Assessment of the impacts of a new artificial lake mouth on the hydrobiology and fisheries of Chilika Lake, India

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Abstract

The degraded state of the fragile ecosystem of Chilika Lake, located on the east coast of India, was undergoing restoration through an effective hydrological intervention during the year 2000. Studies on the lake's hydrobiology and fisheries for the period of 7 years before and 7 years after the hydrological intervention indicated a rapid recovery of the lake fishery immediately after opening of the new lake mouth, with a sixfold increase in the average annual fish landings. During 2000–2001 to 2006–2007, the average fisheries output (11 051.3 t), catch per unit effort (6.2 kg boat^{-1} day^{-1}), the economic valuation of the average annual catch (637 million rupees) and productivity (11.97 t km^{-2}) exhibited dramatic increases of 498%, 464%, 1177% and 498.5%, respectively, compared with the 7-year pre-intervention data. Multivariate statistical analysis inferred that most of the lake's environmental variables are strongly associated with salinity factor, which seems to have governed the lake ecology. The salinity dynamics of the lake are governed by both freshwater inflows and seawater ingress through the new artificial lake mouth. Correlation analysis indicated that salinity was positively correlated with prawn catch ($R^2 = 0.542$; d.f. = 25; $P < 0.01$), crab catch ($R^2 = 0.628$; d.f. = 25; $P < 0.001$) and fish catch ($R^2 = 0.476$; d.f. = 25, $P < 0.05$). The average increase in the salinity regime (43.8%) for the lake during the post-hydrological intervention period, compared with the pre-hydrological intervention period, appears to have positively impacted the fish, prawn and mud crab catches. A gradual decrease in total fisheries output since 2005–2006, however, was attributed mainly to a continuing increase in destructive fishing practices in the absence of any conservation and regulatory measures for fishing, and large-scale collection of shrimp juveniles from the outer channel for shrimp aquaculture. Thus, carefully planned conservation and regulation measures must be ensured, with active participation of local communities during this early phase of lake restoration. In the absence of such measures, the present scenario of fisheries enhancement might not be sustained over the long term.

Key words

Chilika Lake, fisheries, hydrobiology, salinity, water quality.

INTRODUCTION

Chilika Lake is located on the east coast of India (Fig. 1), being an assemblage of marine, brackish and freshwater ecosystems containing an amazing range of biodiversity. It has been a Ramsar site since 1981 and is a wintering ground for more than one million migratory birds. The lake area fluctuates from a monsoon maximum of 1165 km^2 to a dry season minimum of 906 km^2. The annual average surface area is 923 km^2, while the linear axis is 64.3 km, with an average mean width of 20.1 km (Ghosh & Pattnaik 2005). This highly productive lake ecosystem contains rich fishery resources, sustaining the livelihood of >0.2 million fisher folk and 0.8 million people living in the lake's catchment.

The unique and fragile ecosystem of Chilika Lake, with estuarine characteristics, gradually begin losing its ecological character because of changing coastal processes, a significant decrease in its salinity regime, and a degraded drainage basin with associated anthropogenic pressures. Between the 1950s and 2000, the lake fishery was in a continuing state of decline, while invasive weeds began to become established in the lake, subsequently causing the entire lake to progressively shrink in area and water volume. During 1973 and 1993, for example, the weed-covered areas in the lake were 20 and 398 km^2

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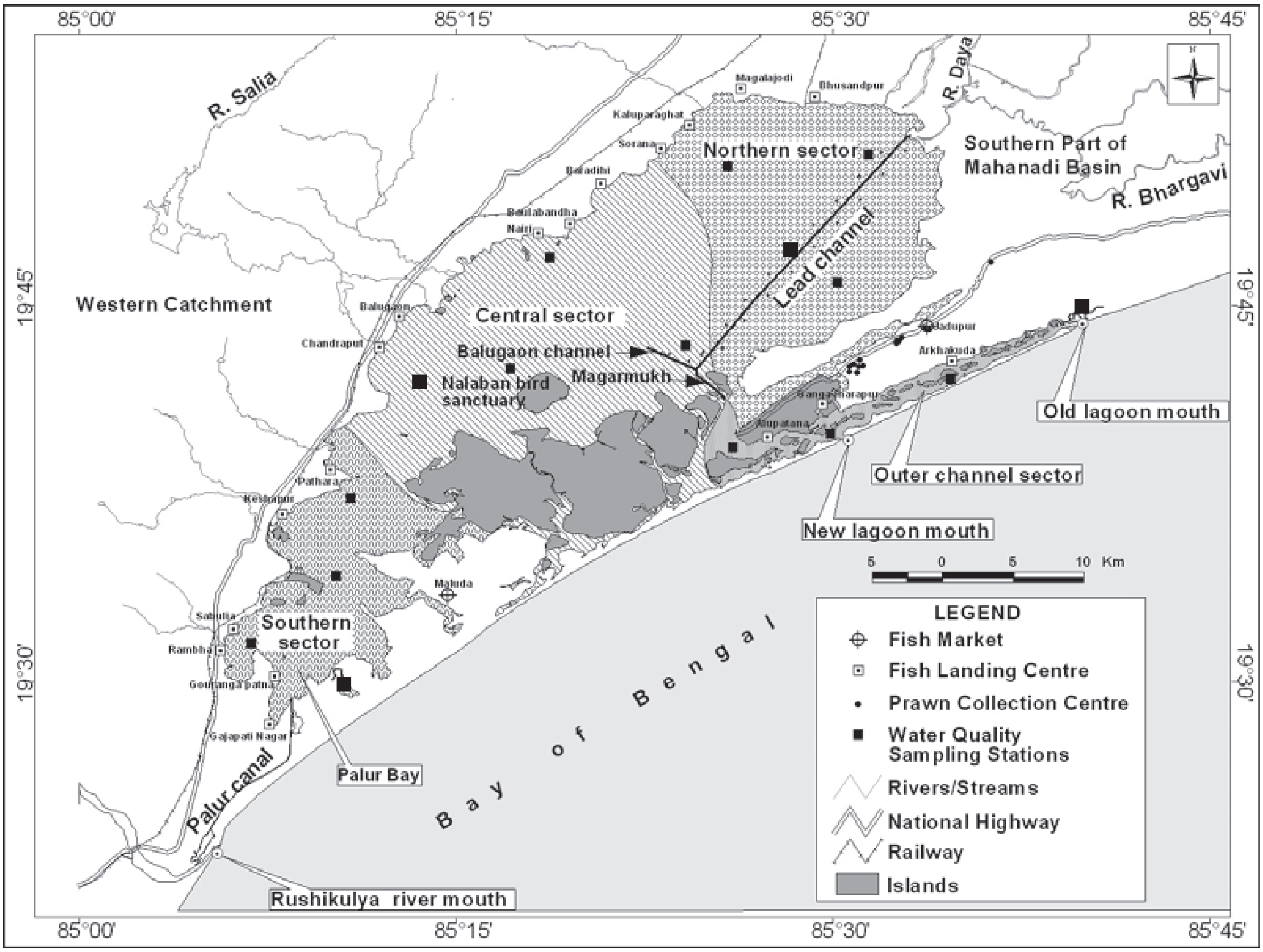

Fig. 1. Location of Chilika Lake, including four ecological sectors, hydrological intervention, sampling sites and fish-landing centres.

respectively, with the annual invasion of weeds calculated to be 15 km^2 $year^{-1}$ by 1998 (Ghosh 2002). The lake's fishery resources has also suffered serious setbacks since the latter part of the 1980s, with the salinity levels sharply decreasing to 9.6 PSU, compared to a level of >22.0 PSU in the 1960s, as reported by Banerjee and Roychoudhury (1966) and Siddiqi and RamaRao (1995). The recruitment routes (outer channel and Palur canal) also gradually silted up, adversely affecting the recruitment of fish and shellfish seed from the sea into the lake. In the aftermath of the gradual closure of the old lake mouth and Palur canal, the lake had begun transformation towards a freshwater ecosystem, causing substantial changes in the species composition in the lake, with significant increases in freshwater forms. As a result of the increasing degraded state of the lake ecosystem, including drastic changes in its ecological characteristics and overall loss of biodiversity, Chilika Lake was included in the Montreux Record in 1993.

Accordingly, it is imperative to restore the fragile ecosystem of Chilika Lake as a means of enhancing *inter alia* its fisheries and biodiversity for the greater benefit of the lake's wetland communities. Thus, the Government of India undertook urgent measures to restore Chilika Lake, and the State Government of Orissa constituted the Chilika Development Authority (CDA). The CDA subsequently implemented the hydrological intervention of opening an artificial lake mouth on 23 September 2000, as well as an eco-restoration programme for the lake, based on an ecosystem approach. After the classic hydrological intervention during 2000–2001, Chilika Lake exhibited significantly improved conditions, with the Ramsar Bureau removing the lake from the Montreux Record, as the first Asian Ramsar site, effective beginning 11 November 2003, because of the improved condition of the lake ecosystem following the restoration initiatives. Against this background, this study was undertaken to analyse/evaluate the fisheries situation in Chilika Lake related to the hydrobiological factors during the pre- and post-intervention phases.

METHODS

Study site

The study area comprises the entire Chilika Lake (19°28′ and 19°54′N and 85°05′ and 85°38′E) lying within the administrative boundaries of the Puri, Khurda and Ganjam Districts of Orissa State along the east coast of India (Fig. 1), with the study duration being from 2004–2005 to 2006–2007.

The newly opened artificial lake mouth resulting from the hydrological intervention has reduced the distance between the lake body proper and the lake mouth from 30 to 12 km. From a hydrological perspective, Chilika Lake is influenced by three hydrological subsystems: (i) the Mahanadi distributaries; (ii) 52 streams from western catchments draining into the lake; and (iii) the sea (Bay of Bengal). The lake is broadly divided into four ecological sectors based on differences in ecological features; namely the northern, central, southern and outer channel sectors (Fig. 1). Magarmukh acts as the gateway between the main lake and the outer channel.

Pre- and post-hydrological intervention monitoring

With the goal of studying fisheries changes in Chilika Lake over time, time-series data on fish landings for the past 74 years, fish catch statistics, and associated information on commercial catches and hydrobiological aspects for the 7-year period prior to the hydrological intervention (1993–1994 to 1999–1900), and the 4-year period after the opening of the new lake mouth (2000–2001 to 2003–2004) after opening of the new lake mouth were compiled. The data sources were the Department of Fisheries, Government of Orissa, and CDA respectively. The fisheries situation from 2004–2005 to 2006–2007 was also studied further in this study.

Investigation methodology for this study

Fish-landing estimations

Collection of fish-landing information and data was carried out at: (i) all 18 established fish-landing centres (located in four ecological sectors); (ii) the two daily fish markets within the lake area, and (iii) all 14 prawn collection centres on the eastern part of the lake (Fig. 1). Data for two consecutive days collected at 10-day intervals (i.e. total of 6 days per month) at each fish-landing centre, sampling 33% of the total boats (i.e. 1 boat from each 3 consecutive boats), and at the daily fish markets and prawn-collection centres, were compiled. Specified formats were used during the data sampling in order to collect specific information relating to fish catch. As recommended by Jhingran and Natarajan (1969), prawn, fish and mud crab catches were monitored separately for yield. One random-sampling method (systematic sampling) with landing centre approach (Gupta *et al.* 1991), as modified for site-specific conditions in Chilika Lake (CDA, 2005), was utilized on a monthly basis from 2004–2005 to 2006–2007 to estimate landings of fish, prawn and mud crab, based on the following equations:

(a) The fish-landing estimate (t) for each sampling day at each landing centre was estimated as:

$$E = QO^{-1}N, \tag{1}$$

where Q is the total catch (kg) for all observed boats, O is the total number of observed boats, N is the total boats with catches at fish-landing centre on sampling day and E is the estimated fish landing (t).

(b) The mean fish landing for each sampling day at fish-landing centre was estimated as:

$$\bar{Y} = (E_1 + E_2 + \cdots + E_6)6^{-1}, \tag{2}$$

where E_1–E_6 are the estimated fish landings for the first to sixth sampling day in a month and $\bar{Y}$ is the mean fish landing for each sampling day (t).

(c) The total fish landing for each landing centre for each month was estimated as:

$$\mathrm{Ml} = \bar{Y}D, \tag{3}$$

where $\bar{Y}$ is the mean fish landing for each sampling day at each fish-landing centre, D is the total number of fishing days availed at landing centre and Ml is the estimated landing (t) at each landing centre during the month.

(d) The total monthly fish landing for all 18 fish-landing centres at the lake was estimated as:

$$\mathrm{TLC} = \mathrm{Ml}_1 + \mathrm{Ml}_2 + \cdots + \mathrm{Ml}_{18}, \tag{4}$$

where TLC is the total estimated fish landing (t) for all 18 fish-landing centres and Ml_1–Ml_{18} are the monthly fish landings at the 1st to 18th landing centre.

(e) The total monthly landing (fish and prawn) for the lake was estimated as:

$$\mathrm{TML} = \mathrm{TCL} + \mathrm{ML} + \mathrm{Pc}, \tag{5}$$

where TML are the total monthly fish landings; ML is the estimated fish landing for two daily fish markets for the month, in a similar manner as followed for the fish-landing centres; and Pc is the estimated prawn landings for 14 prawn-collection centres for the month.

(f) The species/group-wise quantity was estimated by multiplying the average catch composition (%) and the total estimated fish landing for the sampling day at the landing centres and daily fish markets. The catch for commercial species, relative abundance (catch composition), etc. was determined by analyzing catch samples from the landing centres. The mud crab landing was estimated by total (100%) enumeration of packed bamboo baskets, which contained ≈10 kg mud crabs in each basket at each landing centre.

Lake productivity and catch per unit effort

(g) The fishery productivity of Chilika Lake was estimated as:

$$P = \bar{Y}M^{-1}, \tag{6}$$

where P is the productivity (t km^{-2}), $\bar{Y}$ is the annual yield (t) and M is the mean productive (fishable) water spread area (km^2).

(h) The catch per unit effort (CPUE) was estimated as:

$$\text{CPUE} = \bar{Y}(b \times d)^{-1}, \tag{7}$$

where $\bar{Y}$ is the annual yield (t), b is the mean number of fishing boats engaged in fishing in the lake and d is the mean fishing days during the year.

Calculating the CPUE took into account the number of fishing boats, number of fishing days during the year and estimated annual landings. As a result of the problem of multispecies and multigear fishery in Chilika Lake, the CPUE was computed as catch per boat-day.

Physicochemical parameters

Water samples for assessing the physicochemical characteristics (environmental variables) for Chilika Lake, both *in situ* and in the laboratory, were collected between 08.00 and 10.00 h at 16 sampling sites at monthly intervals (Fig. 1). The *in situ* observations involved such environmental variables as water depth (graduated tide gauge), water temperature (digital electronic thermometer), transparency (standard Secchi disc), pH (portable Multi-parameter Water Analyzer, YK-611, Yeo-Kal Electronics Pty. Ltd, NSW, Australia), salinity and turbidity (WQC-22A, TOK, Japan) and dissolved oxygen concentration (dissolved oxygen metre, model-YSI-55; Yellow Spring, USA). The salinity analysis was cross-checked, using the Mohr–Kundsen silver nitrate ($AgNO_3$) titration method (expressed as PSU; APHA, 1998). Primary productivity, chlorophyll-*a* and total suspended solids concentration, and total alkalinity were determined using standard methods outlined in the study of APHA (1998). Other environmental variables were measured as per standard methodologies (e.g. biochemical oxygen demand (BOD; Trivedy & Goel 1984), nitrate and nitrite concentration (Strickland & Parson 1972 and Grasshoff *et al.* 1999), and ammonia, dissolved inorganic nitrogen (DIN) and phosphate concentrations (Grasshoff *et al.* 1999).

Phytoplankton and zooplankton

One litre of water sample was preserved in Lugol's iodine solution for phytoplankton estimation, and allowed to settle for 3–4 days for each sampling site. The upper water layer was decanted in a phased manner, and the phytoplankton volume measured. One mililitre of sample was transferred from these measured samples to a Sedgwick–Rafter counting chamber with a Stempel pipette (ENVCO-environmental equipments, Brisbane, Australia). The phytoplankton were counted under a Leica binocular research microscope (Leica, Germany). The phytoplankton were categorized under four groups (diatoms, dinoflagellates, cyanobacteria, green algae). Phytoplankton identification was performed with standard methods (Subrahamanyan 1946; Desikachary 1987).

Zooplankton samples were collected at each sampling site, by filtering 100 L of surface water by plankton net (40 μ mesh size) on a monthly basis. Immediately after collection, the zooplankton were preserved in 5% formaldehyde solution. The zooplankton were identified to the group level, utilizing an ICES Zooplankton Methodology Manual. The total number was expressed in numbers m^{-3} (Lenz 2000). The zooplankton biomass was estimated by the volume displacement method and expressed in mL m^{-3} (Lenz 2000; Sameoto *et al.* 2000).

Bottom vegetation and benthic fauna

Benthic fauna, sea grass and macrophyte biomass samples were also collected on a monthly basis from the 16 sampling sites. The wet biomass of sea grass and bottom vegetation samples at the fishing ground near the crab-sampling stations in Chilika Lake were determined with a quadrate sampler (Orth & Moore 1983), with the quadrate area being 1 m^2. Three samples were taken at each sampling site and, after soaking away of extra moisture, the weight (g) of individual samples was recorded. Biomass values were expressed as g m^{-2}. Benthos samples for quantitative studies were collected with a Vaan-vin grab (250 cm^2) (KC-Denmark). The collected samples were screened through a 500-μ mesh-size sieve for macrobenthos. All the recorded weights were wet weight, and the molluscs were weighed with their shells. The bottom organisms were expressed as numbers m^{-2} of bottom surface, and the biomass expressed as mL m^{-2}. The specimens of each group were sorted, and their volume determined by the volume displacement method (Pattnaik 1971), in order to estimate the biomass.

Statistical analyses

Statistical analysis of the fish-landing data (estimated landings for 2448 samples from 18 landing centres, 14 prawn collection centres and 2 daily fish markets during the year) was carried out for variance (Vr), standard error (SE), standard deviation (SD), kurtosis and skewness, utilizing the computer software 'SPSS (11.0 version)' (Chicago, USA). Correlation and principal component analyses (PCAs) for various water-quality parameters from the 16 sampling sites, and fish landings, were undertaken.

RESULTS AND DISCUSSION

Physicochemical parameters

Among all the physicochemical parameters that characterize an estuarine ecosystem, salinity has a vital role in influencing its biodiversity, its succession pattern and species distribution, recruitment, migration, maturation, spawning and natural food availability. For this study, the salinity at different sampling sites in Chilika Lake ranged from 0.04 to 36.50 PSU (Table 1), exhibiting clear sectoral and seasonal variation. The northern sector exhibited the lowest salinity among all the sectors throughout all seasons, a not unexpected occurrence since the major influent rivers (Daya; Bhargavi; Luna) enter the lake in this zone. Except for the southern sector, the lake exhibited a higher salinity during the pre-monsoon season, due mainly to high temperature, low precipitation, high evaporation and minimum freshwater dilution (Kaliyamurthy 1973; Nair *et al.* 1984; Mohanty & Mohanty 2002). The higher salinity in the southern sector during the monsoon season could be due to the movement of the saline water mass from the northern and central sectors towards the southern sector because of inflows during the monsoon season, as well as the enclosed nature of the sector (Mohanty & Mohanty 2002). The mean monthly salinity variation for the whole lake exhibited a single oscillation pattern, with a peak from April to June and a minimum from July to December. During the process of lake degradation, the average salinity level decreased from a level of 22.64 PSU (1957–1958), as reported by Banerjee and Roychoudhury (1966) to a level of 8.5 PSU during 1999–2000 (Bhatta 2001). The average salinity of the lake during the study period, however, was 11.75 PSU (Table 1), an increase of 38.25%, compared to the pre-lake mouth intervention year (1999–2000; 8.5 PSU). The annual average salinity for the whole lake during the pre-intervention (8.9 PSU) and post-intervention periods (12.8 PSU), however, exhibited an increase of 43.8% (Table 2).

Table 1. Sectoral variation in selected water-quality parameters for Chilika Lake, 2004–2005 to 2006–2007

Parameter		Northern sector	Central sector	Southern sector	Outer channel	Whole lagoon
Salinity (PSU)	Mean ± SD	3.39 ± 3.71	12.05 ± 7.4	14.8 ± 4.85	17.47 ± 9.34	11.75 ± 9.08
	Range	0.04–21.80	0.05–34.9	5.90–26.9	0.2 ± 36.50	0.04–36.50
pH	Mean ± SD	8.43 ± 0.43	8.32 ± 0.36	8.34 ± 0.26	8.17 ± 0.26	8.24 ± 0.36
	Range	7.14–10.07	6.92–9.29	7.30–9.21	7.30–8.91	6.92–10.07
Dissolved oxygen concentration (ppm)	Mean ± SD	6.05 ± 2.47	7.25 ± 1.25	7.41 ± 0.76	7.62 ± 0.78	7.07 ± 1.57
	Range	0.30–9.76	4.90–10.98	5.08–9.04	6.00–9.86	0.3–10.98
Temperature (°C)	Mean ± SD	27.7 ± 2.2	28.2 ± 2.1	28.8 ± 1.8	28.6 ± 2.0	28.3 ± 2.1
	Range	18.9–32.8	20.6–33.1	22.0–33.6	22.0–33.0	18.9–33.6
Secchi disc transparency (cm)	Mean ± SD	32 ± 19	67 ± 34	127 ± 49	67 ± 32	69 ± 45
	Range	10–112	12–164	37–240	17–155	10–240
Alkalinity (ppm)	Mean ± SD	85.5 ± 40.8	97.0 ± 19.7	110.8 ± 21.3	93.4 ± 20.1	95.6 ± 29.3
	Range	28.0–266.0	48.0–138.0	70.0–326.0	22.0–127.0	22.0–326.0
Chlorophyll-*a* concentration (mg m^{-3})	Mean ± SD	8.69 ± 7.32	9.42 ± 8.97	4.84 ± 3.36	7.65 ± 6.15	7.83 ± 9.68
	Range	1.83–26.53	1.03–33.36	0.88–12.92	1.03–20.78	0.88–33.36
BOD (mg L^{-1})	Mean ± SD	4.09 ± 3.88	2.28 ± 1.18	1.85 ± 0.80	2.03 ± 0.87	2.56 ± 1.83
	Range	0.53–13.68	0.10–8.30	0.35–4.47	0.47–6.00	0.10–13.68
Depth (cm)	Mean ± SD	86 ± 34	135 ± 41	217 ± 32	216 ± 68	158 ± 70
	Range	30–202	61–262	133–309	73–365	30–363

Bod, biochemical oxygen demand; SD, standard deviation.

Table 2 Seasonal and sectoral variations for selected water-quality parameters (mean ± SD) for Chilika Lake during pre- (1994–1995 to 1999–2000) and post- (2000–2001 to 2006–2007) hydrological intervention periods

Parameter	Summer season		Monsoon season		Winter season		Annual average (whole lagoon)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Northern sector								
Water temperature (°C)	30.4 ± 1.1	30.6 ± 1.9	29.5 ± 1.3	30.0 ± 2.6	25.1 ± 0.9	25.9 ± 0.8	28.3 ± 0.8	28.8 ± 0.7
Water depth (m)	0.9 ± 0.1	1.2 ± 0.2	2.4 ± 0.06	2.1 ± 0.1	0.6 ± 0.09	0.9 ± 0.2	1.2 ± 0.1	1.4 ± 0.15
Secchi disc transparency (cm)	52.1 ± 16	39.9 ± 18	69.1 ± 18	38.6 ± 9.3	43.2 ± 14	46.6 ± 11	54.8 ± 9	41.7 ± 7.0
Salinity (PSU)	6.0 ± 2.0	14.4 ± 7.5	2.4 ± 0.9	3.1 ± 2.6	1.7 ± 0.6	2.8 ± 1.9	3.7 ± 0.6	6.6 ± 1.9
Dissolved oxygen concentration (mg L^{-1})	6.6 ± 0.1	6.7 ± 0.8	6.8 ± 0.6	6.2 ± 0.9	6.2 ± 1.1	7.8 ± 1.0	6.5 ± 0.4	6.9 ± 0.3
Alkalinity (mg L^{-1})	96.8 ± 24.9	104 ± 18.5	79.0 ± 4.0	75.1 ± 3.8	78.6 ± 14.3	88.8 ± 9.2	84.7 ± 12.5	89.3 ± 6.0
Central sector								
Water temperature (°C)	30.0 ± 0.5	29.8 ± 1.7	29.3 ± 1.4	29.7 ± 2.9	24.8 ± 0.7	25.0 ± 1.9	28.0 ± 0.4	28.2 ± 0.9
Water depth (m)	1.1 ± 0.1	1.3 ± 0.2	1.6 ± 0.06	1.7 ± 0.2	1.3 ± 0.2	1.6 ± 0.1	1.3 ± 0.06	1.6 ± 0.15
Secchi disc transparency (cm)	77.7 ± 11	68.5 ± 23	96.2 ± 11	89.7 ± 21	75.4 ± 9	89.7 ± 13	82.9 ± 8	82.6 ± 14
Salinity (PSU)	13.4 ± 4.0	16.4 ± 4.7	7.7 ± 4.6	8.2 ± 7.9	5.5 ± 1.24	7.0 ± 2.1	8.8 ± 0.5	10.5 ± 1.9
Dissolved oxygen concentration (mg L^{-1})	6.1 ± 0.5	6.4 ± 0.5	6.5 ± 0.4	6.5 ± 0.4	6.8 ± 0.9	7.4 ± 0.8	6.5 ± 0.1	6.8 ± 0.4
Alkalinity(mg L^{-1})	103.3 ± 11.5	110.2 ± 2.4	87.4 ± 7.4	96.2 ± 9.3	91.5 ± 6.1	93.6 ± 7.1	94.0 ± 7.3	100 ± 0.8
Southern sector								
Water temperature (°C)	30.5 ± 1.2	30.4 ± 1.5	27.7 ± 1.8	30.4 ± 1.4	25.5 ± 0.8	25.9 ± 2.2	28.4 ± 0.9	28.8 ± 0.7
Water depth (m)	1.9 ± 0.09	2.0 ± 0.2	2.3 ± 0.06	2.4 ± 0.1	2.0 ± 0.2	2.2 ± 0.1	2.1 ± 0.08	2.2 ± 0.05
Secchi disc transparency (cm)	91.4 ± 9	96.6 ± 49	110.0 ± 19	130.2 ± 17	103.5 ± 11	121 ± 29	101.6 ± 9	115.9 ± 14
Salinity (PSU)	9.5 ± 0.6	13.3 ± 3.9	11.7 ± 2.9	12.8 ± 4.3	7.4 ± 1.2	10.6 ± 0.8	9.5 ± 0.7	12.2 ± 1.2
Dissolved oxygen concentration (mg L^{-1})	6.4 ± 0.6	6.7 ± 0.9	6.6 ± 0.9	6.7 ± 0.5	7.2 ± 0.7	7.3 ± 0.7	6.6 ± 0.4	6.9 ± 0.1
Alkalinity (mg L^{-1})	106.7 ± 15.9	119 ± 6.4	96.1 ± 6.5	98.6 ± 4.7	88.4 ± 9.0	99.9 ± 9.5	97.0 ± 8.6	105.8 ± 1
Outer channel sector								
Water temperature (°C)	30.0 ± 1.1	29.9 ± 2.4	27.7 ± 1.3	30.1 ± 2.7	25.5 ± 0.8	26.3 ± 1.0	18.4 ± 0.7	28.8 ± 0.6
Water depth (m)	2.7 ± 0.2	3.1 ± 0.5	3.0 ± 0.3	3.2 ± 0.4	2.3 ± 0.3	2.7 ± 0.1	2.7 ± 0.3	3.0 ± 0.1
Secchi disc transparency (cm)	79.1 ± 37	67.2 ± 25	55.7 ± 5	70 ± 15	72.8 ± 14	91.8 ± 12	69.2 ± 2	76.3 ± 15
Salinity (PSU)	27.7 ± 1.3	32.2 ± 1.4	8.5 ± 8.6	13.6 ± 9.4	6.2 ± 2.3	19.9 ± 7.1	13.6 ± 2.0	21.9 ± 2.4
Dissolved oxygen concentration (mg L^{-1})	6.0 ± 0.4	6.9 ± 0.5	6.3 ± 0.2	6.8 ± 0.6	6.2 ± 0.8	7.4 ± 0.6	6.3 ± 0.2	7.0 ± 0.4
Alkalinity (mg L^{-1})	112.2 ± 11.7	118.2 ± 7.5	79 ± 20.8	80.8 ± 11	81.6 ± 10.7	93.4 ± 13	91.0 ± 12.9	99.0 ± 3.0
Whole lagoon								
Water temperature (°C)	30.2 ± 1.0	30.1 ± 1.9	28.6 ± 1.5	30.0 ± 2.5	25.2 ± 0.8	25.7 ± 1.5	25.8 ± 0.7	28.6 ± 0.8
Water depth (m)	1.7 ± 0.1	1.9 ± 0.3	2.3 ± 0.1	2.3 ± 0.2	1.6 ± 0.2	1.8 ± 0.1	1.8 ± 0.1	2.05 ± 0.1
Secchi disc transparency (cm)	75.1 ± 18	68 ± 30	82.8 ± 13	82.1 ± 15	73.7 ± 12	87.3 ± 16	77.1 ± 7	79.1 ± 16
Salinity (PSU)	14.2 ± 2.0	19.1 ± 4.4	7.6 ± 4.3	9.4 ± 4.4	5.2 ± 1.3	10.0 ± 3.1	8.9 ± 0.9	12.8 ± 1.9
Dissolved oxygen concentration (mg L^{-1})	6.3 ± 0.4	6.6 ± 0.7	6.6 ± 0.5	6.5 ± 0.6	6.5 ± 0.9	7.5 ± 0.8	6.5 ± 0.3	6.9 ± 0.4
Alkalinity (mg L^{-1})	104.8 ± 16.0	112.9 ± 8.7	85.4 ± 9.8	87.6 ± 7.1	85.0 ± 10.1	93.9 ± 9.8	91.7 ± 10.4	98.5 ± 6.7

The sectoral depth of the lake during the study period (Table 1) varied between 86 ± 34 cm in the northern sector and 217 ± 32 cm in the southern sector. The average depth was highest during all three seasons in the southern sector, with this sector exhibiting a comparatively stable depth. Siddiqi and RamaRao (1995) and Panigrahi *et al.* (2007) also reported the higher depth in the southern sector. The lower depth was in the pre-monsoon season, followed by the post-monsoon season, due to a lack of freshwater influx. The annual average water depth for the whole lake exhibited an increase of 13.9% (Table 2) during the pre-intervention period (1.8 m) and post-intervention period (2.05 m). Although the water temperature did not exhibit marked sectoral variations, there were clear seasonal variations (Table 1). The water transparency in Chilika Lake exhibited a clear sectoral and seasonal variation, varying between 10 and 240 cm (Table 1). Except for the southern sector (which was less affected by floods), the whole lake exhibited a lower water transparency during the monsoon season, due to the silt-loaded floodwater influx through the northern sector. The low water transparency or high turbidity of Chilika Lake is governed mainly by massive silt-laden surface run-off (Quasim & Gopinathan 1969), resuspension of surficial sediments by stirring action and strong phytoplankton blooms (Panigrahi 2006).

The pH of Chilika Lake is generally alkaline in nature (Banerjee *et al.* 1998; Bhatta & Pattnaik 2002; Nayak *et al.* 2004; Mohapatra *et al.* 2007), varying between 6.92 and 10.07 (Table 1). The pH of the lake was higher in the northern sector, compared with the outer channel, southern and central sectors. A similar observation was made by Nayak *et al.* (2004). The higher pH in the northern sector might be due to a higher photosynthesis level by weeds in this sector. The overall pH (8.24 ± 0.36) observed in Chilika Lake was well within a favourable range for ichthyofauna. The average alkalinity of the lake was highest during the pre-monsoon season, and lowest during the monsoon season, due likely to the low carbonate and bicarbonate content in the river-discharged fresh water (Siddiqi & RamaRao 1995). Examination of alkalinity data suggests a state of homogeneity prevailed throughout the lake, indicative of thorough mixing of seawater and fresh water after the hydrological intervention, as well as a healthy, improved aquatic ecosystem favourable to the lake's ichthyofauna. Opening of the new lake mouth enhanced the annual average alkalinity by 7.5% (Table 2) during the post-intervention period (98.5 ppm), compared with the pre-intervention period (91.7 ppm).

The seasonal mean dissolved oxygen concentrations for the whole lake during this study ranged from 6.55 ± 1.56 to 7.60 ± 1.54 mg L^{-1}, indicative of improved habitat condition for fish, prawn and crabs after the opening of the new lake mouth. The overall dissolved oxygen concentration in Chilika Lake (7.07 ± 1.57 mg L^{-1}) after the hydrological intervention, as concluded from this study (Table 1), appears to be better than the overall dissolved oxygen concentration of 6.7 mg L^{-1} during 1957–1961 (Banerjee & Roychoudhury 1966). The higher dissolved oxygen concentrations in all four sectors were recorded during the post-monsoon season, and the lower during the monsoon season. The northern and central part of the lake is densely covered with macrophytes, which grow luxuriantly in the post-monsoon period, and begin decomposing in the summer with the increased salinity (Pal & Mohanty 2002; Panigrahi 2006). Thus, the increased dissolved oxygen concentration during the post-monsoon period is attributable to their photosynthetically related oxygen release to the water, and decreases when it begins decomposing. Such observations were also reported for other estuarine environments (Divakaran *et al.* 1982; Ramesh 2000).

The nutrients (DIN and inorganic phosphate) were not indicative of eutrophic conditions in the lake (Karydis *et al.* 1983), exhibiting a similar distribution pattern on a spatial and temporal scale. The nitrite (NO_2) and nitrate (NO_3) concentrations during the monsoon season and the ammonia (NH_4) concentration during the post-monsoon season were higher in the northern sector. The low DIN concentration during the post-monsoon season might be attributable to sufficient utilization of nutrients by phytoplankton. The dissolved inorganic phosphate concentration was not indicative of eutrophication, except for the northern sector. Ketchun (1967) reported that 2.55 μmol L^{-1} of phosphate (PO_4) is the maximum limit indicative of lake eutrophication. The maximum PO_4 concentration (Table 3) in the lake as a whole was observed during the pre-monsoon season (0.92 μmol L^{-1}), followed by the post-monsoon (0.81 μmol L^{-1}) and monsoon (0.76 μmol L^{-1}) seasons.

Multivariate statistical analyses inferred that most of the environmental variables are strongly associated with salinity, which seems to govern the lake ecology. The salinity dynamics are governed by both freshwater inflows, and seawater ingress through the new artificial mouth. The PCA (Table 4) for the whole lake exhibited a complete different pattern of factors. Four PCs with eigen values >1 were extracted, representing 62.524% of the total variables. The PC-1 represented 25.899% of the total variance, with the positively loaded ammonia, BOD and nitrate being negatively loaded with depth, transparency and alkalinity. This observation explains that, in the low depth areas of the lake during the high saline phases, decomposition of the freshwater weeds occurs, resulting in higher BOD, nitrate and ammonia concentrations. The PC-2 explained 13.458% of the total variables, with the positively loaded chlorophyll-*a* and water temperature being negatively loaded with the dissolved

Table 3. Seasonal variations in nitrate, nitrite, ammonia, dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations in Chilika Lake from 2004–2005 to 2006–2007

Season		DIP (μmol L^{-1})	DIN (μmol L^{-1})	Ammonia (ppm)	Nitrite (ppm)	Nitrate (ppm)
Pre-monsoon	Mean ± SD	0.92 ± 0.79	15.59 ± 25.6	11.05 ± 14.9	1.43 ± 3.35	3.11 ± 7.34
	Range	0.06–4.14	1.74–160.32	1.33–86.57	0.13–22.59	0.27–57.07
Monsoon	Mean ± SD	0.76 ± 0.59	12.72 ± 22.2	5.99 ± 5.72	1.69 ± 5.16	5.04 ± 11.32
	Range	0.04–3.79	1.14–156.53	0.33–26.67	0.22–42.88	0.50–87.06
Post-monsoon	Mean ± SD	0.81 ± 0.70	12.71 ± 11.1	9.94 ± 6.21	1.02 ± 2.65	1.75 ± 2.27
	Range	0.04–3.79	3.42–61.90	7.76–34.67	0.13–22.59	0.40–17.64

DIN, dissolved inorganic nitrogen; DIP, dissolved inorganic phosphate.

Table 4 Principal component analysis of environmental variables for Chilika Lake

Environmental variable	PC-1	PC-2	PC-3	PC-4
Ammonia	0.818			
Biochemical oxygen demand	0.772			
Nitrate	0.761			
Depth	–0.757			
Water transparency	–0.738			
Alkalinity	–0.613			
Chlorophyll-*a* concentration		0.760		
Water temperature		0.723		
Dissolved oxygen concentration		–0.563	0.449	
Phosphate concentration			0.855	
Nitrite concentration			0.752	
Salinity				0.803
pH				0.789
Eigen values	3.626	1.884	1.723	1.520
% of variance	25.899	13.458	12.309	10.859
Cumulative variance	25.899	39.357	51.666	62.524

oxygen concentration. This finding indicates that the higher temperature facilitated a higher phytoplankton growth, producing a bloom condition, thereby resulting in a decreased dissolved oxygen concentration. The PC-3 explained 12.309% of the total variables, being loaded positively with the phosphate, nitrate and dissolved oxygen concentrations. The PC-4 represented 10.859% of the total variables, being loaded positively with salinity and pH, which is a natural phenomenon. The PCA for the seasonal environmental variables is presented in Table 5. The principal components clearly suggest that the association of the environmental variables significantly changes with respect to seasons. Salinity, water temperature and freshwater inflows are the three major factors controlling the seasonal changes in the lake ecology.

Bottom vegetation and benthic fauna

The estimated annual mean biomass of bottom vegetation was 4365 gm m^{-2} in the northern sector, followed by the southern sector (1200.75 gm m^{-2}), the central sector (983.08 gm m^{-2}) and the outer channel sector (235.5 gm m^{-2}). Seagrass meadows, comprised of *Halophila* and *Halodule* spp. (a favourable habitat for crabs and prawns) ,were almost lost in the lake during its degradation phase, reappeared dramatically in the central, southern and outer channel sectors after enhancement in the salinity regime during the post-new mouth period. The northern sector was devoid of seagrass because of the prevalence of low salinity for ≈6 months each year. The annual mean seagrass biomass was highest in the central sector (1078.8 gm m^{-2}), followed by the southern sector (853.9 gm m^{-2}) and the outer channel sector (618.5 gm m^{-2}).

Gastropods and bivalves were found to be two major groups in this study, regulating the community structure in terms of both qualitative texture and quantitative abundance, both sectorally and season-wise. Banerjee *et al.* (1998) also observed gastropod dominance over the entire lake bed, followed by bivalves and polychaete throughout the year during 1995–1996 (pre-restoration period). The macrobenthos community abundance in Chilika Lake fluctuated between 827 m^{-2} (northern sector) and 3040 m^{-2} (central sector). In terms of annual mean standing crop of bottom fauna, the outer channel sector is comparatively richer (wet weight of 159.20 kg ha^{-1}), while the value for the whole lake was 99.3 kg ha^{-1} (Table 6).

Plankton density and biological productivity

The phytoplankton cell counts determined during this study (Table 7) varied between 43 433 (northern sector) and 53 780 cells L^{-1} (central sector). The phytoplankton population was higher during the pre-monsoon season in

Table 5. Principal component analysis of environmental variables for different seasons for Chilika Lake

	Pre-monsoon season			Monsoon season			Post-monsoon season		
Environmental variable	PC-1	PC-2	PC-3	PC-1	PC-2	PC-3	PC-1	PC-2	PC-3
Water temperature	0.801	—	—	—	—	—	0.521	0.689	—
Water tansparency	0.532	—	—	−0.781	—	—	—	−0.491	—
Depth	−0.561	—	—	0.811	—	—	—	0.418	—
Salinity	0.738	—	—	−0.699	—	—	—	—	0.561
Dissolved oxygen	—	−0.741	—	—	0.446	—	0.791	—	—
Biochemical oxygen demand	0.712	0.598	—	—	−0.418	—	−0.681	—	—
pH	—	—	0.512	—	—	0.416	0.733	—	0.621
Alkalinity	—	0.512	—	—	0.612	—	—	—	0.418
Chlorophyll-*a* concentration	—	—	0.578	—	—	0.421	0.701	0.462	—
Nitrate concentration	0.512	—	—	0.512	—	—	—	—	—
Nitrite concentration	0.619	—	0.611	0.618	—	—	—	—	-.423
Ammonia concentration	0.752	—	—	—	—	0.411	−0.419	—	—
Phosphate concentration	—	—	—	0.415	−0.511	—	−0.561	—	—
Eigen values	3.69	1.89	1.66	3.78	2.01	1.08	3.32	2.01	1.89
% of variance	32.11	18.92	16.36	32.89	18.92	12.91	30.18	23.22	19.16
Cumulative variance	32.11	51.03	67.39	32.89	51.81	64.72	30.18	53.40	72.56

Table 6. Macrobenthic fauna abundance (numbers m^{-2}) in Chilika Lake from2004–2005 to 2006–2007 (percentage of composition in parentheses)

Group	Northern sector	Central sector	Southern sector	Outer channel sector	Whole lake
Annual average					
Polychaetes	54 (6.53)	219 (7.20)	200 (11.72)	226 (9.52)	175 (8.81)
Gastropods	377 (45.59)	674 (22.17)	473 (27.71)	433 (18.25)	489 (24.61)
Bivalves	209 (25.27)	1813 (59.64)	760 (44.52)	1323 (55.75)	1026 (51.63)
Crustaceans	99 (11.97)	145 (4.77)	87 (5.10)	180 (7.59)	128 (6.44)
Amphipods	11 (1.33)	50 (1.65)	47 (2.75)	35 (1.47)	36 (1.81)
Insects	36 (4.35)	45 (1.48)	60 (3.51)	61 (2.57)	51 (2.57)
Isopods	25 (3.02)	65 (2.14)	53 (3.10)	82 (3.46)	56 (2.82)
Others	16 (1.94)	29 (0.95)	27 (1.59)	33 (1.39)	26 (1.31)
Total	827	3040	1707	2373	1987
Total biomass (g m^{-2})					
Pre-monsoon season	5.69	14.83	4.21	10.69	8.86
Monsoon season	3.62	13.62	3.69	12.32	8.31
Post-monsoon season	8.65	19.32	4.55	17.96	12.62
Annual average	5.99	15.92	4.15	13.66	9.93

all the sectors of the lake, followed by the post-monsoon and monsoon seasons. The phytoplankton abundance in different sectors (central sector > outer channel > northern sector > southern sector), and their dominance pattern (diatoms > blue green > dinoflagellates > green algae), exhibited a good correlation with the chlorophyll-*a* concentration. The average chlorophyll-*a* concentration for the whole lake (7.83 ± 9.68 mg m^{-3}) indicated healthy phytoplankton availability. The phytoplankton abundance in Chilika Lake not only assumes greater importance in the context of the lake fishery (Panigrahi *et al.* 2007), but also constitutes one of the major food items for fish, prawn and crab juvenile during their recruitment from the sea. Litulo (2005) recorded similar observations, reporting that

Table 7. Phytoplankton abundance (cells L^{-1}) in Chilika Lake from 2004–2005 to 2006–2007 (percentage composition in parentheses)

Group	Northern sector	Central sector	Southern sector	Outer channel sector	Whole lake
Annual average					
Diatom	15 840 (39.01)	41 400 (76.98)	37 300	42 833 (83.74)	35 843 (71.38)
Dionoflagellates	4707 (9.74)	5140 (9.56)	3420	5067 (9.90)	4583 (9.32)
Blue–green algae	26 640 (48.90)	6147 (11.43)	1643	2267 (4.43)	7669 (17.12)
Green algae	1133 (2.35)	1093 (2.03)	1070	987 (1.93)	1071 (2.18)
Total	48 320	53 780	43 433	51 153	49 167

juvenile recruitment occurs when the phytoplankton concentrations in estuarine areas are higher.

The zooplankton abundance in Chilika Lake during the sampling period (Table 8) varied between 3053 m^{-3} (northern sector) and 8033 m^{-3} (outer channel sector), with an average value of 6102 m^{-3} for the whole lake. The percentage composition of various groups of zooplankton in the lake as a whole exhibited a dominance by copepods (79.04%), followed by rotifers (5.11%), protozoa (4.08%), cladocera (3.98%), mysids (2.38%) and crustacean larvae (2.03%). The total zooplankton biomass in the lake ranged from 0.69 to 6.29 g m^{-3} during the whole year, with the annual mean value for the whole lake being 2.41 g m^{-3}. The season-wise annual average biomass was highest during the pre-monsoon season (3.29 g m^{-3}), followed by winter (2.21 g m^{-3}), and the monsoon season (1.72 g m^{-3}), as illustrated in Table 8. The overall low BOD value (2.56 ± 1.83 mg L^{-1}) for the whole lake (Table 1) was within the limit considered safe for its fisheries resources (NACA, 1994). The BOD was always higher in the northern sector during all seasons. Among the seasonal samplings, the higher BOD value was recorded during the pre-monsoon season in all the sectors, likely due to the decomposition of weeds during the pre-monsoon months, which facilitated the growth of microorganisms.

The nutrients brought to the lake in the monsoon floods/freshwater inflows help enhance primary productivity, while the shallow nature of Chilika Lake facilitates the development of vertical homothermy. These factors, in conjunction with the lake's salinity dynamics, are primarily responsible for its high biological productivity. A 1995–1996 study by the Central Inland Fisheries Research Institute indicated that the annual average primary productivity was 229.8, 86.77 and 77.07 mg C m^{-3} h^{-1} for the pre-monsoon, monsoon and post-monsoon seasons respectively. The value for the whole lake was 131.21 mg C m^{-3} h^{-1} (Banerjee *et al.* 1998). This situation

Table 8. Zooplankton abundance (numbers m^{-3}) in Chilika Lake from 2004–2005 to 2006–2007 (percentage composition in parentheses)

Group	Northern sector	Central sector	Southern sector	Outer channel sector	Whole lake
Annual average					
Copepods	2273 (74.45)	4662 (81.32)	5933 (78.20)	6423 (79.96)	4823 (79.04)
Cladocera	227 (7.44)	136 (2.37)	183 (2.41)	427 (5.32)	243 (3.98)
Rotifer	186 (6.09)	160 (2.79)	813 (10.72)	90 (1.12)	312 (5.11)
Protozoa	129 (4.22)	78 (1.36)	328 (4.32)	461 (5.74)	249 (4.08)
Gastropod veliger	0 (0)	24 (0.42)	48 (0.63)	47 (0.59)	30 (0.49)
Mysids	73 (2.39)	305 (5.32)	36 (0.47)	167 (2.08)	145 (2.38)
Crustacean larvae	73 (2.39)	96 (1.67)	24 (0.32)	302 (6.76)	124 (2.03)
Others	92 (3.02)	272 (4.75)	222 (2.93)	116 (1.43)	176 (2.89)
Total	3053	5733	7587	8033	6102
Total biomass (g m^{-2})					
Summer season	0.69	4.21	1.96	6.29	3.29
Monsoon season	0.92	0.99	1.01	3.95	1.72
Winterseason	1.21	2.11	2.39	3.12	2.21
Annual average	0.94	2.44	1.79	4.45	2.41

was indicative of poor phytoplankton production during the pre-intervention phase. An improved situation was observed from 2004–2005 to 2006–2007, however, with the annual average primary productivity being 209.8, 202.3 and 184.6 mg C m^{-3} h^{-1} for the pre-monsoon, monsoon and post-monsoon seasons respectively. It was 196.2 mg C m^{-3} h^{-1} for the whole lake, an increase of 51.6%, compared with the pre-intervention phase.

Pre- and post-intervention scenarios for fisheries output

Fish and shellfish landings for Chilika Lake in 1986–1987 were 7283 and 1643 t respectively, decreasing to 156.32 and 189.43 t respectively in 1999–2000 (Table 9). The total catch (fisheries output) continued to decline sharply, registering the lowest catch of 1274 t in 1995–1996. This same low yield was maintained till the opening of the new lake mouth. This declining trend in fisheries output could be attributed to a continual decreased salinity, poor water exchange, siltation of the outer channel and palur canal (recruitment routes), breeding and spawning failures of resident species related to degraded habitat conditions, poor recruitment of fish and shell fish seeds from both marine and riverine sources, rapid expansion of 'prawn gheries' (prawn culture pens) and unregulated destructive fishing practices (Pattanaik 2000; Mohanty *et al.* 2004).

Seven years of fish-landing data for the period before the hydrological intervention (1993–1994) to 2000), and 7 years of data for the period after completion of the hydrological intervention, were analysed (Table 10) to provide a comparative scenario of the lake fisheries. The time-series fish-landing data for the period between 1950–1951 and 2006–2007 also highlighted decadal growth trends. During the post-intervention period (2000–2001 to 2006–2007, including the present study period), the 7-year average land of fish (7715.85 t), prawn (3200 t) and mud crabs (135.55 t) was 388.78%, 1128.87% and 1478.0% greater (Table 10), compared with the 7-year average landing of fish (1578.58 t), prawn (260.40 t) and mud crab (8.59 t) during the period prior to the opening of the new lake mouth. The 7-year average fisheries output

Table 9. Fish, prawn and crab yields (t) for Chilika Lake from 1985–1986 to 2006–2007

Year	Fish	Prawn (*a*)	Crab (*b*)	Shellfish (*a* + *b*)	Fish annual growth rate (%)	Shellfish annual growth rate (%)
1985–1986	7446.00	1144.00	79.00	1223.00	—	—
1986–1987	7283.00	1589.00	54.00	1643.00	−2.19	34.34
1987–1988	6863.00	1241.00	39.00	1280.00	−5.77	−22.09
1988–1989	5211.00	917.00	44.00	961.00	−24.07	−24.92
1989–1990	5493.00	1177.00	36.00	1213.00	5.41	26.22
1990–1991	3792.00	481.00	24.00	505.00	−30.97	−58.37
1991–1992	3680.00	876.00	30.00	906.00	−2.95	79.40
1992–1993	3207.00	951.00	15.00	966.00	−12.85	6.62
1993–1994	2799.00	686.00	11.00	697.00	−12.72	−27.85
1994–1995	1239.00	176.00	03.00	179.00	−55.73	−74.32
1995–1996	1056.00	213.00	05.00	218.00	−14.77	21.79
1996–1997	1352.00	281.21	12.00	293.21	28.03	34.50
1997–1998	1491.99	149.51	10.40	159.91	10.35	−45.46
1998–1999	1555.75	136.93	9.68	146.61	4.27	−87.83
1999–2000	1556.32	180.40	9.03	189.43	0.03	29.21
2000–2001†	3592.95	1296.26	93.54	1389.80	130.86	633.67
2001–2002	9530.03	2347.78	111.07	2458.85	165.24	76.92
2002–2003	8265.16	2478.82	149.81	2628.63	−13.27	6.90
2003–2004	10 286.34	3611.37	155.51	3766.88	24.45	43.30
2004–2005	8097.77	5000.71	161.89	5162.60	−21.28	37.05
2005–2006	7774.81	4296.02	154.08	4450.10	−3.99	−13.80
2006–2007	6463.92	3368.97	122.94	3491.91	−16.86	−21.53

†Year of hydrological intervention; data sources: 1985–1986 to 1999–2000, Directorate of Fisheries, Orissa State Government; 2000–2001 to 2003–2004, primary data from Chilika Development Authority; 2004–2005 to 2006–2007; data from present study.

Table 10. Total and relative catch values (% of total catch) of fish and shellfish for Chilika Lake before and after opening of new lake mouth

Commercially important fish and shellfish (group/species)	Seven-year average catch (t) prior to new lake mouth		Seven-year average catch (t) following new lake mouth		Per cent increase in catch	Per cent change in relative catch
	Catch (t)	Relative catch (%)	Catch (t)	Relative catch (%)		
Fish						
Mullets	160.4 ± 13.5	10.1 ± 0.5	742.5 ± 340	9.6 ± 2.4	362.81	−5.3
Clupeoids	376.8 ± 29.5	23.8 ± 1.3	2196 ± 798	28.5 ± 2.9	482.86	19.2
Perches	140.9 ± 29.1	8.9 ± 1.6	446.2 ± 293	5.8 ± 2.2	216.78	−35.2
Threadfins	71.7 ± 3.8	4.5 ± 0.3	328.4 ± 156	4.2 ± 1.3	357.99	−6.16
Croakers (Sciaenids)	107.6 ± 12.6	6.8 ± 0.9	721.9 ± 316	9.4 ± 2.3	570.41	37.2
Beloniformes	70.8 ± 12.6	4.5 ± 0.7	345 ± 203	4.5 ± 1.4	388.36	−0.2
Catchfishes	186.2 ± 25.2	11.8 ± 1.5	1416.8 ± 607	18.3 ± 2	660.66	55.6
Triacanthus sp.	49.8 ± 5.2	3.2 ± 0.3	392.6 ± 125	5.1 ± 1.4	687.48	61.1
Cichlids	104.7 ± 12.9	6.6 ± 1.0	288.5 ± 183	3.7 ± 3.3	175.53	−43.6
Murrels	58.8 ± 7.9	3.7 ± 0.5	182.1 ± 94	2.4 ± 1.3	209.67	−36.6
Feather backs	91.9 ± 10.3	5.8 ± 0.5	287.4 ± 195	3.7 ± 2.1	212.51	−36.2
Others	158.6 ± 18.5	10.1 ± 2.0	367.2 ± 54	4.8 ± 2.3	131.45	−52.6
Total landing	1578.58	100.00	7715.8	100.00	388.78	—
Shellfish						
Penaeus monodon	28.05 ± 5.4	10.4 ± 0.7	382.3 ± 66	11.4 ± 1.6	1263.14	2.55
Fenneropenaeus indicus	37.35 ± 7.1	13.9 ± 0.6	556.4 ± 238	16.6 ± 3.7	1389.85	20.17
Metapenaeus monoceros	95.0 ± 20.1	35.3 ± 2.6	1052.2 ± 484	31.5 ± 16.1	1007.6	−10.67
Metapenaeus dobsoni	100.0 ± 24.8	37.1 ± 2.4	966.3 ± 245	28.9 ± 11	866.24	−22.1
Macrobrachium sp.	NA	NA	242.6 ± 35	7.3 ± 4.5	—	—
Mudcrabs (*Scylla* sp.)	8.59 ± 1.1	3.2 ± 1.1	135.5 ± 26	4.07 ± 1.0	1488.51	28.39
Total landing	269.02	100.00	3335.5	100.00	1139.96	—

NA, not available.

during the post-intervention period (11 051.39 t) exhibited an increase of 498.16% (about sixfold), compared with the average output of 1847.57 t during the pre-intervention period before the new lake mouth was constructed (Table 10).

Fisheries enhancement

Analysis of 7-year commercial catch statistics, including the average fisheries output (1847.6 t), productivity (2.002 t km^{-2}), CPUE (1.1 kg $boat^{-1}$ day^{-1}), and the economic value of the average annual fish and shell fish landings (49.88 million rupees) before the opening of the new lake mouth illustrated the declining state of the lake fisheries. During 2000–2001 to 2006–2007, however, the average fisheries output (11 051.3 t), CPUE (6.2 kg $boat^{-1}$ day^{-1}), economic valuation of 637 million rupees for the average annual catch and the productivity (11.97 t km^{-2}) exhibited dramatic increases of 498%, 464%, 1177% and 498.5% respectively, compared with the pre-intervention period. The enhanced fisheries output also suggests that the spawning and recruitment were more successful, and environmental conditions (particularly salinity and water transparency) were more conducive to the lake fisheries (Table 2). Correlation analysis indicated an inverse relationship between water transparency and fish catch ($R^2 = 0.715$; d.f. = 25; $P < 0.001$), while salinity was positively correlated with prawn catch ($R^2 = 0.542$; d.f. = 25; $P < 0.01$), crab catch ($R^2 = 0.628$; d.f. = 25; $P < 0.001$) and fish catch ($R^2 = 0.476$; d.f. = 25, $P < 0.05$). Thus, the average increase in the salinity regime (43.8%) for Chilika Lake during the post-hydrological intervention period appears to have positively impacted the fish, prawn and mud crab catches.

The continual increase in shell fish landings after the hydrological intervention up to 2004–2005 can be corroborated with the salinity factor, as indicated by the higher significance value of the correlation coefficients for prawn ($P < 0.01$) and mud crab ($P < 0.001$). The prawn and mud crab fisheries are also influenced, however, by their breeding, and spawning success or failure, in adjacent coastal waters (Jhingran & Natarajan 1969). Their populations also are more cyclical in nature, due at least in part to changes in local coastal waters that affect spawning and recruitment to the estuary/lake, as also observed in Peel–Harvey Estuarine System in Australia (Lords and Associates PTY Ltd 1998). Other water-quality parameters did not illustrate any relationship with the fish catch because of complex nature of the functioning of the Chilika Lake ecosystem.

Fish and shellfish landings (total fisheries out put) exhibited a sharp ascending trend immediately after the opening of the new artificial lake mouth in September, 2000, registering 185.43%, 586.74%, 524.02%, 705.0%, 659.58%, 600.27% and 470.29%, during 2000–2001, 2001–2002, 2002–2003, 2003–2004, 2004–2005, 2005–2006 and 2006–2007 respectively. The exception was a slight decrease in 2002–2003. The increasing trend in fisheries output after the opening of the new lake mouth could be attributed to a sudden shift in the ecosystem ('trophic burst') attributable to enhanced salinity dynamics, tidal and salinity flux over 40% (Pattanaik 2001), flushing of long-deposited sediments, proper exchange of lake and seawater, successful spawning and unhindered auto-recruitment of fish, prawn and crabs, an administrative drive to prevent *prawn gheries*, and increased fishing efforts. A gradual decrease in total fisheries output since 2005–2006, however, was attributed mainly to a continual increase in destructive fishing in the absence of any conservation and regulatory measures for fishing and large-scale collection of shrimp juveniles from the outer channel for shrimp aquaculture. Thus, carefully planed conservation and regulation measures must be ensured, with active participation of local communities during this early phase of restoration. Otherwise, the present scenario of fisheries enhancement might not be sustained over the longer term.

CONCLUSION

The opening of the new mouth for Chilika Lake apparently resulted not only in a quick recovery of the degraded fishery, but also dramatically altered the trends in the annual catch. There has been some reversal of fisheries output (fish, prawn and crab yields) after 2003–2004 (Table 9). This observation suggested that not only the fisheries definitely improved after the hydrological intervention, but also the overall trend exhibits some fluctuations. Such an observation is quite natural for a lagoonal ecosystem with estuarine characteristics. The lagoon fisheries are dependent on three major factors, including: (i) effective recruitment of juveniles of fish, prawn and crabs related to proper functioning of the new lagoon mouth; (ii) improved salinity dynamics; and (iii) rational exploitation. This means that timely measures are required to maintain the *status quo* regarding these factors. As the current fishery for Chilika Lake, after the hydrological intervention, is still in a transient mode, detailed monitoring is recommended as a means of recording possible changes in it, as well as facilitating understanding of the level at which the fishery might be stabilized over the long term. In view of the changed ecological regime for Chilika Lake, including the enhanced fish yield attributed to the hydrological intervention, there is an urgent need to manage the lake's ecology and fisheries in an integrated, responsible manner. This can be best achieved through such measures as active participation of the lake resource users (fishers) and other stakeholders in fishery conservation and management process, protecting the interests of traditional fishers, gathering scientific evidence, setting appropriate conservation and management objectives, regulating fishing practices (phasing out of destructive fishing) through appropriate legislation, post-harvest practices, education and capacity building measurers, maintaining the new lake mouth, flushing channels, restorating catchment ecology and ensuring preferential freshwater inflows through the Naraj Barrage. There is a need for an ecosystem approach to periodically evaluating changes and assessing the status of the restoration efforts in the future, particularly the successes and failures of conservation and management of the living resources within the lake and its catchments, effective participation of local communities in such conservation and management processes, potential gains from such management in an economic context, and ensuring functioning and maintenance of ecosystem services.

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