRM, MON & POM respectively (Fig. 2). Maximum (31.17°C) and minimum WT (21.30°C) were recorded during PRM and MON respectively. Maximum temperature was attributed to increase in atmospheric temperature[22].

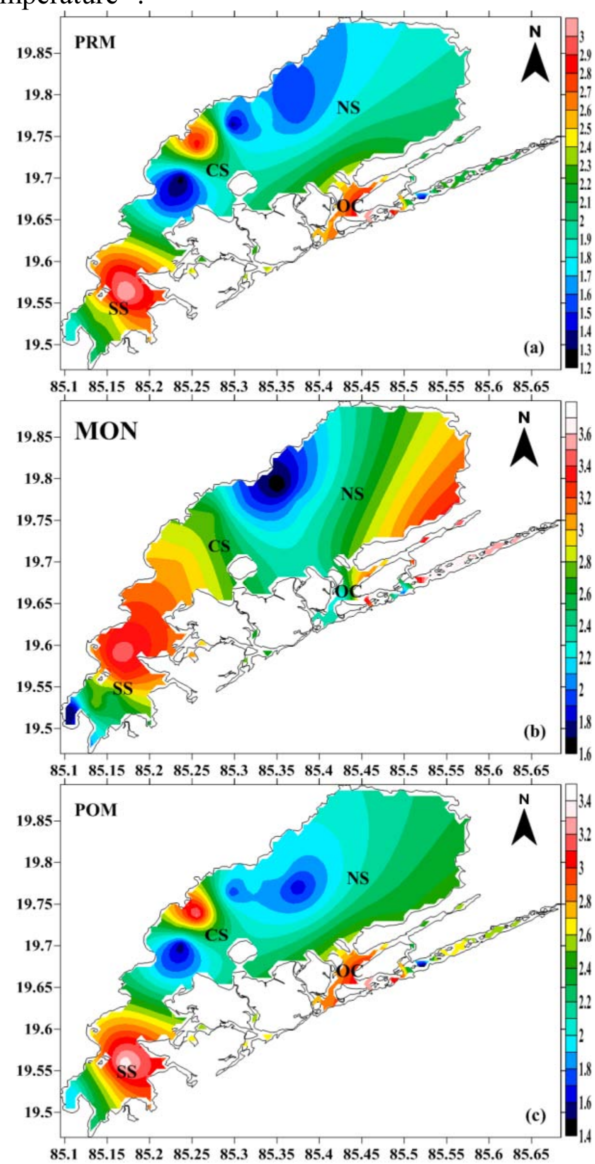

Fig. 3—spatial distribution of Depth (m) in Chilika Lagoon during PRM, MON & POM

The depth of the lagoon at different stations varied from 1.14 to 3.18 m, 1.60 to 3.75 m and 1.17 to 3.40 m during PRM, MON and POM respectively (Fig. 3, Table.1). Lowest average depth was recorded during PRM (1.14 m) and the highest average water depth (3.75 m) during MON which was primarily attributed to increase in water level due to river discharge and monsoonal rain fall. Throughout the year, NS was found to be shallow in comparison with other sectors which might be attributed to the siltation of distributaries of the Mahanadi River in this sector[23].

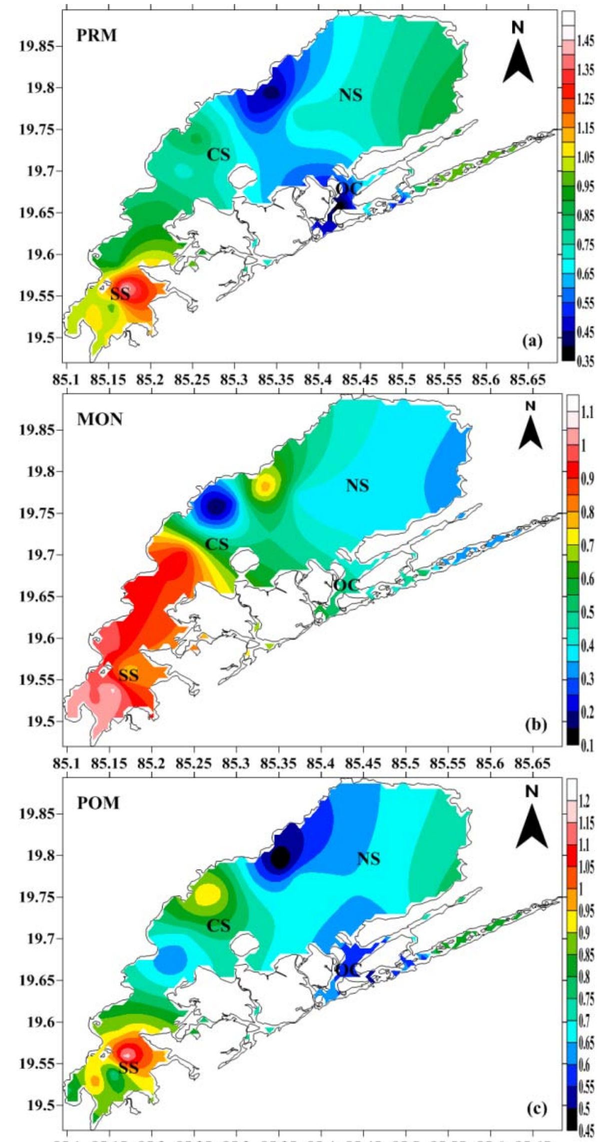

Fig. 4—spatial distribution of Secchi Disk Depth (m) in Chilika Lagoon during PRM, MON & POM

Transparency or water clarity plays a vital role in the lagoon as it indicates the growth and development of aquatic plants. Transparency of water column in terms of SDD was 0.36 - 1.50 m, 0.13 - 1.07 m and 0.44 - 1.20 m during PRM, MON & POM respectively (Fig. 4, Table.1). Average SDD was lowest at 0.13 m in MON which might be due to the mixing of river discharge. The average high SDD was observed (1.5 m) in PRM with an average depth (3.15 m).

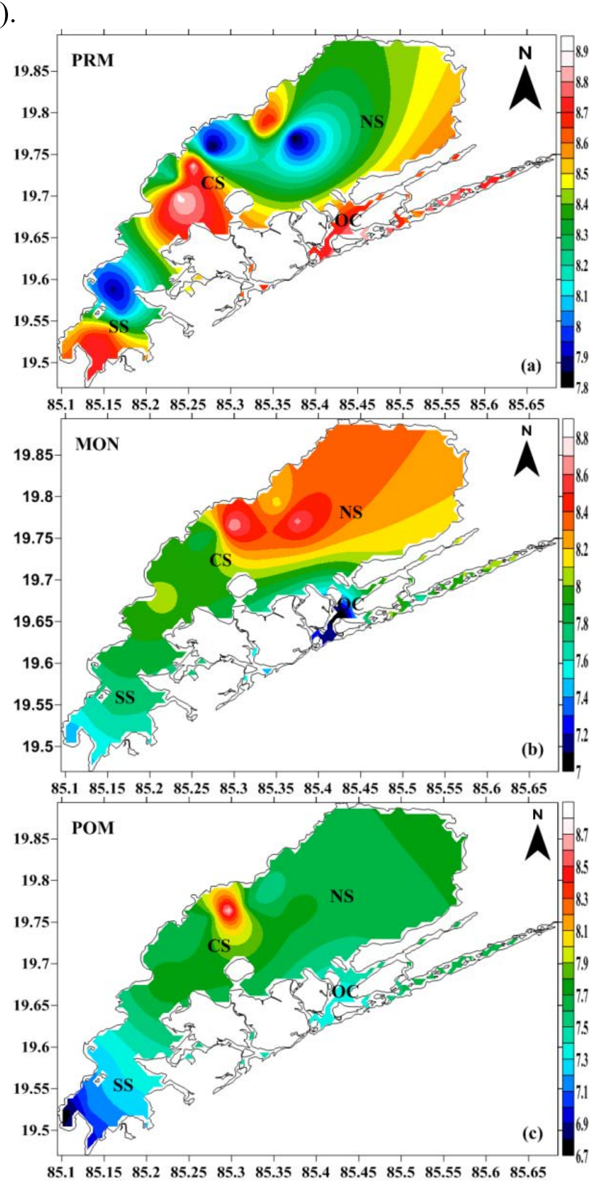

Fig. 5—spatial distribution of pH in Chilika Lagoon during PRM, MON & POM

In marine and brackishwater systems, pH is always taken as a function of the salinity[24]. Monitoring of pH is considered to be important in the brackishwater system, as they are sensitive to changes in pH. The pH of the lagoon indicated slightly alkaline. It varied from 7.80 to 8.90 in PRM, 6.96 to 8.72 in MON and 6.78 to 8.82 in POM (Fig. 5, Table.1). The pH range is most appropriate for the maintenance of the fish community[2]. Higher pH was found in the regions where large amounts of aquatic weeds are present. Photosynthesis of weeds might have caused the increase in pH of the lagoon[6, 25, 26]. The pH variation in the lagoon was due to the resultant mixing of freshwater through riverine input and sea water through inlet of Bay of Bengal[27]. During the present study pH followed the same trend of salinity as agreed by earlier workers[2, 28].

Table 2 One way ANOVA for water quality parameters of Chilika Lagoon

Parameters	P-value	F-value
WT	0.00	21.62
Depth	0.06	3.05
SDD	0.21	1.63
DO	0.03	3.84
Salinity	0.00	7.75
pH	0.00	7.79
TSM	0.00	25.39
NH_4^+	0.00	11.09
NO_2^-	0.09	2.55
NO_3^-	0.23	1.52
PO_4^{3-}	0.17	1.85
SiO_4^{4-}	0.00	12.21
Chl-*a*	0.01	5.00

Like pH, salinity also plays a key role in the biogeochemistry of the lagoon. Lagoon is brackish in nature because it receives much freshwater by via river runoff and saline water through the tidal inlet. Salinity varied substantially with respect to space and time due to its shallowness and input of saline and fresh water. Salinity of the lagoon water ranged from 1.57 to 32.43. Salinity ranged between 5.75 and 32.42 psu during PRM, 1.57 and 18.97 psu during MON and 2.90 and 20.29 psu during POM (Fig. 6, Table 1). Lower value was observed during MON which might be due to the influx of flood water through the tributaries *viz*. Daya, Nuna, Bhargavi in NS and some rivulets in SS & also mixing of rain water. The higher values were observed during PRM as a result of high rates of evaporation and no influx of fresh water. Generally NS was found to be less saline as compared to the OC. The obvious reason is that, there exist a decrease in marine influence on the NS stations which are increasingly distant from the Bay of Bengal. Apart from this, the SS also had higher values compared to both the NS & CS which indicated that this sector was hardly under the river influence. The study reveals to believe that the influx and out-flux of fresh and saline water into the lagoon play a vital role for salinity distribution and it is very significant throughout the year as supported by single factor ANOVA explaining a strong variation for salinity as well as pH ($p<0.01$) (Table 2).

Traditionally in the aquatic system, the more concern water quality parameter is DO, because at low concentrations, it may cause fish mortality. Low concentration of DO allows increase in the toxicity of certain trace metals[29]. DO concentration is controlled by photosynthetic activities of autotrophs (phytoplankton and submerged macrophytes) and aeration[23]

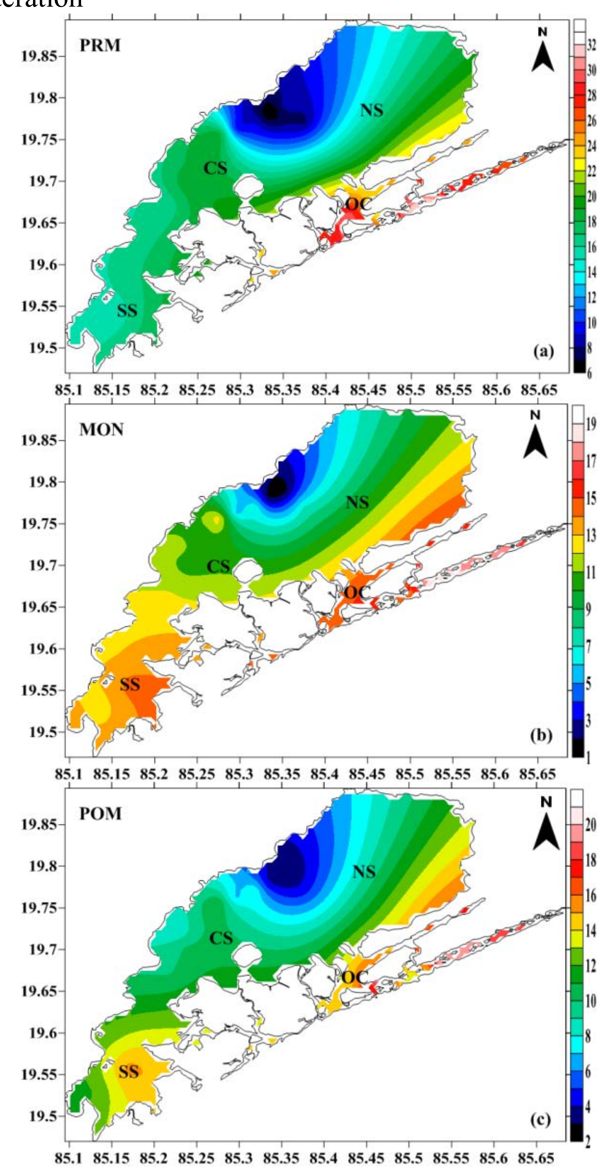

Fig. 6—spatial distribution of Salinity (PSU) in Chilika Lagoon during PRM, MON & POM

In our investigation, DO was found varied from 5.54 to 8.25 mg/l during PRM, 5.96 to 8.22 mg/l during MON and 3.22 to 8.54 mg/l during POM (Fig. 7, Table.1). DO values were noticed more in the regions where more aquatic weeds are present which might be due to the photosynthetic activities of the weeds[6].The presence of TSM load is the key factor in governing light penetration in this ecosystem. TSM was recorded in higher concentration in the study area (Fig. 8, Table.1).

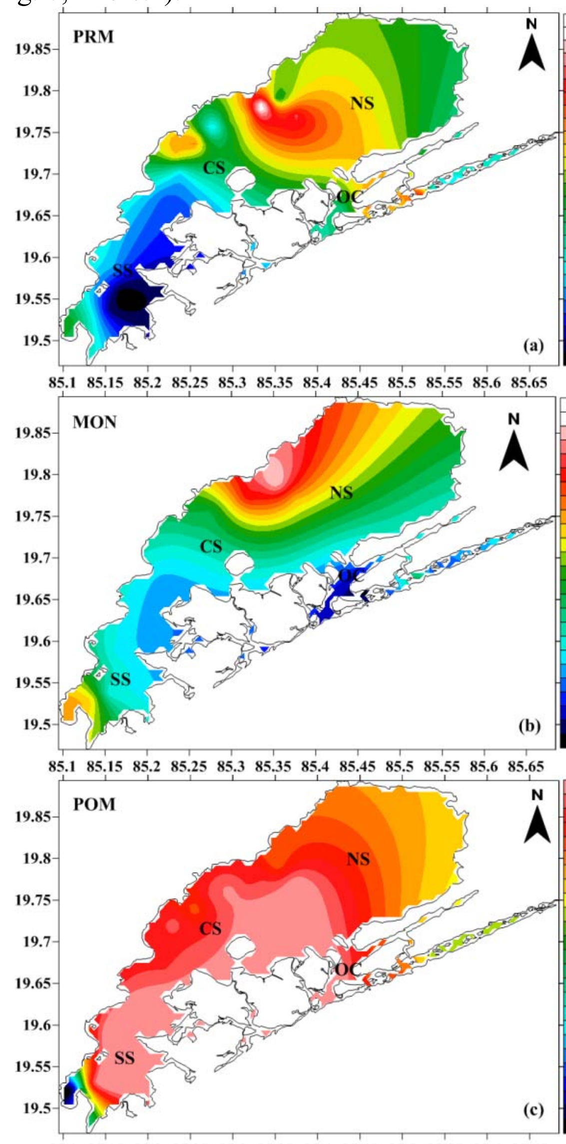

Fig. 7—Spatial distribution of DO (mg/l) in Chilika Lagoon during PRM, MON & POM

In PRM maximum value of TSM was 30.15 mg/l in sea mouth area of OC and minimum amount was found to be 2.5 mg/l in NS. In MON maximum value of TSM was 105.6 mg/l in CS. During POM, TSM was found to be between 3.8 and 35 mg/l. High TSM found in mouth area both during PRM and POM seasons which might be due to high rate of evaporation that caused accumulation of salt and no inflow of fresh water to the lake during this period[2]. During MON higher amount of TSM was noticed in CS near Balugaon in comparison to other seasons might be owing to the anthropogenic activities. A strong seasonal and spatial variation of TSM ($p<0.01$) is explained by one way ANOVA (Table 2).

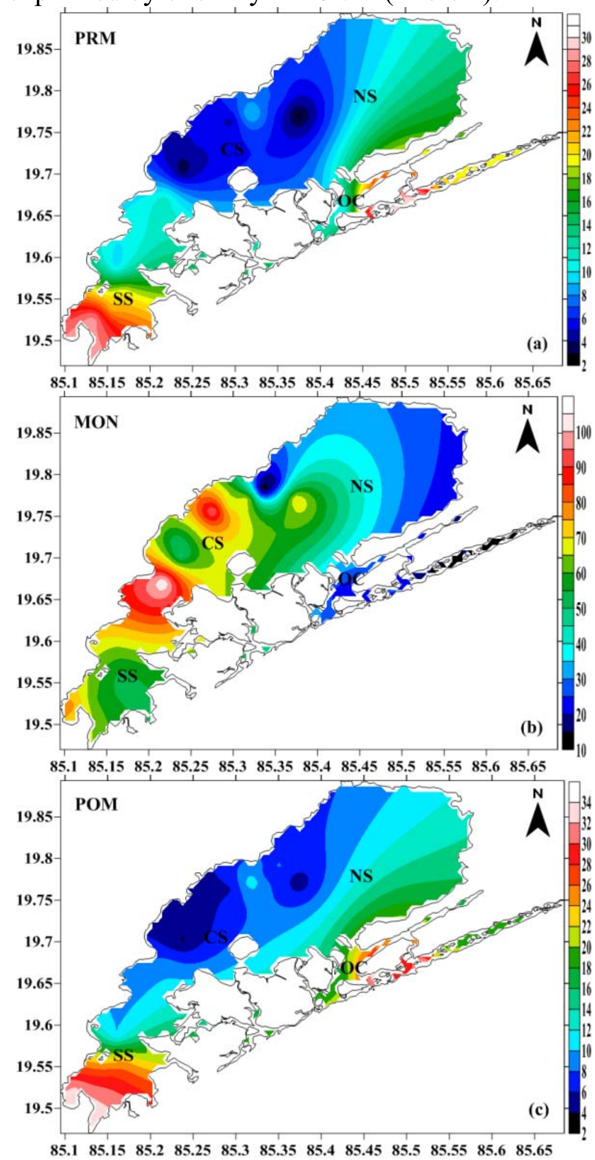

Fig. 8—spatial distribution of TSM (mg/l) in Chilika Lagoon during PRM, MON & POM

Chl-*a* constitutes, the chief photosynthetic pigment of phytoplankton and is an index that would provide the primary production of any aquatic ecosystem upon which the biodiversity, biomass and carrying capacity of the system depends. The total amount of algal biomass in a water body can be intended by the estimation of Chl-*a*[30]. Generally the Chl-*a* and primary production are well co-related. Average Chl-*a* concentration was ranged from 2.33 to 22.92 mg/m^3, 2.10–34.81 mg/m^3 and 2.65 to 22.81 mg/m^3 during PRM, MON and POM respectively (Fig. 9, Table 1). During MON, Chl-*a* concentration was found more as compared to other seasons which might be due to the influx of river discharges through the tributaries of the river Mahanadi in the NS of the lagoon and presence of more freshwater phytoplankton (Unpublished data). Significant seasonal variation ($p<0.01$) was observed in the distribution of Chl-*a* (Table 2).

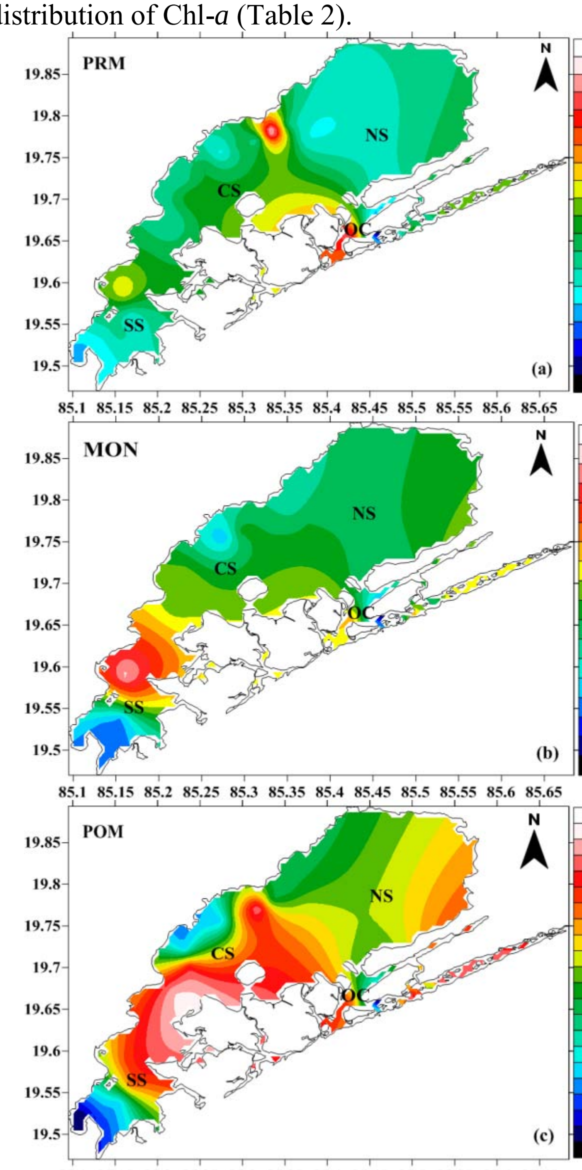

Fig. 9—spatial distribution of Chl-*a* (mg/m^3) in Chilika Lagoon during PRM, MON & POM

Aquatic flora uptake nitrogenous nutrients for their growth. Besides that, the nutrients regulate primary production in coastal marine waters. When present in enriched condition, it can also fuel phytoplankton blooms leading to oxygen depletion in water[31]. It is thus the responsibility of the coastal lagoon managers to control the nutrients input into such sensitive ecosystems. In the present study, the results of the nutrients are presented in Table 1. NO_2 being the intermediate oxidation state appears as transient species of nitrogen. This is also released to the water as an extra cellular product of phytoplankton[32, 33]. The NO_2^- level in the Chilika Lagoon ranged from 0.33 to 4.96 μmol/l, 0.32 to 3.76 μmol/l and 0.16 to 1.21 μmol/l during PRM, MON and POM respectively (Fig. 10, Table 1).

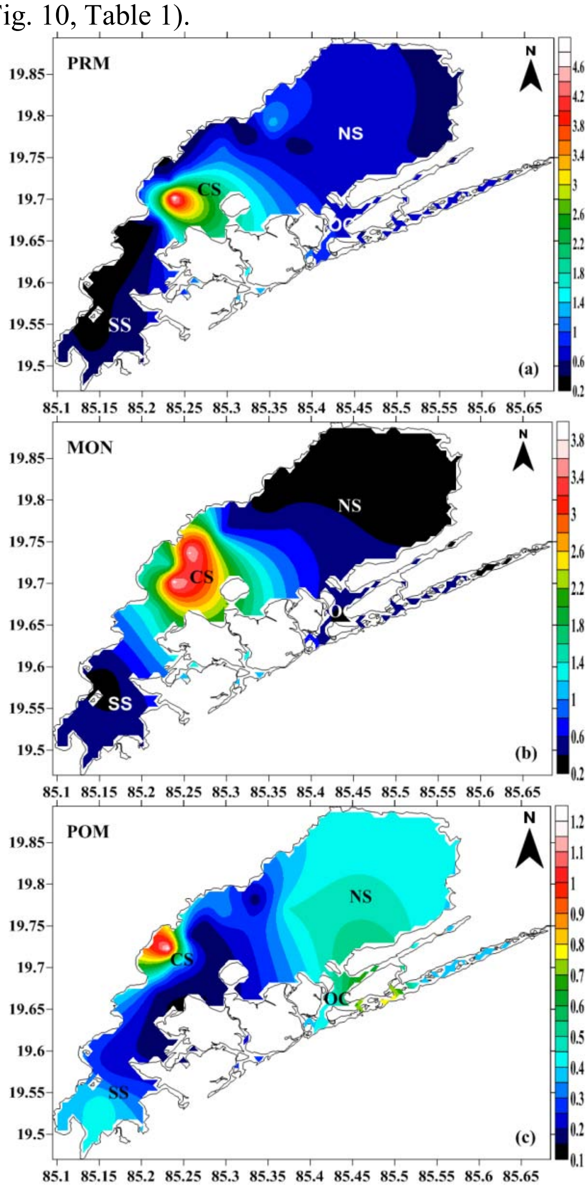

Fig. 10—Spatial distribution of NO_2^- (μmol/l) in Chilika Lagoon during PRM, MON & POM

Lower concentration of NO_2^- was observed as compared to that of NH_4^+ and NO_3^- concentration. The NO_2^- concentration at station CS-2 near Balugaon was remarkably high (4.96 μmol/l) during PRM, which might be due to anthropogenic influence from Balugaon Township and Boat Jetty. During MON, a conspicuous decreasing trend in nitrite level from CS towards both the NS and SS was noticed (Fig. 10(b)). The established trend therefore, is believed to indicate the influence of nutrient laden river runoff from the north towards the central and anthropogenic activities of the adjacent townships. Within seasons, the NO_2^- level during PRM was higher than the other two seasons which might be due to the release of nitrite from the decomposed aquatic weeds[23].

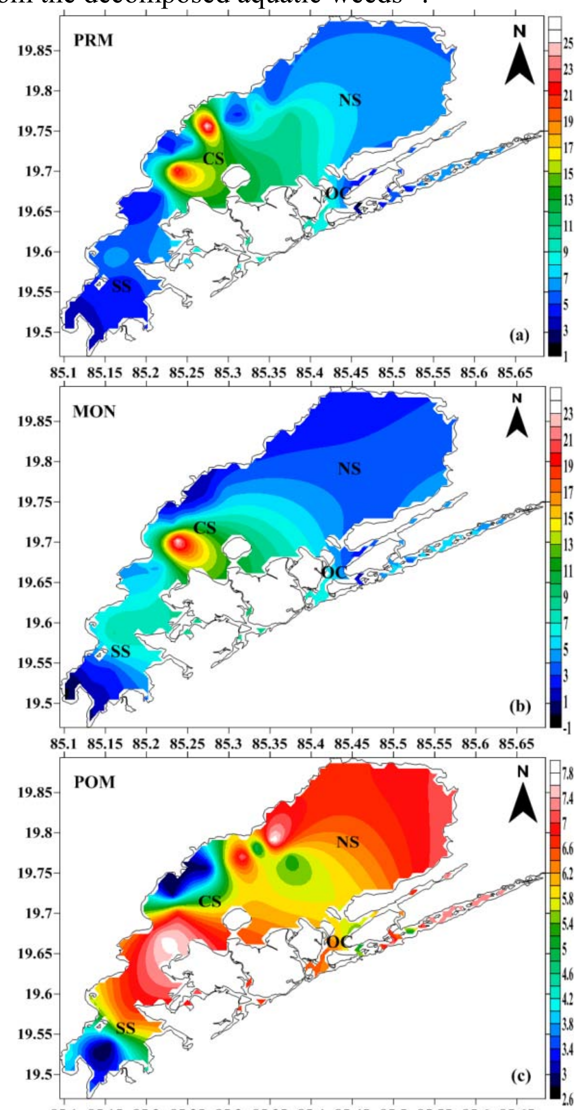

Fig. 11—Spatial distribution of NO_3^- (μmol/l) in Chilika Lagoon during PRM, MON & POM

NO_3^- is an essential nutrient for autotrophs as well as limiting factor for algal growth. In aquatic environment they present in trace quantity in the surface water. However, when its concentration becomes excessive along with other nutrients, problem of eutrophication and algal bloom takes place. A narrow range of fluctuation in NO_3^- concentration was noticed during MON and PRM whereas a sharp decrease during POM. Behaving as a trace nutrient in the system, the NO_3^- varied from 1.04 to 27.33 µmol/l during PRM, 0.04 to 24.27 µmol/l during MON and 2.81 to 7.98 µmol/l during POM (Fig. 11, Table 1). Higher concentration of NO_3^- was observed during PRM and lowest during POM.

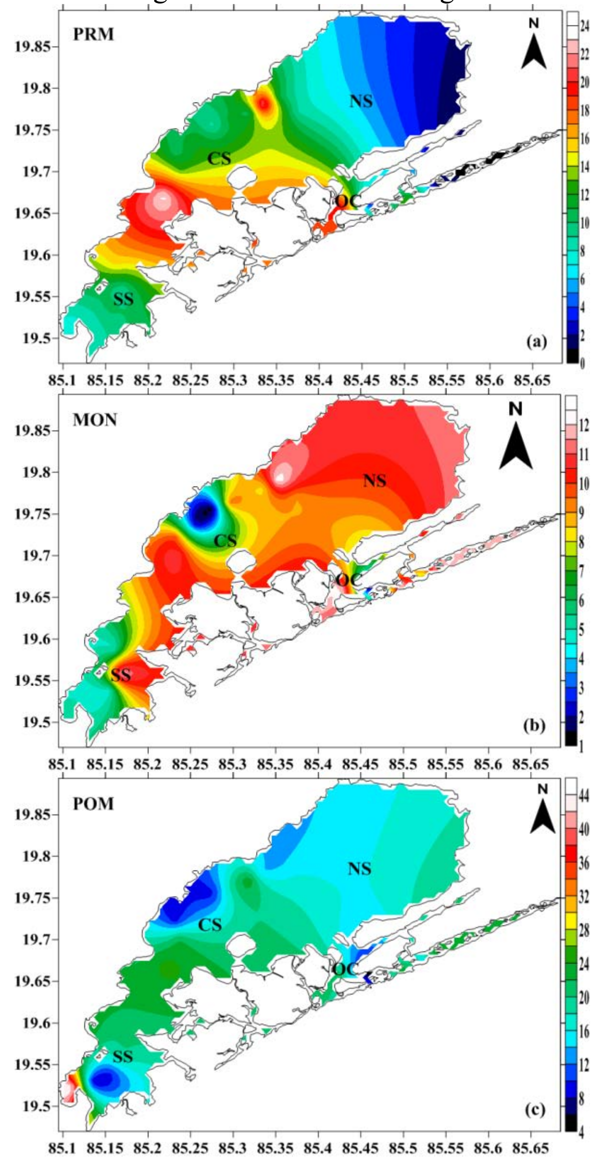

Fig. 12—spatial distribution of NH_4^+ (µmol/l) in Chilika Lagoon during PRM, MON & POM

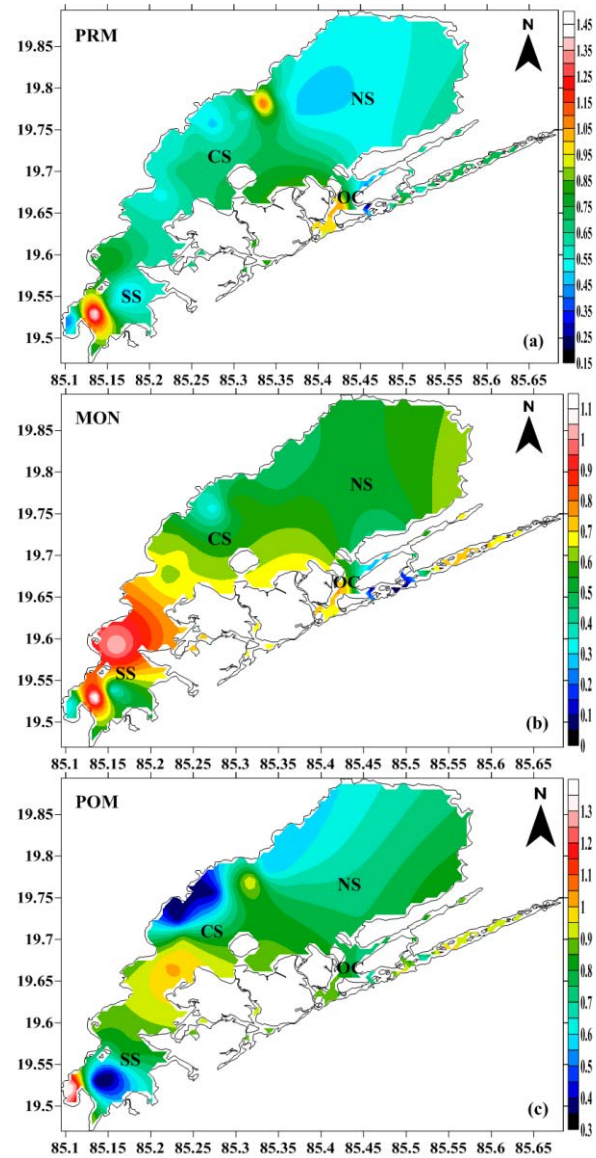

Fig. 13—spatial distribution of PO_4^{3-} (µmol/l) in Chilika Lagoon during PRM, MON & POM

NH_4^+ is an important inorganic nutrient which is released as excretory material from different aquatic animals and also reutilized by phytoplankton[35, 36]. These two above effects i.e. release from excretory & utilization by phytoplankton affect the concentration of NH_4^+ significantly[37]. When present in higher concentration, NH_4^+ is regarded as one of the pollutants in the aquatic environment. In the present investigation, the concentration of NH_4^+ of the lagoon was found between 1.18 and 23.56 µmol/l during PRM, 1.04 and 12.56 µmol/l during MON and 2.83 and 43.88 µmol/l during POM (Fig. 12, Table 1). From the investigation, relatively high concentration of NH_4^+ was observed during POM in comparison to other seasons. A clear trend in NH_4^+ distribution was not observed, which could be due to its oxidation to other forms or reduction of nitrate to lower forms [37, 38].

The PO_4^{3-} concentration was observed very low in comparison to previous observations[39,40]. PO_4^{3-} concentrations in the lagoon varied throughout the study period. PO_4^{3-}concentration range was from 0.12 to 1.57 µmol/l, 0.04 to 1.22 µmol/l and 0.32 to 1.35 µmol/l during PRM, MON and POM respectively (Fig. 13, Table 1). High PO_4^{3-} content in the lagoon might be attributed to nutrient diffusion from the bottom sediment (because of its shallowness) into the water column and excessive organic load in the water[41]. This also could be because of addition of phosphate along with the land drainage and detergent rich sewage effluents. Such additive PO_4^{3-} helps in growth of the weeds in the lagoon. Previously it was observed that maximum limit of PO_4^{3-} concentration was 2.55 µmol/l, and was accepted as the danger signal of evaluating the eutrophication of lake[23, 39]. In the present study, however, the concentration of PO_4^{3-} was well below the pollution limit for better sustenance of aquatic lives.

The lagoon water was found to be enriched in SiO_4^{4-} concentration throughout all the three seasons (Fig. 14, Table.1). In PRM maximum value of SiO_4^{4-} was 43.04 µmol/l in NS and minimum value was 14.82 µmol/l in SS where as in POM maximum value of SiO_4 was 40.38 µmol/l in the stretch of OC and minimum value 11.22 µmol/l in SS. In MON maximum value of SiO_4^{4-} was 30.86 µmol/l in SS and minimum value 6.55 µmol/l in NS. Although rivers are draining into the NS of the lagoon, the biological removal and sediment dispersal due to monsoon river current, dissolution of particulate silicon carried by the river, the removal of soluble silicates by adsorption and co-precipitation of soluble silicates with humic compounds and iron may be some of the processes operative for depletion of silicate in the NS[42]. Such processes were not captured during this one year study and shall be addresses with further study and monitoring.

In POM, SiO_4^{4-} was found in higher concentration which might be due to influx of river borne silt. Lower SiO_4^{4-} concentration noticed in the study area might be resulted due to the consequent utilisation of SiO_4^{4-} by diatoms[43].

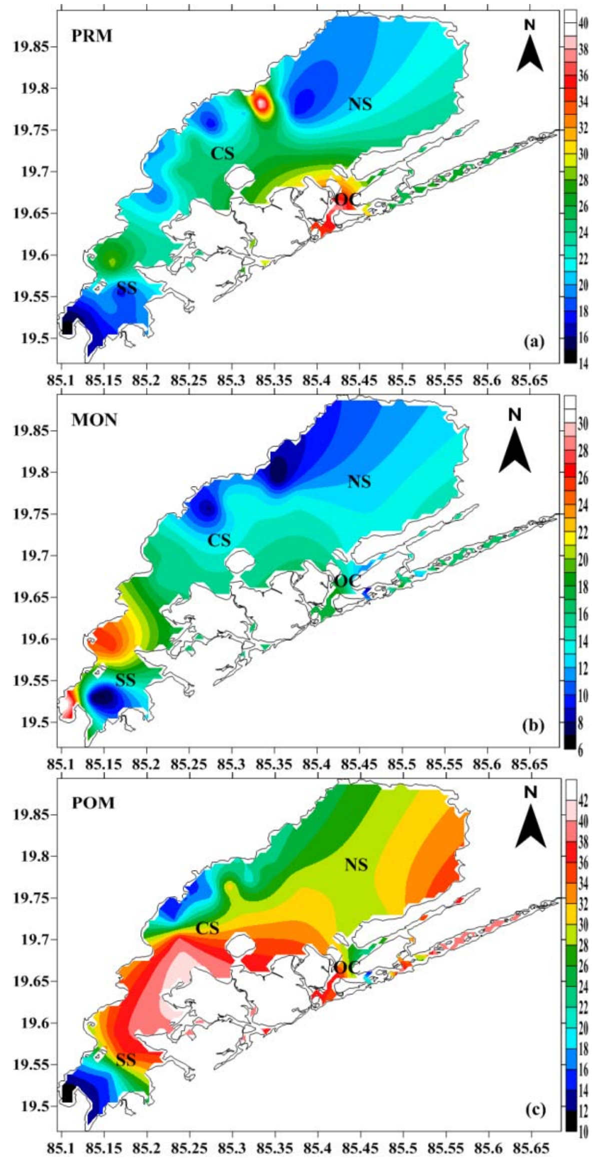

Fig. 14—Spatial distribution of SiO_4^{4-} (µmol/l) in Chilika Lagoon during PRM, MON & POM

Variation in water quality parameters was evaluated using a one-way ANOVA which indicated significant seasonal variation in the whole lagoon. The nutrients *viz.* NH_4^+, SiO_4^{4-}, observed a strong variation ($p<0.01$) throughout the year (Table 2).

Statistical Analyses

Pearson correlation coefficient matrix was computed among all the 13 hydro-biological variables which are collected in three different seasons covering all sectors of the Chilika Lagoon (Table 3).

Table 3 Correlation coefficient matrix of different physico-chemical parameters of Chilika Lagoon during PRM, MON & POM (*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

	WT	DO	Salinity	pH	TSM	NH_4^+	NO_2^-	NO_3^-	PO_4^{3-}	SiO_4^{4-}	Chl-*a*
WT	1										
DO	-.241	1									Premonsoon
Salinity	.193	-.110	1								
pH	.439	.078	.359	1							
TSM	.245	-.087	.518*	.366	1						
NH_4^+	.058	.061	-.164	.073	-.386	1					
NO_2^-	-.150	-.119	.038	.278	-.336	.049	1				
NO_3^-	-.144	-.159	-.006	-.207	-.477*	.102	.599**	1			
PO_4^{3-}	.313	.008	.019	.227	.036	.392	-.028	.027	1		
SiO_4^{4-}	.112	.406	.231	.365	-.091	.435	.052	.008	.388	1	
Chl-*a*	.156	.159	.025	.132	-.356	.645**	.097	.183	.630**	.759**	1
WT	1										
DO	.174	1									Monsoon
Salinity	-.053	-.754**	1								
pH	.124	.449*	-.658**	1							
TSM	.176	.081	-.077	.183	1						
NH_4^+	-.230	.035	-.173	.118	-.353	1					
NO_2^-	.052	-.136	-.032	.014	.394	-.280	1				
NO_3^-	.089	-.222	-.039	.051	-.067	.386	.496*	1			
PO_4^{3-}	-.040	.062	-.020	-.152	.133	.171	-.065	.257	1		
SiO_4^{4-}	-.012	-.156	.226	-.229	.107	.259	-.142	.198	.164	1	
Chl-*a*	-.144	-.224	.028	.007	-.077	.608**	-.080	.491*	.447*	.589**	1
WT	1										
DO	.136	1									
Salinity	-.457*	-.157	1								Postmonsoon
pH	.675**	.345	-.349	1							
TSM	-.629**	-.409	.674**	-.551*	1						
NH_4^+	-.182	-.621**	.014	-.175	.092	1					
NO_2^-	.025	-.020	.187	-.028	.248	-.238	1				
NO_3^-	.256	.035	-.010	.228	-.148	.454*	-.212	1			
PO_4^{3-}	-.092	-.531*	.177	-.101	.155	.917**	-.168	.644**	1		
SiO_4^{4-}	.179	.277	.107	.344	-.246	.346	-.204	.744**	.455*	1	
Chl-*a*	.264	.303	-.014	.371	-.311	.403	-.262	.806**	.496*	.893**	1

During PRM, strong positive correlation (p=0.01) of Chl-*a* was observed with SiO_4^{4-}, PO_4^{3-} & NH_4^+. This might be attributed to utilization by phytoplankton. A strong positive correlation was observed between two nitrogenous nutrients i.e. NO_3^- and NO_2^- which indicated that conversion of NO_2^- to NO_3^- with the reaction of oxygen in the lagoonal ecosystem (Table 3).

During MON, a strong negative correlation between DO and salinity (p=0.01) (Table 3) was observed which indicated high freshwater influence in the study area[5]. The result reveals an inverse correlation between these two factors confirming that, DO is primarily controlled by salinity[44, 45].

As like PRM, during MON, positive correlation between NO_3^- and NO_2^- (p=0.05) was observed. A strong positive correlation was between Chl-*a* with NH_4^+ & SiO_4^{4-} (p=0.01) whereas a comparatively poor positive correlation with NO_2^- & NO_3^- (p=0.05). During MON, negative relation between TSM and salinity was observed, whereas it was significant in PRM and POM. This indicated the TSM influx to the lagoon was due to marine influx during PRM and POM whereas due to freshwater influx during MON. During POM, Chl-*a* exhibited a strong positive correlation with SiO_4^{4-} and NO_3^- (p=0.01) and a comparative poor positive correlation with PO_4^{3-} (p=0.05), which indicated SiO_4^{4-} & NO_3^- play a key role in regulating the primary productivity of the lagoon ecosystem (Table 3). The overall correlation analysis explored SiO_4^{4-} as the major influencing factor for phytoplankton growth throughout all the seasons. Whereas different nitrogenous nutrients *viz.* NO_3^- and NH_4^+ also played a major role in Chl-*a* distribution.

Conclusion

Spatio-temporal variation in water quality of the lagoon was attributed to seasonal forcing, river influence, marine water influx and anthropogenic activities. Salinity and pH were mostly regulated by the salt water influx and river discharge according to different seasons. Amongst all the nutrients, $SiO_4^{4-}$was determined as the most influencing factor regulating phytoplankton production of the lagoon throughout the year. NH_4^+ was found as the second influencing factor for distribution of Chl-*a*. Further it is recommended that all potential nutrient sources in the catchment (point source and diffuse) be identified and quantified. This can provide information on Chl-*a* distribution coupled with nutrient variation. Future studies are required to monitor the biogeochemistry of the lagoon to assess its trophic status. This study provides the latest observations on overall baseline water quality conditions.

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