

## Variability of nutrients and phytoplankton biomass in a shallow brackish water ecosystem (Chilika Lagoon, India)

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**Abstract** Seasonal and spatial variations in water quality parameters, such as nutrients [ $\text{NH}_4^+$ -N,  $\text{NO}_2^-$ -N,  $\text{NO}_3^-$ -N,  $\text{PO}_4^{3-}$ -P, total nitrogen (TN) and total phosphorus (TP)], Secchi disc depth, salinity, dissolved oxygen, chlorophyll *a*, primary productivity and phytoplankton standing stock, were studied in Chilika Lagoon (from 27 sampling locations) during 2001–2003 to assess the present ecological status. The study was undertaken after a major hydrological intervention in September 2000, which connected the lagoon body and the Bay of Bengal via a manmade opening (new mouth). Current and old data on water quality were also compared to establish the changes that had occurred after the hydrological intervention. Multivariate techniques and gridding methods were used to investigate the spatial and seasonal variability of the data and to characterize the trophic evolution of the basin. Results of principal component analysis (PCA) indicated that the 27 stations can be classified into five groups based on similarities in the temporal variation of nutrients, chlorophyll *a* concentration, salinity, and

other physicochemical parameters. The tributaries and the exchange of lagoon water with the Bay of Bengal most probably determine the water quality and the dynamics of the ecosystem. Hydrodynamics of the lagoon, weed coverage, input of urban sewage through tributaries and agricultural runoff are probably the key factors controlling the trophic conditions of the lagoon. An increase in salinity and total phosphorus was noted after the new mouth was opened, while the total suspended sediment load, the water column depth, and nitrogenous nutrients decreased. The new mouth opening also brought changes in the phytoplankton species composition.

**Keywords** Siltation · Eutrophication · Chilika · New mouth

### Introduction

The ecological effect of change in pressure is a current theme in ecology, and one that emphasizes the dynamic aspects and historical processes involved in ecosystem change. Due to high variability in their physical, chemical and biological parameters, coastal lagoons are typically unstable environments and therefore the short- or long-term variations that occur in these ecosystems are large in comparison to other saline environments. These lagoons usually exhibit estuarine characteristics and are regions of high primary productivity. Transfer of this productivity through the food web often yields prolific fisheries. Water characteristics in lagoons can be strongly influenced by both freshwater flow and ocean exchange; terrestrial runoff supplies nutrients and the tidal exchange of ocean water typically dilutes nutrient concentrations. Hence the temporal and spatial variability of the water quality depend

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upon the relative strengths of river and tidal flows. Over the last few decades, an increase in the anthropogenic input of nitrogen and phosphorus has led to severe eutrophication problems in estuarine and marine environments (Fisher et al. 1995; Kinney and Roman 1998; Cloern 2001).

Coastal lagoons became the subject of active scientific research relatively recently (the 1970s), and except for some well-known examples they are grossly underrepresented in the English-language peer-reviewed literature. Venice Lagoon in Italy (Bianchi et al. 2003; Acri et al. 2004; Gačić and Solidoro 2004; García et al. 2007; Pastres et al. 2005; Solidoro et al. 2005), poorly flushed Chiku Lagoon of Taiwan (Lin et al. 2001, 2006), lagoon and estuarine systems of South Africa (Schleyer and Roberts 1987; Perissinotto et al. 2003; Froneman 2004), some of the lagoons of Spain (Salas et al. 2005; García et al. 2007), France (Chomérat et al. 2007), and the lakes of the Netherlands (Gulati and Van Donk 2002) have been studied extensively and exhibit similar characteristics to those of Chilika Lagoon (a coastal lagoon of India).

Chilika Lagoon, a tropical coastal ecosystem, has been studied in detail in terms of its origin, geology, geomorphology and issues related to management strategies (Bhattacharya et al. 1994; Panigrahy 2000; Sekhar 2004). Until recently, most of these investigations either focused on analyzing specific processes or were driven by contingent environmental emergencies. There are some individual studies (Chandramohan and Nayak 1994; Panda et al. 1995; Sahu and Adhikary 1999; Shaw et al. 2000; Nayak et al. 2004; Panda et al. 2006; Mohapatra et al. 2007), but they lack concrete multidisciplinary, systematic, lagoon-wide efforts. This has resulted in a still rather poor quantitative knowledge of the behavior and functioning of the lagoon ecosystem as a whole. The present study has been undertaken by considering, at a quantitative level, how such a complex ecosystem behaves and responds to the inputs it receives from its tributaries.

In this paper, an attempt has been made to identify different areas of the lagoon undergoing severe anthropogenic stresses, based on the water quality characteristics. This gives a description of the seasonal variations and spatial distributions of the dissolved nutrients, chlorophyll *a*, phytoplankton, and some other environmental variables. We also present some evidence for the effects of an anthropogenically generated increase in water exchange with the open sea, due to a new mouth that was dredged and opened in September 2000, on the overall ecology of Chilika lagoon.

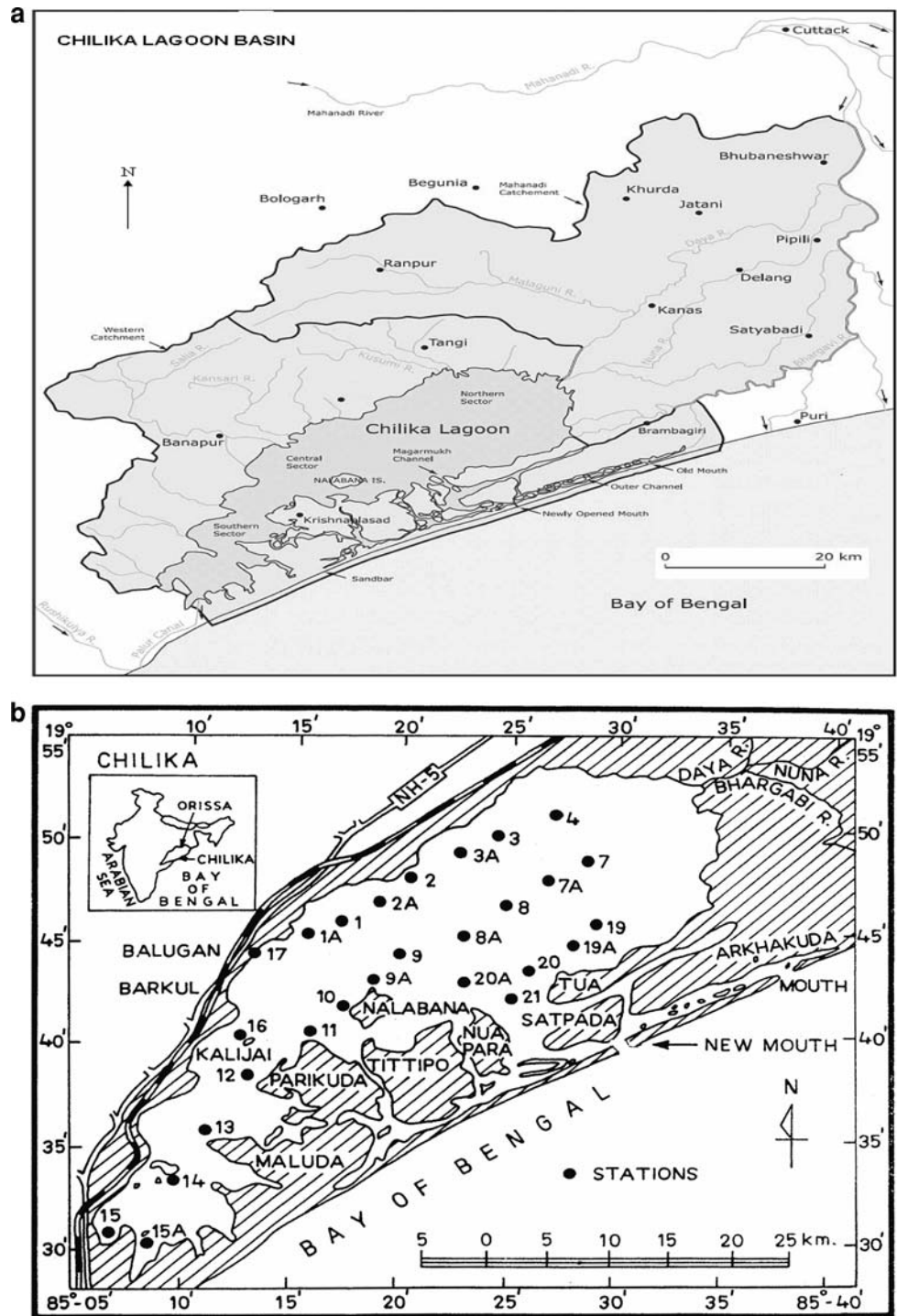
## Study area

Chilika lagoon (19°28'–19°54'N:85°06'–85°35'E) on the east coast of India is the largest brackish water lagoon in

Asia and is one of the largest tropical lagoons in the world. This shallow water body (average depth 2 m) is about 65 km in length and spreads from northeast to southwest parallel to the coastline with a variable width (reaching 20.1 km). The lagoon is spread over an area of 950 km<sup>2</sup> during the summer, and swells up to 1165 km<sup>2</sup> during monsoon season (Siddiqui and Rama Rao 1995). During winter (November–January), a large portion of this lagoon remains submerged and acts as a wetland, which also serves as breeding and nesting grounds for millions of migratory water fowl. High evaporation from the shallow water body during summer (April–June) and a large inflow of fresh water through various rivers and rivulets at the northern end of the lagoon during the monsoon (July–September) and post-monsoon (October–November) seasons significantly influence the area of the lagoon (Mohanty et al. 1996). The catchment area (Fig. 1a) of the lagoon is about 4406 km<sup>2</sup>; 68% of this is constituted by the western catchment and 32% by the Mahanadi Delta in the northeast. The lagoon has several hydrological influences. The most important among them are (1) drainage from the unregulated and degraded catchment basin lying on the western and southern boundaries, (2) silt-borne freshwater discharges from the tributaries of the Mahanadi River, and (3) the exchange of lagoon water with the Bay of Bengal. Changes in the strength and nature of these hydrological connections can have drastic and potentially unexpected consequences for the lagoon. The lagoon is separated from the Bay of Bengal by a sand bar of 60 km length. The lagoon has a 24 km long narrow and curved channel which runs parallel to the coast to join the Bay of Bengal near Arakhakuda, the only mouth of Chilika until September 2000. The exchange of water and sediment between the lagoon and the sea was considerably affected by the choking of the outer channel and the northward shift of the inlet mouth (Chandramohan and Nayak 1994).

The shift in and blockage of the lagoon mouth occurred due to the addition of silt from upstream catchments as well as oceanic longshore transport. The longshore sediment transport (littoral drift) along the coast of the Bay of Bengal is  $\approx 0.1$  million metric tonnes (MT) annually, and tends to shift the lagoon mouth (the opening to the sea) every year, thereby adversely affecting tidal exchange. The major silt load carried by the tributaries of the Mahanadi River system is 1.5 million MT year<sup>-1</sup>, while 0.3 million MT year<sup>-1</sup> of sediment enter from the western catchment (Ghosh et al. 2006). The upstream erosion and sedimentation processes in the lagoon have directly contributed to the loss of lagoon depth as well as the blockage of the mouth. The total sediment load discharged into the lagoon was described as 1.8 million MT in 1998 (Patnaik 1998), and went up to 2.94 million MT in 2001 (Anonymous 2003).

**Fig. 1** **a** Drainage basin of Chilika Lagoon showing different catchment areas. **b** Locations of sampling stations on Chilika Lagoon and the new inlet channel



There has also been a general increase in the pollution load from agricultural, aquaculture and domestic sources from the drainage basin. The western catchment contributes an average of  $\approx 536 \text{ m}^3 \text{ S}^{-1}$ , and the distributaries of the Mahanadi River (Daya, Bhargavi and Nuna rivers) contribute an average of  $\approx 850 \text{ m}^3 \text{ S}^{-1}$  (Patnaik 2002). Furthermore, the introduction of prawn culture (“gheri” or bund fishing) in 1991 led to various changes in hydrology

and sediment transport processes, mainly as a result of the use of split bamboo and very fine mesh nets encircling the culture area, which prevented free sediment flow. The amount of sewage discharged to the lagoon from the capital city Bhubaneswar was observed to be  $\approx 550$  million liters day<sup>-1</sup>, along with a huge amount of untreated domestic wastewater from the 141 villages in and around the lagoon. Analysis of the capital city’s wastewater

indicates suspended solids concentrations of roughly  $275 \text{ mg l}^{-1}$  and an average biochemical oxygen demand of  $110 \text{ mg l}^{-1}$ , far above the permissible limit of  $20 \text{ mg l}^{-1}$  (Orissa State Pollution Control Board, unpublished data, 1998). The siltation, reduced salinity, increased pollutant load from the catchment basin, and restricted outflow of lagoon water (to the sea) resulted in the rapid growth of invasive weed species in the northern sector and eutrophication throughout the lagoon.

The lagoon is severely threatened by problems like shrinkage of area and decreased depth due to siltation, decreased salinity, macrophyte infestation, eutrophication and loss of biodiversity. The weak circulation of the lagoon water and poor tidal influx are responsible for the reduction in salinity. These changes in the lagoon environment are a cause of concern for both the local and the national governments, and several conservation measures such as the dredging of a new mouth and public awareness campaigns have been initiated. However, the lack of true catchment basin management has led to the influx of a huge amount of suspended sediment into the lagoon, which has altered its ecology significantly.

Siltation, declining salinity and nutrient inflow has led to extensive macrophyte growth in the lagoon. Free-floating invasive species (e.g., *Azolla*, *Eichhornia*, *Nymphaea*, *Pistia*) and emerging species (e.g., *Ipomea*) have become a common sight. Among the submerged species, *Potamogeton*, *Hydrilla* and *Najas* are common. Weed infestation increased from  $20 \text{ km}^2$  in 1973 to  $440 \text{ km}^2$  in 1998, and reached  $523 \text{ km}^2$  in 2001. In 2001, emergent weeds covered  $86.07 \text{ km}^2$ , free-floating weeds covered  $110.74 \text{ km}^2$ , and submerged weeds covered  $326.19 \text{ km}^2$  of the lagoon. *Paspalum vaginatum*, *Paspalidium punctatum*, *Potamogeton nodosus* and *Potamogeton pectinatus* dominated the macrophyte community. *Potamogeton* alone accounted for 78% of the invasive species (Ghosh et al. 2006).

## Materials and methods

From December 2001 to June 2003, surface water samples from 27 stations covering the entire lagoon (a few centimeters below the surface) were collected on a seasonal basis (Fig. 1b). The spatial variability of the lagoon was investigated in terms of “relatively homogeneous” stations with respect to various parameters. The stations were fixed uniformly in a grid pattern. The salinity, pH and dissolved oxygen (DO) concentration in the water were measured onboard using a portable digital water analysis kit (WTW MultiLine) with different probes. Water samples for nutrient measurements were filtered directly using Whatman GF/C and stored in 1,000 ml glass bottles and then frozen for the analysis of nitrate, nitrite and

orthophosphate. Samples for ammonium measurements were immediately fixed by the addition of working reagents (Koroleff 1969) and kept in the dark. Later on, ammonium was analyzed according to Koroleff (1969). Other dissolved nutrients [nitrate, nitrite, total phosphorus (TP) and total nitrogen (TN)] were analyzed based on the original work of Grasshoff and Ehrhardt (1976), with suitable modifications as reported by the International Council for the Exploration of Seas (ICES) (ICES 1977). The phosphate content was estimated from the level of inorganic phosphate ( $\text{PO}_4^{3-}\text{-P}$ ), while the TP analysis included all forms of phosphate (organic and inorganic). Chlorophyll *a* pigment levels in the water samples were estimated in the laboratory following the methods described by Strickland and Parsons (1972). The samples were filtered through GF/C Whatman filter paper for the analysis of chlorophyll *a*. Measurement of the optical density of the acetone extracts, before and after acidification, was done by means of a UV–visible spectrophotometer (Chemito 2500 recording UV–visible spectrophotometer). Samples for the identification of phytoplankton species composition were preserved on board with an acid Lugol’s solution. Phytoplankton species were identified and counted by microscopic examination on an inverted microscope (Zeiss). A minimum of 400 cells were counted, leading to a range of accuracy of 10% (Lund et al. 1958). Physical parameters such as temperature and Secchi disc depth were measured on board.

Principal component analysis (PCA) was employed for the possible detection of clusters emerging from the data in such a manner that the clusters were kept heterogeneous. In particular, PCA was performed by considering a six-dimensional space defined by different water quality parameters (salinity, transparency, TN, TP and chlorophyll *a*), while each case was represented by the yearly averages of the variables in each station. All variables were log-transformed in order to normalize their distributions. Conversely, in the cluster analysis, each station was considered an object, while seasonal measurements of the standardized variables were the characteristics on which the classification was based (the variables in the cluster analysis program). Analyses of variance (ANOVAs) for salinity, TN and TP were carried out to establish the annual, seasonal and basin-wide variabilities of these water quality parameters.

The scattered data were interpolated in order to get a temporal sequence of spatially continuous maps of the parameters. We used the “inverse distance to a power” gridding method as a smoothing interpolator. In this method, data are weighted during interpolation such that the influence of one point relative to another declines with distance. In particular, we use a quadratic law to compute the weight, and a low value (0.2) as the smoothing

parameter. In this way, the bull's eye effect is reduced by introducing little smoothing, and the information in the experimental data is retained. In some circumstances, the application of gridding methods in coastal areas, which are characterized by a high spatial heterogeneity, may not lead to very accurate results. Therefore, care was taken in the quantitative interpretation of the spatial distribution; indications should only be considered robust from a qualitative point of view.

Principal component analysis, cluster analysis and correlation analysis were performed using the software STATISTICA (provided by Statsoft). Data gridding was performed by using the software SURFER (provided by Golden Software).

## Results

Figure 2 depicts the seasonal variations in the spatial averages of some water quality parameters. Salinity exhibited a distinct variation among the seasons, with higher values during summer and minimal values during the monsoon season. During monsoon, the transparency of the lagoon varied between 0.2 and 0.95 m Secchi depth, while it ranged from 1 to 1.5 m post-monsoon and from 1 to 1.1 m in summer. The presence of suspended load was the key factor governing light penetration in this ecosystem, as also reported by Panigrahi (2006).

The seasonal changes in the spatial distributions of the water quality parameters, obtained by gridding the raw data, are presented in Fig. 3. This shows a clear pattern in the distributions of those parameters in a spatial gradient over the whole lagoon during the study. It was observed that the shallow northern region of the lagoon was greatly influenced by freshwater during the monsoon period and saline water during the summer season (Fig. 3a). This indicates that the circulation pattern is more influential in the northern region of the lagoon. The highest nitrate N concentration was recorded during monsoon, followed by the post-monsoon and summer seasons. Other inorganic forms of nitrogen, like nitrite N and ammonia N as well as the total nitrogen also exhibited a similar distribution pattern on a seasonal scale. The concentrations of these nutrients in monsoon were almost double those of the summer values. The observed values of  $\text{NO}_3^-$ -N and TN in the lagoon during 2001–2002 were higher than those observed in 2002–2003 (Fig. 2 and Fig. 3e). This was probably due to heavy rainfall ( $\sim 550$  mm) during the monsoon months of the year 2001–2002, leading to higher runoff from the surrounding catchment area, which contained a higher nitrogen load (Panigrahi et al. 2007).

Inorganic phosphate and total phosphorus levels during monsoon remained high, and gradually decreased post-

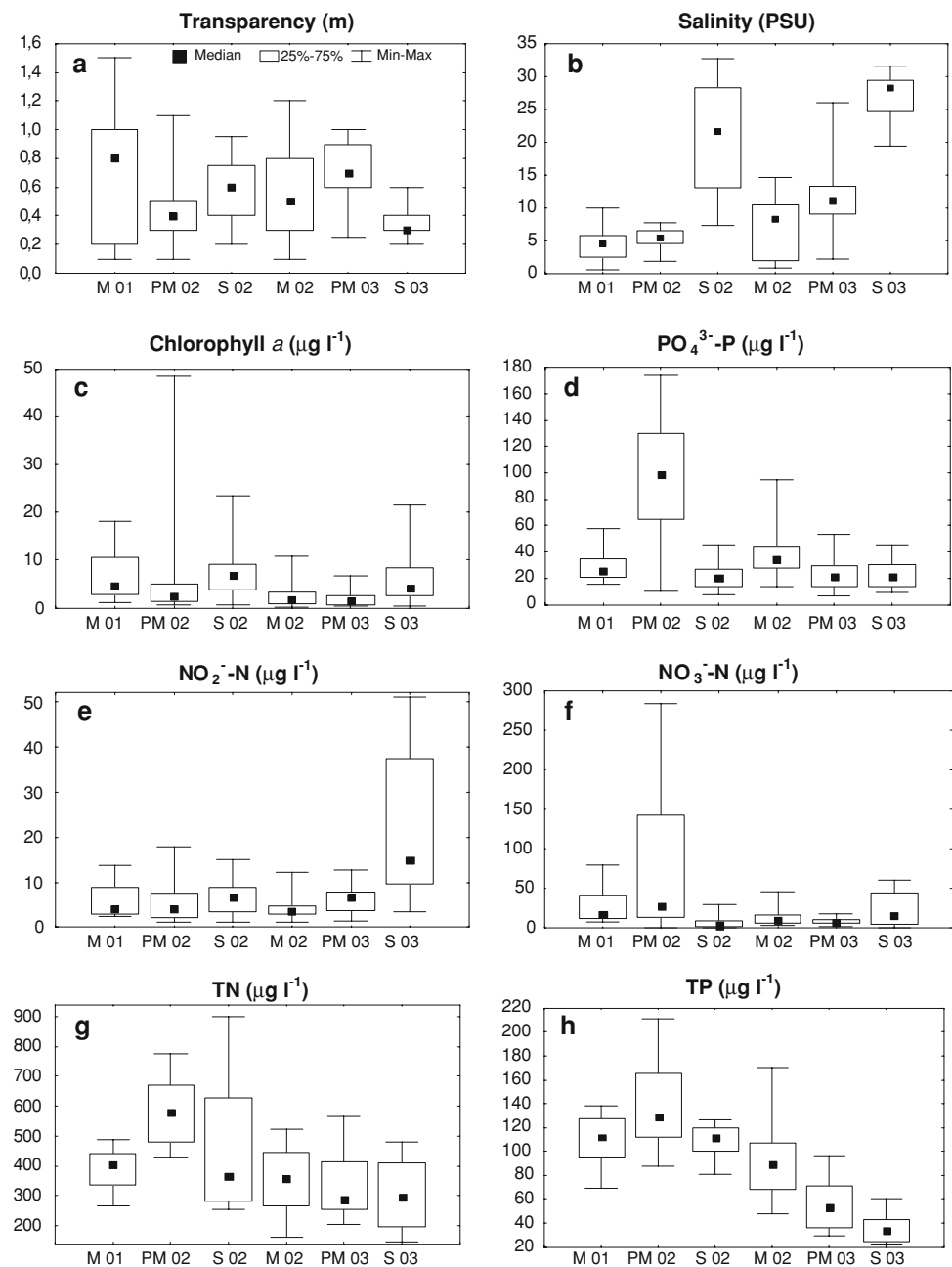
monsoon, showing very low values in summer. In monsoon the reactive phosphate constituted  $\sim 60\%$  of TP, which decreased to  $\sim 30\%$  during monsoon months.

The average chlorophyll *a* concentrations ranged from 1.95 to 5.75, 2.55 to 7.58 and 3.79 to 8.33  $\mu\text{g l}^{-1}$  during the post-monsoon, monsoon and summer seasons, respectively. The interannual variability of chlorophyll *a* fluctuated greatly, with lower concentrations observed during 2002–2003 (Fig. 3d). Phytoplankton of Chilika Lagoon consisted of a mixture of marine, brackish-water and freshwater taxa, mainly represented by four groups of algae—diatoms (*Bacillariophyceae*), dinoflagellates (*Pyrrophyceae* and *Dinophyceae*), blue-green algae (cyanobacteria) and green algae (*Chlorophyceae*). In total, 128 species of phytoplankton were identified. Diatoms were the dominant group and were represented by 79 species, (41 centrales and 38 pennales). The dinoflagellate population was represented by 13 species. Blue-green and green algae (with 9 families and 15 genera) were represented by 18 species each. Some of the dominant taxa of phytoplankton, including those distributed throughout the lagoon as well as those in the more freshwater-influenced northern sector and the saline water-dominated outer channel area, are presented in Table 1.

One more noteworthy feature encountered in the phytoplankton assemblages of the lagoon was the predominance of diatoms and certain dinoflagellates and blue-green algae during the summer seasons when the salinity in most parts of the lagoon was  $>17$  psu. However, during the winter season, the plankton flora was mainly represented by blue-green and green algae. Phytoplankton species composition also showed great variations spatially between seasons. Different regions of the lagoon exhibited significant variations in their plankton assemblages. In general, the outer channel area had higher species diversity than the other regions. Diatoms dominated the species composition in the entire lagoon except for the northern region. Dinoflagellates occurred frequently in the outer channel area and in the southern region of the lagoon. Northern and central regions had overwhelming numbers of blue-green and green algae. The saline water-dominated outer channel area acts as a euryhaline environment and was dominated by some diatoms that can withstand a wide range of salinity fluctuations (Table 1). Mean values of phytoplankton density in the lagoon during the post-monsoon season varied from 37,100 to 68,000 cells  $\text{l}^{-1}$ , while it ranged from 65,800 to 129,000 cells  $\text{l}^{-1}$  during summer season and from 49,000 to 112,000 cells  $\text{l}^{-1}$  during monsoon period.

Principal component analysis was performed by considering a six-dimensional space that included water quality parameters like salinity, TN, TP, transparency and chlorophyll *a* (Fig. 4). Each case was represented by the yearly average of each variable at each station. Inspection of the loads revealed that the first component explains

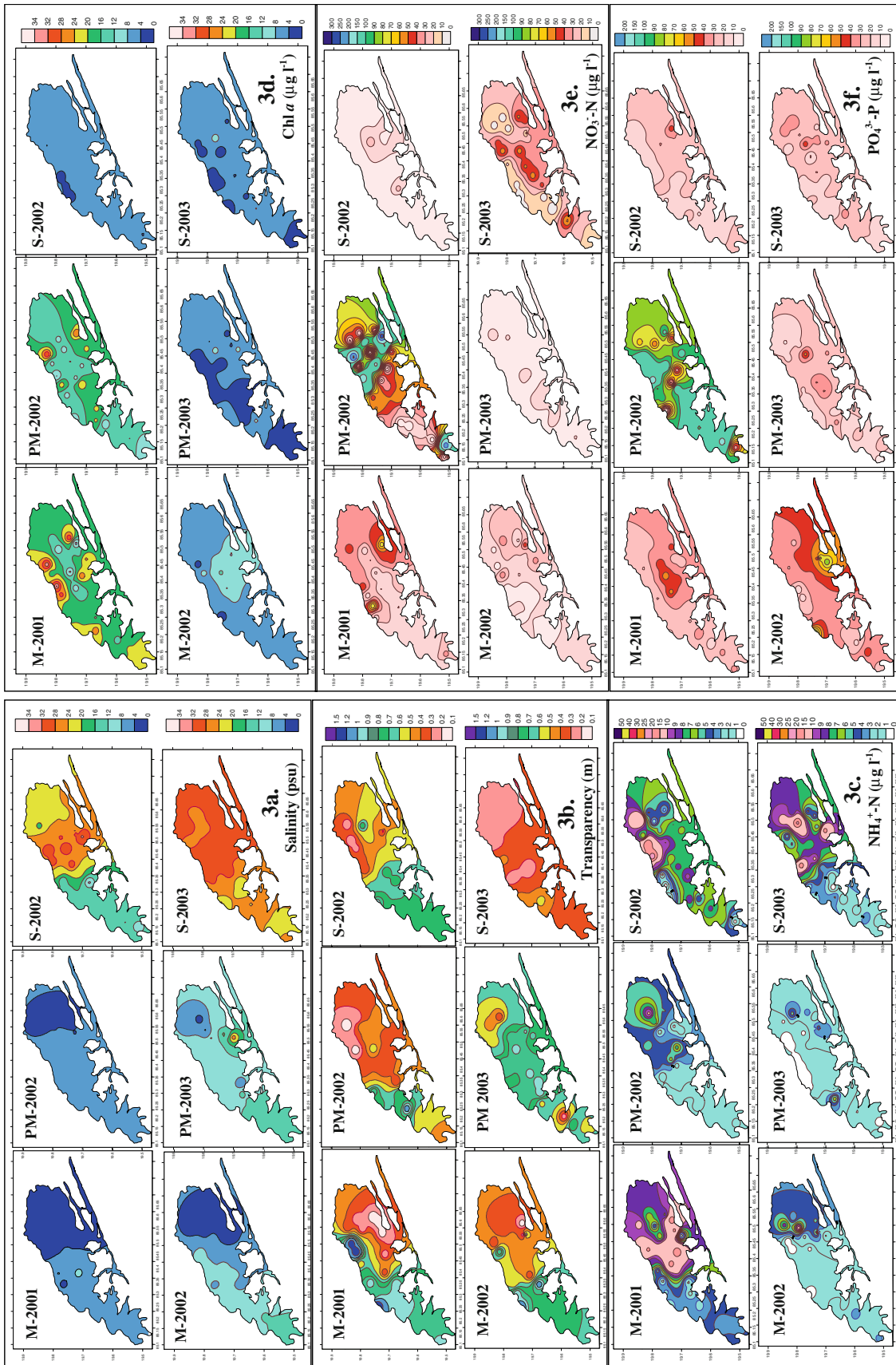
**Fig. 2** Seasonal variations in the spatial averages of transparency (a), salinity (b), phytoplankton chlorophyll *a* (c), phosphate (d), nitrite (e), nitrate (f), total nitrogen (g) and total phosphorus (h) in Chilika Lagoon. In each box plot, the central point represents the median, the box gives the interval between the 25% and 75% percentiles, and the whisker indicates the range (M, monsoon; PM, post-monsoon; S, summer)



about 60% of the total variability. The first component (PC1 or Factor 1) is a linear combination of dissolved nutrient and chlorophyll *a* concentrations; it can therefore provide useful indications of the water quality and trophic state of the lagoon system. The second component (PC2 or Factor 2) accounts for 23% of the total variance and represents the salinity concentration; ultimately the input of fresh or saline water to the lagoon. The first two components account for almost 83% of the total variance. The projection of the stations onto the PC1 vs PC2 plot produces very prominent clusters resulting from differences in ecological status (Fig. 4). Stations belonging to the same

group or ecological background often occur close together on the PC1 vs PC2 plot and have similar PC indices (Fig. 4).

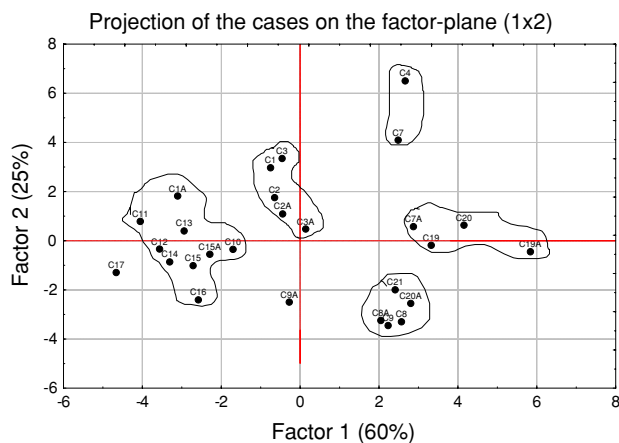
The results of the cluster analysis are summarized in the tree diagram presented in Fig. 5, which was obtained using the “weighted pair group average” (WPGA) method, taking the distance measured to be the “Euclidian distance,” as discussed by Davis (1967). The tree diagram shows groups of stations that gave similar results, as determined by performing a *k*-means cluster analysis under the hypothesis of partitioning the stations into four clusters (Table 2). Comparison of the results obtained by the above two methods



**Fig. 3** Seasonal and spatial gradients of salinity (a), transparency (b), NH<sub>4</sub><sup>+</sup>-N (c), chlorophyll a (d), NO<sub>3</sub><sup>-</sup>-N (e) and PO<sub>4</sub><sup>3-</sup>-P (f) (M monsoon, PM post-monsoon, S summer)

**Table 1** Some predominant taxa of phytoplankton in Chilika Lagoon

Sector/zone	Planktonic taxa
Whole lagoon	<b>Diatom:</b> <i>Biddulphia heteroceros</i> , <i>B. granulata</i> , <i>Odontella sinensis</i> , <i>O. mobiliensis</i> , <i>Asterionellopsis glacialis</i> , <i>Bacillaria paradoxa</i> , <i>Chaetoceros didymus</i> , <i>C. lauderi</i> , <i>C. densus</i> , <i>C. compressus</i> , <i>C. diversus</i> , <i>C. lorenzianus</i> , <i>C. paradoxus</i> , <i>C. peruvianus</i> , <i>Cocconeis pediculus</i> , <i>C. placentula</i> , <i>Nitzschia closterium</i> , <i>N. seriata</i> , <i>N. obtusa</i> , <i>Navicula pygmaea</i> , <i>Pinnularia alpina</i> , <i>Pleurosigma normanii</i> , <i>P. elongatum</i> , <i>Coscinodiscus gigas</i> , <i>C. marginatus</i> <b>Synedra ulna</b> . <b>Green algae:</b> <i>Chaetomorpha linum</i> , <i>Cladophora glomerata</i> , <i>Pediastrum reticulatum</i> , <i>P. tetras</i> , <i>Closterium</i> sp., <i>Scenedesmus acuminatus</i> , <i>S. quadricauda</i> <b>Blue-green algae:</b> <i>Oscillatoria limnetica</i> , <i>O. princeps</i> , <i>Lyngbya aestuarii</i> , <i>Trichodesmium</i> , <i>Phormidium corium</i> , <i>P. submembranaceum</i> . <b>Dinoflagellate:</b> <i>Ceratium furca</i> , <i>C. tripos</i> , <i>Protopteridinium depressum</i> , <i>P. brevipes</i> , <i>Prorocentrum micans</i>
Outer channel area	<b>Diatom:</b> <i>Chaetoceros paradoxus</i> , <i>Coscinodiscus gigas</i> , <i>C. marginatus</i> , <i>Coscinodiscus</i> sp., <i>Lauderia annulata</i> and <i>Cylindrotheca closterium</i> . <b>Dinoflagellate:</b> <i>Prorocentrum micans</i> and <i>Ceratium linetum</i>
Northern	<b>Diatom:</b> <i>Rhizosolenia delicatula</i> and <i>Fragilaria crotonensis</i> . <b>Blue-green algae:</b> <i>Chroococcus turgidus</i> , <i>Merismopedia elegans</i> , <i>M. glauca</i> , <i>Synechocystis aquatilis</i> , <i>Arthospira platensis</i> , <i>Anabaena flos-aquae</i> , <i>Nostoc</i> sp., <i>Fischerella</i> sp., <i>Microcystis</i> sp. and <i>Monoraphidium</i> sp. <b>Green algae:</b> <i>Eudorine elegans</i> , <i>Scenedesmus acuminatus</i> , <i>S. quadricauda</i> , <i>Pediastrum reticulatum</i> , <i>P. tetras</i> , <i>Xanthidium sexmamillatum</i> , <i>Spirogyra</i> sp., <i>Oedogonium</i> sp. and <i>Desmidiium</i> sp.

**Fig. 4** First and second component scores for each station as obtained from PCA. Proposed alternative classifications are indicated by the *continuous lines*

indicates that several stations fall into the same group in all cases; for example the southern stations C16, C14, C15, C11, C12, C15A and C13 (Table 2), and that they also form a part of a larger group, as obtained from the tree diagram (Fig. 5). The stations which receive maximum agricultural runoff and urban sewage and are densely covered by macrophytes (e.g., C1, C1A, C2A, C2, C3A, and C3) were grouped together in the PCA analysis. The same group has been added up to C4, C7 and C17 in the *k* means cluster analysis and C4, C7 in the tree dendrogram as obtained by WPGA. Subsequently, the estuarine group influenced by salinity (C8, C8A, C9, C20A and C21) is also grouped together in both cluster analyses. The groups of stations influenced by the most relevant point sources of nutrients (C4 and C7), agricultural runoff from the catchments area (C1, C1A, C2A, C2, C3A and C3) and urban sewage (C17) form a single cluster in the *k*-means cluster analysis, whereas they are more distinct and segregated into three

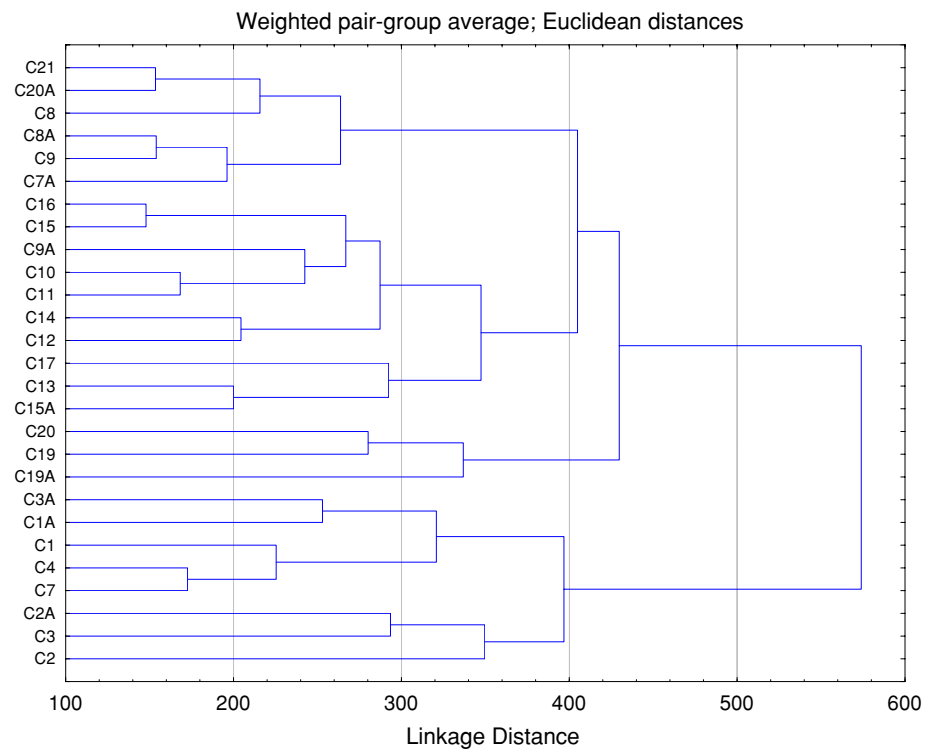
different clusters in the PCA factor plan (Fig. 4). However, the stations in the southern part of the lagoon persistently form a group in all types of cluster analyses performed.

Seasonal and spatial effects on the contributions of TP, TN, chlorophyll *a* and salinity have been explored through ANOVA, as described in Table 3. In all cases, the results show that seasonality has a significant ( $p < 0.01$ ) effect on the distribution of these parameters (Table 3). Salinity was found to be more controlled by seasonality and geographical differences in the lagoon system. The spatial and temporal scales of the distribution of salinity and chlorophyll *a* are highly significant ( $p < 0.01$ ). It is evident from the results of ANOVA that both the seasonal and spatial factors are working in tandem here. However, the seasonal variations in TN and TP are significant ( $p < 0.01$ ), while spatial differences were not significant (sector-wise). The differences between the years of observation were significant ( $p < 0.01$ ) for chlorophyll *a*, TN and TP, in contrast to the salinity.

A significant change in water quality was experienced after the opening of the new mouth (connecting the lagoon and the bay). It is essential to compare the pre- and post-mouth-opening conditions (Fig. 6) in order to assess the changes in the lagoon environment. The mean seasonal values of different parameters indicated significant changes in the lagoon environment. The mean depth of the water column of the lagoon during 2001–2003 was lower than that of 1998–2000. This could be due to better flushing of water and sediment from the lagoon to the sea, as facilitated by the new opening. A remarkable increase in salinity was observed during 2001–2003, compared that reported before the opening of the new mouth (1998–2000). The average salinity of the lagoon has undergone a series of visible changes, such as 27–33 ppt in 1957; 13–20 ppt in 1960–1961; 9.4–11.8 ppt in 1961–1964 and 1.38–6.3 ppt during 1995 (Sarkar 1977; Raman et al. 1990; Siddiqui and Rama Rao 1995; Panigrahi 2006). In the present study, the



**Fig. 5** Tree diagram of cluster analysis obtained by using the “weighted pair group average” as the linkage rule and Euclidean distances as the distance calculated



**Table 2** Groups of stations obtained by *k*-means cluster analysis, with four clusters

Groups	Stations grouped
Group 1	C10, C9A, C9, C8A, C20A and C21
Group 2	C16, C14, C15, C11, C12, C15A and C13
Group 3	C17, C1A, C1, C2A, C2, C3A, C3, C4 and C7
Group 4	C7A, C19A, C19, C8 and C20

salinity concentration of the lagoon reached 21.5 psu on average, with individual values varying between 0.5 and 31.6 psu (Fig. 3a). The change in salinity had largely occurred due to the exchange of sea water and lagoon water through the newly opened inlet channel. No significant change in pH was observed after the new mouth was opened. The average total suspended solid (TSS) values of the lagoon remained much below those seen before the mouth was opened (1998–2000). This indicates a better flushing out of suspended sediments from the lagoon to the sea. The chlorophyll *a* concentration lowered in the lagoon; phosphorus nutrients ( $\text{PO}_4^{3-}\text{-P}$  and TP) were enriched and nitrogenous nutrients decreased in concentration following the opening of the new inlet.

## Discussion

The Chilika Lagoon ecosystem is extremely complex, partly due to the strong influence of many different sources

of pollution (industrial, urban and agricultural) and the intensity of tidal inflow and outflow. The results presented above suggest that the temporal variability of the system is the result of the superposition of the seasonal changes in light, temperature and salinity and the noncyclic evolution of the loads of dissolved nutrients which are discharged into the lagoon by the tributaries and other point sources. The temporal variation in the salinity (Figs. 2b, 3a) reveals the importance of tributary discharges and drainages from the catchment basin. The same cause can also explain the clear patterns of the spatial distributions of nitrate, ammonia and inorganic phosphate. Dissolved nutrient concentrations also remained high in the inner parts of the lagoon, receiving discharges from several tributaries and the influence of rich macrophyte infestations and their decomposition. In these areas, high nutrient concentrations were rarely accompanied by low salinity. It has been observed that the post-monsoon period of 2002 showed a boom in all of nutrient concentrations, especially in the northern and central parts. This could be due to the intensive dredging activity inside the lagoon during that period, and could thus be due to the regeneration of nutrients from the bottom layers. The lagoon was dredged in its northern and central basins and a channel was opened allowing the free exchange of water from the bay to the lagoon and vice versa.

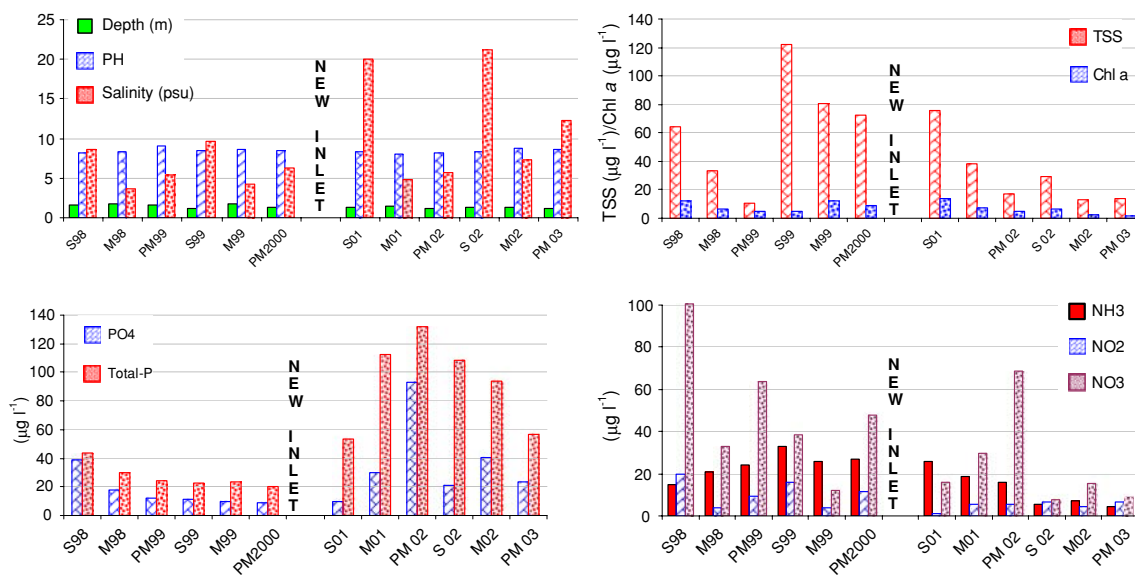
Chlorophyll *a* concentration showed a peak in the summer season. However, a bloom was observed in the monsoon season of 2001. Comparison with the spatial distributions of

**Table 3** Results of ANOVAs of some selected trophic parameters

	<i>df</i>	Chlorophyll <i>a</i>		TN		Salinity		TP	
		F	<i>p</i> value	F	<i>p</i> value	F	<i>p</i> value	F	<i>p</i> value
Intercept	1	151.1929	<b>0.000000</b>	1659.679	<b>0.000000</b>	1213.312	<b>0.000000</b>	2582.294	<b>0.000000</b>
Sector	2	8.9088	<b>0.000225</b>	2.152	0.120004	6.346	<b>0.002283</b>	0.191	0.826263
Year	1	13.4715	<b>0.000340</b>	53.814	<b>0.000000</b>	0.307	0.580295	258.939	<b>0.000000</b>
Season	2	4.8086	<b>0.009516</b>	5.615	<b>0.004487</b>	120.559	<b>0.000000</b>	26.999	<b>0.000000</b>
Sector × year	2	1.1805	0.310070	0.463	0.630581	13.660	<b>0.000004</b>	0.729	0.484164
Sector × season	4	0.9682	0.426960	1.306	0.270596	12.567	<b>0.000000</b>	1.697	0.153898
Sector × year × season	4	2.3732	0.055005	0.314	0.868267	5.765	<b>0.000248</b>	1.716	0.149617
Error	144								

Significant values ( $p < 0.01$ ) are given in bold

*p*, probability value or level of significance; *F*, results of *F* test; ×, interaction effects; *df*, degrees of freedom



**Fig. 6** Comparison of the pre- and post-mouth-opening levels of some water quality parameters of Chilika Lagoon (*M* monsoon, *PM* post-monsoon, *S* summer)

dissolved nutrients and salinity indicated that the phytoplankton proliferate in the areas of the lake that are influenced by the tributaries. The same is also true of the dense growth of macrophyte vegetation. Higher chlorophyll concentrations were less pronounced in the areas that were more influenced by water exchange with the sea, regardless of the nutrient concentrations. Spatial distributions of ammonia, nitrate and phosphate underwent significant changes during this time, which could be related to the phytoplankton uptake. The nutrient levels were lower during post-monsoon and summer and increased in the monsoon season. This variation leads to the following conceptual scheme: in 2001–2003, the plankton productivity/biomass was triggered by light availability, salinity changes and sustained by the pool of nutrients, which were supplied mostly through tributary discharges. The higher average

population density of phytoplankton (higher chlorophyll *a* concentration) in summer can be linked to the lack of orthophosphate. This is probably due to the rapid uptake of phosphate by phytoplankton in summer, when there is a limited supply from the tributaries. This is supported by the fact that nutrient concentrations were lower in summer when the tributary discharges were negligible (Fig. 3a); therefore, orthophosphate concentrations were very low all over the lagoon (Fig. 2d).

The stations C10, C11, C13, C14, C15, C15A, C16 and C1A form a cluster of stations. Almost all of these lay in the southern region of the lagoon, which is more or less stagnant. Tidal effects are minor in this zone due to its distance from the mouth, and moreover it is enclosed by land masses. All of the stations that are influenced by the marine flow (C21, C20, C8A, C8 and C9) were clustered together. C4

and C7 formed a different cluster. Geographically, this is the region where the major tributaries meet the lagoon water, and these stations can be treated as exhibiting the greatest impact of the supply of nutrients from the tributaries. Stations in the northwestern region of the lagoon (C7A, C19, C19A and C20) form a group where the depth is low and fishing activity is very high throughout the year. From February to August this zone is generally thickly covered by floating decomposed weeds, which have a foul smell. The inflow of agricultural runoff from the catchment area with high levels of organic silt seems to be the key factor in clustering the stations C1, C2A, C2, C3A and C3 that lie close to each other. This region has dense weed coverage with transparent water. The stations C17 and C9A could not be included in any of the above clusters due to their special ecological characteristics. C17 is situated close to the jetty of Balugaon, a small but thickly populated town. Along with human activities, the region nearby receives untreated urban sewage and emissions from agro-based industries, including a prawn processing plant. This greatly affects the water quality and ecology of C17. C9A is situated close to the northern region of Nalaban Island, the wintering ground for millions of migratory waterfowl. During this period the area remains swampy, in contrast to the monsoon and post-monsoon seasons, when the area becomes submerged. It experiences high nutrient concentrations due to the guano depositions from the millions of migratory birds. The clustering of the stations is probably most influenced by the point sources of nutrients from the major tributaries (C4, C7 and C1, C2A, C2, C3A, C3) and the tidal inflow/outflow of water through the new mouth. Interestingly, overall evaluation of the scores of each station in the PC factor plot reveals the existence of a north–south and west–east gradient, with higher values close to point sources and lower values where the influence of the exchange with the sea is greater—nearer to the inlet channel.

The above considerations suggest that physical features such as the distribution of the inputs from the tributaries and the exchange with the sea determine the spatial distribution of the “trophic” features. This is qualitatively confirmed by the fact that the groups identified by means of multivariate analysis (Fig. 4) are geographically compact and “centered” around the nutrient sources. Therefore, the grouping derived from Fig. 4 is a trophic-based classification. The results of the multivariate analysis emphasize that the annual average level of such an indicator can be explained well by a linear model with independent variables that are related to the freshwater input, salinity changes and tidal mixing.

#### Pre- and post-mouth-opening changes

A reduction in nitrogenous nutrients ( $\text{NH}_4^+$ -N,  $\text{NO}_2^-$ -N and  $\text{NO}_3^-$ -N) and total nitrogen in the lagoon environment was

observed after the opening of the new mouth compared to previous reports. Interestingly, an overall increase in orthophosphate and total phosphorus was observed during 2001–2003. The enhancement in TP seems to be mainly organic in origin, because there was only a moderate increase in inorganic  $\text{PO}_4$  (Fig. 6). The addition of organic phosphate is probably due to the decomposition of macrophytes that arose due to the increase in the salinity of the lagoon water.

The change in water quality was reflected in the changes in biota too. Panigrahi (2006) has reported the reappearance of 35 algal species from the lagoon under its changed environmental conditions. The fishery yield of the lagoon has also gone up significantly after the hydrological intervention (Patnaik 2005). Taxonomic composition, relative abundance and species succession of phytoplankton in estuaries and brackish water lagoons differ significantly from those of the neritic and oceanic communities as a result of the rapid changes in the physicochemical and biological properties of the water column. In brackish water ecosystems, the phytoplankton populations are known to be influenced by spatiotemporal variations in hydrochemical parameters and tidal dynamics. This may also interfere to a large extent in the overall functioning of the ecosystem. Patnaik (1973) reported that the phytoplankton assemblages in the Chilika Lagoon consisted of 54% diatoms, 44.7% blue-green algae, 0.8% dinoflagellates and 0.6% green algae. In contrast to the above observations, the phytoplankton population density in the present study showed a higher proportion of dinoflagellates during summer, when they were the second most dominant group next to diatoms. During winter, however, the green and blue-green algae components were more dominant than the dinoflagellates.

The available literature on the lagoon before inlet opening indicate a high degree of variability in phytoplankton composition and density in this lagoon. Biswas (1932), Roy (1954), Patnaik (1973), Patnaik (1978), Panigrahy (1985), Raman et al. (1990), and Adhikary and Sahu (1992) reported taxon richnesses of 22, 33, 57, 21, 82, 97 and 28, respectively. During the present study, the number of phytoplankton species was found to be 128 and as many as 48 species of planktonic algae were recorded which had not been reported earlier from this lagoon. Also, some of the planktonic algal species reported earlier were not observed during the present study. This could be due to the recruitment of some brackish water forms after the free exchange of sea water with the lagoon and the changing environmental conditions in the lagoon after the opening of the new inlet channel. Furthermore, sediment resuspension, reduced light penetration, nutrient availability, grazing pressure exerted by zooplankton and the salinity regime could be jointly responsible for the change in taxonomic composition and the succession of phytoplankton as reported by Acri et al. (2004) and Bianchi et al. (2003) for the Venice Lagoon.

The enhanced salinity resulted in a significant decrease in the coverage of invasive freshwater weeds. The infested area declined from 523.01 km<sup>2</sup> in October 2000 (after just a month of the new mouth being open) to 351.01 km<sup>2</sup> by May 2001 (Ghosh et al. 2006). This change can be taken as a noteworthy feature of the ecology of the lagoon environment after hydrological intervention.

## Conclusion

The present study is the most comprehensive monitoring study of water quality parameters at Chilika Lagoon after the opening of the new inlet mouth. Previous studies focused on specific parameters like macrophytes, phytoplankton diversity and fisheries. The water quality parameters of the whole lagoon before the opening of the new mouth were reported by Nayak et al. (2004); at that time the nutrient dynamics of the lagoon were heavily influenced by the proliferation of macrophytes. A significant decrease in macrophyte proliferation has been reported since the opening of the inlet (Patnaik 2005). The results of PCA, cluster analysis (by the *k* means and WPGA methods), and ANOVA indicated that the distributions of parameters like nutrients, chlorophyll *a* and salinity are mainly influenced by the freshwater discharges into the lagoon, the intrusion of saline water through the inlet channel, and the circulation caused by the overall hydrodynamics of the lagoon system. Principal component analysis led to the identification of several groups of sampling stations, where the groupings could be linked to specific environmental parameters. There were pronounced seasonal and spatial impacts on the distributions of water quality parameters in the lake. The findings confirm the importance of physical forcing in determining the trophic levels inside the lagoon. Seasonal variability was the result of the superposition of the seasonal cycles of light and temperature and the stochastic and aperiodic river dynamics. In our opinion, these results represent an important reference for future studies and provide a sound basis for constructing an integrated approach to the management of this complex ecosystem. Significant changes were observed in the lagoon after the opening of the new mouth. Some of the noteworthy features were a large increase in salinity within the lagoon due to the influx of sea water, rapid decomposition of freshwater macrophytes, the flushing of suspended sediments loads into the sea, and the dispersion of localized pollutants. Thus, overall restoration of the wetland ecosystem was observed.

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