Geo Dynamics, Salinity Gradient, and Vegetation Interdependence in Chilika Lagoon, a Tropical Wetland in Eastern India

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ABSTRACT

Chilika a shallow brackish lagoon, India, is shrinking for sediment surplus budget. South Mahanadi deltaic branches i.e. Daya and Bhargavi terminate at the southwest swamps of the Lagoon. The annual average salinity of the lake was depleted from 22.31 ppt (1957-58) to 8.5 ppt. (1999-2000) as the mixing process of saline and fresh water was influenced from 1995. Trepidation of conversion of Chilika to a atrophied fresh water lake due to blooming population and their hydrologic interventions like Kolleru lake in (India), Aral Lake (Uzbekistan) was apprehended by 1950's and was alarming by 1999 when the shallow inlet(s) shifted extreme north. The shallow mud flats of lean salinity were reclaimed further for agriculture. The ecology and biodiversity degraded with substantial pecuniary loss to the lagoon dependents. Anthropogenic interventions like, Hirakud Dam (1956), dredging of Sipakuda Inlet (2000), Naraj barrage at delta head (2004), Gobardhanpur barrages (1998) and Gabkund cut with weir (2014) were made to the hydraulic system. The deteriorating health, perturbed biodiversity and declined ecosystem of the lagoon has forced to have a comparative study of the various morphologic changes passed over the Chilika with time. The meteorological, hydrologic, and the salinity study of the lagoon area for the period 1990 to 2016 have shown changes. Topographic study using GIS is developed by collecting data from Glovis Classic (Google) and the interpretation is done using ERDAS 9.2 software for various geomorphic features (1984 and 2017) before and after the current anthropogenic interventions and compared with previous studies.

Key words: Chilika Lagoon, Tidal inlet, Geomorphology, Mahanadi Delta

INTRODUCTION

Coastal lagoons vary decreasingly in number from equator to pole and cover about 13% of the onshore coastal areas. The sea level fluctuations play pivotal role on the young dynamic water body, which was formed during mean sea level rise (MSL) fluctuation during Holocene. The Venice Lagoon (Italy), Jubho Lagoon (Pakistan), Coorong Lagoon (Australia), Lake St. Lucia (South Africa), and Lagoa dos Patos (Brazil) and most of the lagoons are in a state of threats from climatic quirks, sedimentation, anthropogenic activities and salinity regime. The lagoons in India are the Chilika (Odisha), Pulikat (A.P. & TN), Kaliveli (TN), Vembanad (Kerala). They are also victims of MSL variability, meteorological extremes, river inputs, and salinity variations.

Chilika Lake, the largest in Asia and second in the world, is a shallow lagoon sprawls along east coast of India. The brackish water body spreads over an average 1045 km² during monsoon, 790 km² during mid-eighties and further reduced to 760 km² during nineties (Ghosh 2003). The pear shaped wetland has maximum and minimum depth from 4.88m-

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0.6m (1858) (Pearson 1858) to 1.42 m to 0.42 m in monsoon and summer respectively (1995-1996) (Mishra et al 2015). The 64.3 km long barrier spit between the lagoon and the Bay of Bengal (BoB) is stable for its 33.3 km and width 3-15 km from south is thickly habituated. Rest 31 km is of width 0.15 to 1.5 km is narrow, dynamic and fragile with all Tidal inlet (TI) dynamics and mangroves Fig. 1(a). The lagoon comprises of three sectors northern sector (NS), central sector (CS), southern sector (SC) and with a shore parallel outer channel (OC) of varying length 30 to 32 km. The salinity gradient and all fluvial hydrodynamics are controlled by the tidal inlets (TI) in the spit.

The Chilika has an overall area of 1570 km² (including coast) and extends from the Rambha Hills to extreme southern corner of

South Mahanadi Delta (SMD). The lagoon lies between two deltaic promontories of the rivers Daya and the Rushikulya. The lagoon acts as a balancing reservoir for discharge of the rivers Daya and Bhargavi system which contribute 60-70% water volume of the lagoon Fig. 1(b). The basins area of SMD is 1777 km² and the western catchment area is 2800 km² (Mishra et al., 2013). The lagoon has a fragile marinebrackish-fresh water ecosystem.

which is maintained by salinity gradient. The major sediment transport to the lagoon area is either with the floods or by tides. The area adjacent to NS is of young alluvial landform of SMD whereas the western catchment is hilly terrains of the EGB Hills Fig 1(a) and Fig 1(b).



Figure 1. The Chilika and morphologic division (a) and the South Mahanadi Delta and Chilika (b)

The study area is bounded by latitudes 19° 28' and 19° 54' N. and 20° 24' N lat., and 85° 67'E, 85° 35' E and 86.57' E long. The area is covered in Survey of India (TS) numbers E45B, 74 E/01, 74 E/02, 74, 74 E/03, 74 E/05, 74 E/06, 74 E/09, 74 E/10 E74/6 and E74/16 of

scale 1:50000. Present monitoring of the area was done by GIS studies. The present research work elucidates the geodynamic transforms, barrier spit, topography, morphology, salinity gradient of the Chilika Lagoon. The interdependence of the geodynamic transforms

and the consequential changes LU/LC within the lagoon and adjoining areas of Puri District in SMD is also studied using GIS imageries from 1975 to 2017.

In 1870, the geographical coastal length, maximum average width of the lagoon were 70.81, 32.2, 8.05 km respectively and average depth 0.9 to 1.5 m except some places more than 3 m Sterling (1846). Pearson (1858), Harrish J. C. (1860) were the investigators who prepared the first Bathymetry map of the lagoon. The first spur (human intervention) was constructed at Naraj in 1958 and furthers improved to a barrage in 2004. The flow distribution in the branches Daya and Bhargovi Rivers were 2.6% and 1.9% respectively of total flow of the trunk river Mahanadi Mahalanobish (1928). There were changes in the geomorphology, hydrology, and hydrodynamics of the lagoon and in the (SMD) with time (Das and Jena, 2008; Gupta, 2008; Mishra et al., 2012). The average length, breadth, depth of the lagoon were reduced to 64.5 km, 3-25 km and 0.5-2.9 km respectively except the dredged channel of 6.0 m. There was prolific change in lake ecology and biodiversity after dredging of the mouth in front of Sipakuda as reported by CDA Report (2012-13) (Gupta et al., 2010; Sahu et al. 2014).

The lagoon was reported of about 3000 years old and had gone many a geospatial transformation (Venkatratnam, 1970; Mahalik, 1996; Kadekodi, 1999; Nayak et al., 2006; Lal et al. 2009; Iwasaki, 2016). CWPRS evaluated the rate of drift was 1.2 Mcum in 2000. The average annual sediment load to Chilika during 1999 2007 was 0.89 MMT *i.e.* 75% of total load (0.66 MMT) was contributed by the Mahanadi system. In 2007, the Bay deposited 0.81 MMT of sediments within the lake (Chilika Newsletter

Volume - V - Wetlands International). The vertical gradient of the lagoon undergoing dispersal mechanism like surface water, salinity and pH of the lagoon is $\approx 1, \approx 2$ and ≤ 1 (Panda et al., 2008). During 2009-10, 1400 Cumec flood was discharged to sea through all the inlets during flood and inflow from Bay of Bengal was 1110 cumec during ebb tides whereas total tidal prism during flood is 19.2 Mcum and 18.0 Mcum during ebb tides (Gopi Krishan et al., 2014). About 13 MMT of sediment enter the Chilika carried by 10667 MCum of water (Kadekodi et al., 1999) out of which 90% of silt surpasses the lake and enter direct to sea during flood (Chkrapani et. al., 2005). Sediment studies on the lake has been undertaken showing excess sedimentary balance is depleting the lake Delta Development Plan (Chandramohan, 1993; Mishra et al., 2012; Abinash, 2013). The distribution of sea grass meadows were within the central and southern west coasts of the shallow lagoon, with annual carbon sequent ion rate 10.1 to 16.8 Ton CO₂ equivalent ha⁻¹ covering an area of 85 km² (Ganguly et al., 2017). The water of the lagoon from 2006 to 2014 was in eutrophic state and trophic state index was low during post monsoon period in 2013-14 (Jally et al., 2016).

Study of land use and land cover (LU/LC) by using GIS and satellite imageries are widely accepted at present for monitoring and management of basins/watersheds of the water bodies. (Lo Yang et al., 2002, Ye Bai et al., 2008; Singh et al., 2013; Rawat et al., 2014). Ojha et al., (2013), Singh et al 2013, Rout J 2013, Islam (2013), Rawat et al. 2014, Sahu et al., 2014 Gupta, 2014) and Goswami et al. (2017) have reported from their GIS studies of the lagoon area that vegetation, flora and fauna in the catchment (*i.e.* SMD and western

catchment) have deteriorated and there is diminution of the lake area and changes in geomorphology. The greenery transform have upset of biodiversity, hydrology, limnology, and other geomorphologic features which has influenced the climatic and ecological alterations. Mahanty et al, 2016 found the residence time is 4 to 5 days in the outer channel and 132 days in the lake body. Watanbe et al., 2016; Fabiola et al. (2016) have shown through GIS imageries that tsunami-2004 has less impact on the geomorphology of Chilika Lagoon. The action of turbulent flow on the suspended sediment in a plume and found turbulent bursting occurs with a momentum sediment flux correlation Wijeratne et al 2017. High NO_3^- concentration, low DO value of water in Chilika (0.01 to 02 µ mole/L) result in increase in chlorophyll (4 m cum⁻¹) Rajkumari et. al., 2010. Chilika Lagoon is at eutrophic (49-63 Carlson TSI) state from 2013 to 2015, Jally et al 2016. Nazneen 2017 reported that the

texture, influx of sediment, algal growth and the human interventions play pivotal role in variation of low organic carbon but high N, P, and silica concentration which is found in the sediment cores of the OC and NW swamps of the Chilika. Sea grass are proliferated in the west bank of the Chilika Lagoon as a mark of Blue Carbon Sequestration covering an area of 86.84 km in 2012. Philips J. D., 2017 reported that the geomorphic resilience in a coastal lagoon is not absolutely a property of the system but are geospatially free. The MSL rise of adjacent sea is governed by local geomorphology. The residence time of the lagoon is heterogeneous, site specific and regulated by seasonal activities and varies from a week in OC to 132 days in swamps of northern sector during a year Mohanty et al 2016. Islam Sk. M. 2016 reported that the total catchment area of the Chilika lagoon (SMD + Western) is approximately 5240 km².



Figure 2. The fresh water inflow system from SMD to the Chilika Lake.

The lagoon had a depleted TI (at Motto) in 1999, 32 km from Magarmunha, was delaying the ingress/mix and thus reduces the salinity of the lagoon. Following the risk model results, Sipakuda inlet was dredged in front of

Magarmunha to augment flow exchange and to raise salinity gradient to save the eco-health of the lagoon. Hirakud dam (1956), Sipakuda TI (23rd Sept, 2000), Naraj barrage at head of SMD (2004), Gobardhanpur barrage (1998),

Gabkund (submerged weir) and weir (2014), Mangala cuts to BoB from the river Bhargavi are the major hydrological interventions. Seasonality and anthropogenic activities have heterogeneity in coastal ecosystem Bharati et al, 2017. Hirakud dam was unable to control sedimentation of Chilika lagoon. The 940 m long Naraj barrage, (latitudes 20° 24' N and longitudes 86.57' E) with design discharge of 29500 cumec has been effective. But a dry spell is running from 2015 to 2017 in the Mahanadi basin. But after construction of Gabakund submerged weir with a pilot channel, the summer flow is regulated in the river Bhargavi. But 55-60% of the flood of the Bhargavi drains to Bay without reaching the Chilika depriving its flushing flow. The flow scenario of Mahanadi system is draining to Chilika (Fig. 2).

MATERIAL AND METHODS

Hydrological data (1998 to 2013) for eight river gauge and discharge (G/D) stations of the inflowing rivers around the lake catchment were collected and analyzed. Hydrologic data of the inflowing major rivers to Chilika, have been taken for the period 2001, 2002, 2003 (preinterventions) and 2009, 2011 and 2013 for post interventions. The discharge data of Naraj Barrage which is the major source of flow has been collected. The Morpho-dynamic changes in the lagoon have been gathered from field visits, old available literatures, books and web sites.

The synoptic view in GIS is designed to capture, preserve, handle, study and manage the

 Atmospheric correction for any meteorological interventions like noises and clouds existing geographic data. The Satellite data and GIS were used to analyze the dynamics of evolution and morphologic changes and study the Land use and land Cover of the Chilika. Images from Landsat 2 Multispectral Scanner System (MSS), Landsat 5 Thematic Mapper (TM), and Landsat 8 Operational Land Imager (OLI) were available to extract the land cover maps. A cross-tabulation detection method in the geographic information system (GIS) module was used to detect land cover changes during the 1st period (1976-1998) and 2nd period (1998–2014). GIS technology was developed using the Multi Spectral Scanner (MSS), Thematic Mapper Sensors (TMS) and Enhanced Thematic Mapper Sensor Plus (ETMS+) in satellites LANDSAT 5 or 7 (or 8) and RESOURCESAT to get better resolution results. Google Earth uses high resolution images like digital Globe quick bird which is 65 cm panchromatic at nadir that operates few hundred km above the Earth's surface to give resolution those high images (https://www.gearthblog.com/blog/archives/201 4/04/google-earth-imagery.html). The steps involved in the process are:

- Collection of satellite data from Land Sat series from Glovis classic (Landsat Series Thematic mapper -5)
- Interpretation of the data using ERDAS
 9.2 software to create a layer stack (Digital Image Processing)
- 3. Focal analysis was done to check the disc tripping
- 5. Data preparation was done and a subset image was prepared

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- 6. Classification was done to have a thematic map (Land Use and Land cover map)
- Accuracy was checked (should be more than 85%)
- 8. Preparation of Land use /Land cover (LU/LC) map

Satellite imageries were collected from Google Earth for the thematic maps of Chilika from 1984 to 2017 and processing was done. Transgressed geomorphologic changes of the coast were studied before and after anthropogenic interventions.

Present study covers the vicissitudes in LU/LC in the lacustrine brackish water body and adjoining areas in SMD in Puri district for past 42 years. The Landsat &IRSP6 LISS III

satellite imageries of 1975, and 1995, 2012, 2013 of Ojha et al. (2014), and Rout J. (2013) were considered in the study. The GIS technique was used to find the land use and land cover map of Chilika and SMD area for the year 1985 and 2017 with an accuracy of 86%.

Chilika lagoon has a catchments area of 4577 km² (Mahanadi catchment and Western catchment) consisting of 52 rivers, rivulets and drainage channels. They contribute fresh water into the lagoon only during the monsoon and post-monsoon season. For the convenience of the study, only 13 major rivers and rivulets contributing 90% of the fresh water were taken for monitoring the monthly discharge for the period 2001 to 2003 (Fig. 3).



Figure 3: Annual flow to the Chilika from during SW Monsoon in the year 2001, 2002, 2003

Figure 4 represent the pre-barrage and 2009, 2011, 2013 Figure 4 the post barrage where flow to Chilika through the main rivers are recorded. From the graphs, it shows the river Daya carries maximum flow to Chilika and Sep and Oct are the months of high quantity

of inflow to the lake. In 2009, there was excess rainfall in the basin which discharged excess runoff to the lagoon. The flow has drastically reduced owing to dry spell in Mahanadi basin 2014 to 2017 (Fig. 4).

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Figure 4. Annual fresh water flow to the Chilika during SW Monsoon from catchment year 2009, 2011, 2013

Tidal Inlets

Chilika has continuously north moving TI's, varying in number and dimension which maintain the marine-brackish-fresh water ecosystem. The post intervention geomorphologic changes in the in the Tidal inlets (TI) are the closure of old Motto TI's 2004, subsequent merger and closing of Sipakuda, Mirjapur and Gabakunda TI by 2014, further opening/migration of the five new natural tidal inlets Dahlbali (Baidhar) (2012), Chadachadi (Dhaulakuan) (2014),), Dhala Kuan near Nanganasi (2016) and Gaikona (2017) till date. The high tides from 18th to 21st Oct and from 15th Nov 17th November 2017 have eroded the guard walls in the OC near Sanapatna (Fig. 5).

Tidal prism

Paul et al. (2014) estimated the tidal prism volume during pre-human interventions were 93,312,000 m³, 62,208,000 m3 and 38,880,000 m³ in the year 1972, 1990 and on 12. 09. 2000 during pre-interventions respectively. The vertical mix was improved during postintervention and multi-TI period. It was 62,208,000 m³, 93,312,000 m³ and 202176,000 m^3 in the year 2004, 2009, and 2013, respectively. The flow dynamics of the Chilika is governed by the flood deltas in OC not by the insignificant ebb deltas like the river estuaries of the Mahanadi System. The number and dimensions of flood deltas in OC increase during the drought period in the basin.





Figure 5. Spit dynamic TI's and flood deltas (a. Dt. 4. 4. 2013 and on Dt. 11. 6. 2016)

Long shore drift

The semi-stable coast of the Lake is microtidal with mean tidal range of 1.29 m & semidiurnal tidal cycle 12.42 hours. The tidal flux is increasing from 0.36 m to 0.80 m (observation 1999-2006) along Chilika curved coast (CDA Report 2012)^[4]. Waves of 3 m high (maximum) strike coast obliquely (S- to SW direction). The long shore sediment drift near shore is northerly of about 6000 Cumec with maximum wave height of 3.8 m (post monsoon) to 19000 Cumec (pre-monsoon) with spring tidal amplitude 2.39 m and neap tidal amplitude 0.85 The surplus sediment budget m. of longshorsediment and inland sediment from floods is the major causes for sedimentation of the lagoon. Inland floods contribute less to sedimentation as 90% of sediment directly flows to the bay without settling within the lake. The silting process is accelerated by the aquatic manifestations.

Inflow from Mahanadi system

Rivers in the SMD are ephemeral and provide little fresh water flow in summer. The lake receives 5-6% of flow of Mahanadi system at present instead of 8-10% in 1990's. It is due to the diversion of 60 to 70% of water through Gabakunda Cut to Bay of the river Bhargavi. The river Makara, a small drain prior to 1990's, is active at present and carrying more flow to the lake than the parent river Daya. The delta faced very high peak floods more than 31500 umec in 2001, 2003, 2006, 2008, 2011, and 2014. The years 1995 to 2000 and 2015 to 2017 were the most vulnerable years for the lake due to prevalence of dry spell in the SMD with a small warm period (peak in 1998). The ever recorded least peak discharge of the basin was 5050 cumec in 2000 at delta head, Naraj.

Sediment transport to lake

There is long shore drift from SW to NE and transport in average 1.2 cum of sand in the near-shore regime. The average annual suspended load of 2.70 MMT is carried from inland by the Mahanadi to Chilika during the monsoon (Delta Dev. Plan, Orissa, 1986) whereas annual sediment exchange between the lagoon and Bay was 1.0 cum Chandramohan et al. (1991).

Salinity Exchange

The salinity of the lagoon increases during summer due to evaporation, southern wind and spring tides. It is estimated to rise from 2 to 6, 8 to 13 and 9 to 15 PSU in NS, CS and SS respectively. Mohanty et al., 2015 have reported that the salinity of the lake is of fluctuating nature. It manifests the growth of see weeds, aquatic biodiversity. The instability of the TI, proliferation of planktons, weeds growth and salinity change affect the hydrodynamics of the lagoon and changes the salinity gradient. Delayed resiliency of salinity concentration after a monsoon discharge develops the major concern for the management, as salinity is the primary indicator for the eco health of the lagoon. Tidal prism is absent during monsoon flow but during non-monsoon it is 150 um. The rate of tidal fluctuation is 1.0 m in monsoon and 0.2 m during non-monsoon. The tidal flux during post intervention has improved by 45%. The long shore drift, diurnal tidal fluctuation, and tidal prism govern the salinity of the lake (<u>http://iczmp</u>odisha.org/projectreport/Project%2 0 Report.pdf).

The average salinity of the lake was 22.3 PSU in 1957.58, 13-20 PSU in 1960-61 and 9.4 -11.8 PSU from 1961 to 1964 and was reduced to average salinity of 8.3 PSU in 1999 (Bando padhyay et al 1991 & Kadekodi et al (1999). After intervention, the average salinity of the lagoon increased gradually to 13.2 PSU (one PSU = 32.4 ppm or ppt) in 2005. The average salinity was oscillating till 2005 to 2015 in flood years (2004, 2006, 2008 & 2014) The average salinity was less than the previous years as the lagoon receives its flushing flood and residence time changed.

The sectorial salinity data (1999 to 2015) indicates that the salinity of all the sectors was declining 4 to 10 PSU from 2008 onwards after the historical flood of 44750 umec in 2008. The basin is running with a dry spell (2014-2017) at present. Barrages, fall in rainfall in the upper Mahanadi basin have declined annual runoff from the Mahanadi delta, which is under the constraint of flow and paucity of sediment. The continuous depletion of quantum of flow, rise of surface temperature of the lake and plunge in average salinity has affected its eco-health (Fig. 6).

Saline Embankments

Saline embankments of length 246.7 km were constructed and maintained by the W.R. Dept. Odisha to save the island from distortion and its islanders from flooding. It was 232.19 km before intervention, which hinder free discharge to the sea and encroaching flood plain.



Figure 6: Maximum, Minimum and average salinity of the Chilika from (1999 to 2015)

Lake dimensions

In 1984 the lake area was 1027km². Tripathy 1995 reported the lake depth was 2.5 m in SS and maximum 3.4 m in CS in 1990. Dry spell prevailed in the Mahanadi basin 1985 to 1999 and also ENSO activities. The lake was deprived of flushing flood except 1992. There was irregular silting and sedimentation was accelerated up to 2000. The N-sector observed to be the shallowest with depths ranging from 0.2 m to1.5m and in central sector the depth varies from 1.5-2.5 m. The central sector after dredging has increased depth of maximum 6.0m whereas southern sector has depth of 2.5-3.5 m. (CDA Report 2012-13). Panda et al.,2008 reported the minimum area to shrunk Chilika in 2008 was 690km² (from Sahu et al 2014). The water levels in the lagoon during SWM are higher in average by 1.22 m as compared to summer.

The water spread area

The water spread area of the lagoon was 1165 km² during flood and 906 sq.km during summer (Sterling 1848). Gupta 2014 reported minimum water spread area as 865km² during 2014. CDA in its health card reported the lagoon had water spread area 824 km² in 1972-

Journal of Wetlands Environmental Management Vol 7, No 1 (2019) 1 - 22 http://dx.doi.org/10.20527/jwem.v7i1.186 73 and in 2000 it was reduced to 790km^2 . Panda et al., 2008 reported that the spread area has been reduced to 690sq.km. The water spread area of the lake varies daily and seasonally. During diurnal daily tides water spread area of Chilika varies from 720 to 846 km² in low and high tides respectively (Gopi krishnan. 2014)[28]. Extreme meteorological events i.e. severe cyclonic storms, Tsunamis, eclipses and very high floods etc can abruptly changes the water spread area. Maximum and minimum depth (in cm), salinity, rainfall, aqua catch and ENSO activities information of Chilika lagoon are given in Table 1.

The islands and isles of OC

The106 numbers of islands of 203Sq.km that contribute about 17% areas (CDA report). They decide Lake Stratigraphy, the geomorphology and ecology. Islands are continuously in the process of either building or dispersing. The sand spits and islands close to S-sector have permanent habitation. Isles in O.C. (flood deltas) govern the mouthing activities and tidal prism and no habitation. They restrict/enhance flow that influence the resident time of the lake, which is 132 days during monsoon and 4-5 days in non-monsoon.

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Table 1. Maximum and minimum de	pth ((in cm), salinity	, rainfall, a	agua catch and ENS	D activities in Chi	lika lagoon.
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Year	Max	Min	Av.	Flow	Area 31 st	Rainfall	Aqua	Meteorological	Source
	depth	depth	(appx)	SMD to	Dec	in mm	catch	Extremes/Flood/	
	(cm)	(cm)	salinity	Chilika	(Sa.km)		(MT)	storm/ENSO/	
	(0111)	(0111)	in PPT	(cumec)	(54)		(111)	drought/Tsunami	
Pre interventio	ons		miii	(cullec)				drougin/ i sunann	
1988-89	330	50	8.2	761	967	1270.5	6172	Strong La Niña	Adhikary et al -92
1989-90	300	20	73	560	954	1283.9	6706	SCS (T6 5) GPL	Sahu et al 2014
1990-91	340	20	7.8	2040	950	1865.8	4297	VSCS(T 6.5)	Rajat et al 2012
1991-92			4.1 app	2627	1008	1465.7	4586	La Nada (Neutral)	Rajat et al 2012
1992-93	340	74	6.0	2464	984	1344.1	4173	La Nada (Neutral)	Ghosh et al. 2003
1993-94	210	65	8.0	1522	995	1421.6	3496	La Nada (Neutral)	Ghosh et al. 2003
1994-95	332	58	11.0	1895	994	1700.2	1418	4-MF, Mod El Niño	Ghosh et al. 2003
1995-96	382	60	4.2	1473	999	1739.3	1274	VSCS Gopalpur	Ghosh et al. 2003
1996-97	142	42	5.1	747	967	1042.4	1645	La Nada (Neutral)	Ghosh et al. 2003
1997-98	189	72	4(app)	1363	955	1493.0	1652	Very strong El Niño	P. S. Edwards
1998-99	480	40	4.0	1294	942	1277.5	1702	Strong El Niña	Ghosh et al. 2003
1999-00	330	35	8 28	1015	950	1435 7	1746	SC/VSCS GPL	Ghosh et al. 2003
2000-01	677	28	9.32	285	1025	1022.9	4983	Weak La Niña	Ghosh et al. 2003
Post Intervent	ion	-							
2001-02	540	31	10.15	2254	1013	1005.5	1611	High flood	Ghosh et al. 2003
2002-03	586	29	12.96	940	1011	1658.7	11989	Mod El Niño	Ghosh et al. 2003
2003-04	NA	NA	12.19	2160	1025.7	1273.6	10894	High flood	W R Dept. Odisha
2004-05	NA	NA	12.51	1226	1047.8	1519.5	14053	Sumatra Tsunami	IMD Report
2005-06	420	38	13.17	1445	989.6	1682.7	13260	Weak La Niña	CDA report
2006-07	350	35	9.57	2053	1012.3	1490.0	12225	High flood	Panigrahi et al -07
2007-08	620	235	10.71	1188	997.5	1498.6	9956	Strong la Niña	CDA Report
2008-09	682	28	9.89	2531	1014	1550.3	10047	History flood	Jeong et al. 2008
2009-10	NA	NA	10.58	1384	956.2	1576.0	10702	Mod. El Niño	http://ggweather.com/enso/oni.htm
2010-11	NA	NA	11.90	1103	1005.1	964.00	11955	Strong La Niña	
2011-12	NA	NA	10.54	2185	997.7	1275.1	13066	HF Mod La Niña	W R Dept. Odisha
2012-13	620	38	11.61	1082	997.70	1932	14228	La Nada (Neutral)	CDR 2012-13
2013-14	NA	NA	10.17	1149	10117	1524	12936	VSCS/High flood	IMD F/C
2014-15	NA	NA	8.80	1781	997.00	892	12963	VSCS Hudhud	IMD F/C
2015-16	NA	NA	10.98	<1120	1021.5	954		Very strong El Niño	http://ggweather.com/enso/oni.htm
2016-17	420	38		<1120	971.00	1140.0		Weak La Niña	



Figure 7. LU/LC map of Catchment with Chilika lake (http://bhuvan.nrsc.gov.in/gis/thematic/index.php)



Figure 8. LU/LC Chilika Lake and catchment year 1975, 1985, 1990, 1999, 2011, 2013 and 2017 (Wetland international South Asia and CDA and Jha et al., 2013, 1987 and in Mishra and Das 2017)

Edaphic factors of some Islands are small hillocks and others made up of fine-grained sand overlain by the swampy mud flats. The isles migrate in any direction or remain delta near the shoreline by the surplus sediment near an inlet and the wave dynamics with Aeolian process triggers their deposit. Slow emergences build and emergence shatters the dunes.

Land forms

The changes in Land use and land Coverage has been studied by the Land sat

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satellite imageries using the RESOURCESAT -1 (IRS-P6) continuity mission to IRS- 1C/ 1D. A comparative study is given in Fig -9. Generally the land use and land cover data of the terrain in the catchment of Chilika is available from Landsat -7 up to 2012-13. It is observed that the Land Sat images are received noisy and there is di-striping of Image beyond 2013 to 2017. So it is difficult for analysis of the data. Noise from the Satellite picture is eliminated radiometric correction (Focal analysis). The identification of data was done as per LULC, 50K, ORISSA, NRSC, ISRO, Thematic Services, Version 2, Vector data, Bhuvan, as per NRSC data dissemination policy (Fig. 7).

The sandy islands exists along the coast from Satapada extends up to 36km towards NE. The barrier spits are of recent formation (500 years). But the associated sand dunes all along the coast are 1300 to 2200 years old and young alluvial plains are paddy cultivated areas (granary) with major plantations are coconut and thickly populated Jhanu trees (Tamarix dioica). The recent alluvial plains are water logged areas have intermittent paddy fields covered with sweet water aquatic plants like Water Hyacinth and Ipomeas and other planktons. The west coast was filled with many phyto-planktons, Nala grass (Local name) and sea grasses augmenting the sedimentation process of the lake. The sandy beaches, islands and barrier spits were covered with mangroves,

Table 2. The type of land use during pre and post interventions in the period 1999-00,2005-06 and 2011-12

Type of land use	1999)	2005	-06	2011-12	
	km ²	%	km ²	%	km ²	%
Total Area	3479.00	100.00	3479.00	100.00	3479.00	100.00
Agricultural Land	1755.24	50.45	1755.24	50.45	1700.87	48.89
Chilika Lake	900.95	25.90	900.95	25.90	894.49	25.71
Forest (all types)	167.78	4.82	168.58	4.85	169.81	4.88
Settlement	289.55	8.32	290.45	8.35	291.62	8.38
Water Body (all)	263.19	7.57	262.59	7.55	269.58	7.75
Others	102.29	2.94	101.19	2.91	152.63	4.39

The land cover in and around the Chilika depends upon the soil characteristics and the salinity of the water of the lake which is further a function of the residence time and decadal summer surface water temperature (SSWT) rise trend is 0.39° C Ralei M O C (2009). The residence time is in maximum 132days in northern sector during summer and 35days in

southern sector in rainy season Mohanty et al (2016). The change in the dimension of the TI, and impact of meteorological extremes in the SMD, the anthropogenic Eco destruction like devastation of mangrove forests, Gherry bundh's, dredging of depleted channels, proliferation of algae/phyto-planktons, ipomeas

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and water hyacinths were the causes for changes in LU/LC of the lake.

The exposed strings of mudflats are abundance with the marine fauna (crabs, fish, algae, polychaetes, molluscs, crustaceans, etc.). The lake lies on the migratory Pala- arctic flyway, sustain regular visit of about 0.7-1.0 million avifauna annually (both migratory and country). Lake ecology refurbished with fish

catch from 1352 MT in 1996 to 14,228 MT in 2012, Irrawaddy dolphin from 70 (2003) to 152 number in 2013, increase in tidal flux 0.36 to 0.52m and decrease in stratification of phytoplanktons, Ipomeas and water Hyacinth. The wet land support live hood to.23 million lake users out of which 45% are native fishermen residing inside the lake. (CDA report 2012-13).



Figure 10. The GIS figures of Chilika Lake and south Mahanadi delta for the year 1987 and 2017

The area taken for study and identification of images and color coding procedures are different for different researchers. The greenness and water spread area are different seasonally and after each meteorological extreme event are also different. Hence the results reported by GIS visuals may vary from the actuals in the fields.

The GIS imagery of 1975and 1999 (preintervention) reveals that , the agricultural land were (34.84%), water body (19.2%), settlement (10.6%) and Forest area (9.3%), land without scrub (4.5%) and the swamp area reduced drastically from 2.65% to 0.24 in the periphery of the lagoon in NW fringe The results were compared with the GIS analysis of the same area in 2012 and the changes are given in Table 5), Ojha et al 2013 (Table 3).

Onam B 2006 reported that the geomorphic features in the SMD around Chilika lake were deltaic plain 238.24 km², Flood plain, levee and ridges 16.22 km², Paleo and abandoned drainage channels 57.92 km2 .buried channels,/Pediment 142.94 km2, Mud flat 483.34 km2, lateritic upland 71.05 km2 and others hills and valleys etc were 9.80 Km². Paul et al. (2014) estimated the geographic features of the South Mahanadi delta has young and recent delta alluvial plains 1963.77 km², Water spread area of lagoon including swamps 884.80 km², Coastal plains 320.67 km², Barrier spit 23.06 Km² and old/recent barrier spit up to Puri is 310.68 Km².

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The analysis of the received imageries bodies has decreased during last 40years shows that the gross agricultural area, water whereas the prominent land use has increased

Table 3. Change in vegetation, water spread area and settlement in study area by the

No	Study area	Year	Agricultural	Area of lagoon	Settlement rural	Reference			
			Area / % of	(water body) /	&Urban /% of				
			total area	% of total area	total area				
			Km ²	Km ²	Km ²				
1	Chilika	1975	879.53/18.18%	1034.1/21.4%	654.77/13.54%	Ojha A., Rout J.,			
	+SMD	1999	910.48/18.81%	1686.1/ 34.3%	1004.3/20.75%	et. al., (2013)			
		2012	887.4/ 18.38%	1257.3/ 26.0%	1097.6/22.74%				
2	Chilika	1999	127.68/ 27%	146.60/ 31%	141.87/03%	Rout J.,2012,8 km			
	area	2013	92.69/ 19.6%	140.92/29.8%	25.064/ 5.3%	from coast line			
3	Puri dist.	1987	Tot area taken	856.94/7.94%	498.87/4.62	Present study(Fig-			
	+Chilika		=10799			10)			
		2004	1755.2/50.45	900.95/25.90%	289.6/ 8.32%	http://bhuvan.nrsc.			
		2011	1700.9/48.89%	894.49/25.71%	291.62/8.38%	gov.in/gis/thematic			
						/index.php#			
		2017	Tot area taken	750.32/6.58%	1052.2/9.57%	Present study(Fig -			
			=10996			10)			
4	Chilika+ca	1987	1302/21.2%	999/16.3%	DNA	Goswami et al.,			
	tchment	2016	1187/19.35%	860/14.02%	DNA	2017			
5	Chilika+ca	2016	1840.9/35.13%			Sk. Majharul Islam			
	tchment					et al., 2009			

present and other authors

by urbanization, swamp area and the reserved and the unreserved forest in the catchment area. Last 25 years the lagoon has decreased its water spread area, agricultural area and swamps at the sacrifice of habitation, sands and shrimp culture, which is the deteriorating factors for the Lake. The land use and land cover of the Chilika Lake and the connected the Mahanadi catchment and Western catchment from the studies of various authors have been studied 200 km2 of the lagoon area in the northern sector is infested with Nalagrass which is of high fibre content (Jaykumar et. al., 2011) The impact of the changes in the barrier spit, TI's and the outer channel configuration has maximum in the peripheral blocks of Puri district i.e. Puri Sadar, Sakhigopal, Krishna Prasad, Brmhagiri, Pipili, Delang and Kanas. Present study has excluded the upper deltaic zone of the south Mahanadi delta and analyzed the TM imagery of the lower SMD and the Chilika lagoon and the results were given in Table 6.

RESULTS & DISCUSSION

After studying the GIS and Land Sat series from Glovis classic (Landsat Series Thematic

mapper -5) of Google of the barrier spit, outer channel, spread of Chilika lagoon the following inferences are drawn:

- 1. Chilika barrier spit is divided into stable towards south and fragile to north.
- 2. Stable barrier spit is continuous and are land connected, least affected by erosion and accretion, wider barrier spits. Sand dunes of the barrier islands are coast perpendicular. The beach length is narrow in the south and wider towards north.
- 3. The unstable barrier spits in north is approachable through the outer channel. The spit geometry is ever changing and the tidal inlets within are nomadic and observed continuous oscillatory propagation to north.
- 4. The swamps in the NW fringe of Nsector of the lagoon is dried up and converting gradually to agricultural land.

The Report of the Fact Finding Committee on Chilika Fisheries Submitted to Orissa High Court on 16.8.1993 depict that the lake Chilika was shrunk by 393km² during 1920 to 1993 (Pattanaik S., 1993). The evolution of this land mass in the central sector on the foot hills of Eastern Ghats hills range mostly converted either as agricultural land or homestead land. Similarly, a large portion of northern sector of the lake is being used either as prawn culture or agriculture. The construction of Gobardhanpur Barrage has stabilized or created an area of ten thousand hectares of marsh to irrigable land. A part of such land is from the swamps and mud flats of the lagoon. (W. R. Dept., Odisha 2014).

The lake has very strong prolific ecosystem that protract the livelihood of more than 0.23 million fishermen and 0.8 million stake holders in the region. Ramble in population are the districts Puri, Khordha and Ganjam in and around Chilika lagoon. But the growth in yield is not synchronous with the hike in population. The people has changed their land use pattern and explored the non-habitable area to habitation. GIS studies reveal that in the local catchment area of the lake, the agricultural land use was trim down from 42.86 to 31.94% to accommodate as home stead land (Both rural and urban), swamp area and shrimp culture area. After hydrological interventions the swamp area and agricultural land has decreased at the cost of human settlement and shrimp culture within the lake.

Results of observations for major sediment flow to the lagoon via the rivers Daya and Bhargavi during monsoon months has been taken for the period both pre and post Naraj barrage period. (Table 3). From data analysis it is found that the rate of flow to the lagoon has improved with regulatory operational procedure of the barrage. But it is found that the % of carriage of silt has increased in River Bhargavi than the river Daya.

As per the AWIFS studies the months under consideration are Jan (Post monsoon), May (pre monsoon) and August (active monsoon) for the period 2004-2012. The corresponding monitoring of NSRC imageries have provided the average water spread area post barrage period is 777.7 Km² excluding swamps, mud flats and raised islands. Similarly the average total area of the lake has been found as 1010.6 sq.km including swamps and mud flats Excluding the spits and sand bars of the coast. The average perimeter of the water spread area of the lake has been evaluated as 458.7 km. Pre barrage and pre Official mouth per the report of Chilika scenario as Development Authority was 790 sq.km, 1045

sq.km for the average water spread area and average lake area. The result obtained can be compared with evaluated results of Gupta et al., (2008) maximum water spread area to be 1020sq.km and minimum in summer to be 704sq.km. The increase in the water spread area was due to the opened active mouth at Dahalabali in front of Sanapatna.

Dredging of TI of lagoons frequently is used for improving the water quality. When it is carried out without prediction modeling and scientific study, can sometimes have negative impact of destruction to benthic habitats and deterioration water quality (Kennish, 2012). Anthropogenic interventions to the natural ecosystem subject to judicious scientific background may affect its habitats and ecosystem. Dredging of Sipakuda TI (2000) after 17 years of excavation is in controversy. The TI has improved the lagoon character, salinity gradient, fishery wealth but could not sustain as a permanent solution to Chilika's health. The dredged TI made the lagoon stable for only 8 years but the fragility character of the barrier spit prevailed after 2008.

The Gherri bundhs the saline or embankments in and around the lake area have obstructed the natural flow. These high lands are the flood plains of the lake, which were absorbing the flood stress. The average perimeter of the lake 458.7 km and 54% of it was protected from natural flow. Consequently, the flow is channelized, the swamps and mud flats in the NE sector are retrieved for agriculture constructing the Gobardhanpur barrage. Gabakund barrage has diverted 50% flow of river Bhargavi to sea at its middle reach. The tail end of the river has dried up, reducing flow. The effect of Gherri Bundhs on the health of the lake needs to be studied.

The Pearson's Chilika bathymetry Chart (1848) indicate the depth of the lake is maximum at the tidal inlet of about 4.5 to 4.88 m, the depth of lake in northern sector was varying from 0.6 to 1.5m, the central sector was having depth 2-3 m whereas the southern sector having depth 2-4 m. The present bathymetry map of the lake prior to hydrologic interventions has shown that the lagoon is depleting. However, hydrological after interventions with flushing flow the lake has retrieved and presently maintaining the status of 150 years back.

In the southern spits where the sand dunes were shore perpendicular, a number of hydrologic shifts were seen, the last shift is near Jahnikuda. These disseminating points are almost symmetrical in nature and moving from south to north. These shifts represent the age of the lagoon. From the land pattern it can be predicted that this hydrologic triple point may shift somewhere near Gabakund in future.

CONCLUSIONS & RECOMMENDATIONS

Keeping pace with the changing climate and weather, the migration of the TI's to north, in the hydraulics and anthropogenic interventions shall invite threat to the lake ecosystem by:

- 1. The Chilika Lagoon exhibit semi cyclic character from choked to restricted. Pre barrage it was choked with single depleted inlet but post barrage period it is now restricted with multiple inlets.
- 2. Tidal inlets migrate northward. Opening of mouths may be associated with storm surges, triggered by solar eclipses, There is retrogression of coast towards sea. The shifting/migration of inlet towards

north assured and the biology have improved than that of two decade past.

- 3. The depleted salinity of the lagoon had improved till 2008 and then onwards started decreasing and the rate of decrease has observed more from 2014.
- 4. Sediment transport to the lagoon through major inflowing rivers Daya and Bhargavi have decreased due to construction of Naraj barrage. The concentration of sediment transport to the lagoon is more in Bhargavi River than the river Daya.
- 5. The AWIFS monitoring of NRSC shows the average minimum water spread area without islands is 777sq.km and the average overall area including swamps and mudflats is 1011sq.km. The minimum and the maximum water spread width during post barrage are 3km and 27km respectively. The coastal length is 66km whereas the outer channel length is 30km. The water spread area and the overall area during pre-monsoon and monsoon period depends upon the spring tides and the amount of input flood respectively of that year.
- 6. The islands in the southern sector and central sector exhibit minimum geomorphic changes after construction of barrage whereas the islands in the outer channel are constantly changing in dimension and are due to shifting of inlet and their flood and Ebb deltas.
- 7. The construction of the Gabakund cut have reduced the flushing flow to the lagoon since it is opened 1987 onward diverting major flow of Bhargavi River directly to sea and depriving the Chilika

lagoon to get its flushing velocity and flow during floods.

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