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The Values and Blue Carbon Ecosystem of the Chilika Lagoon through Ages, India

Siba Prasad Mishra [1], Saswat Kumar Mohapatra [2], Kumar Chandra Sethi [1]

[1]Department of Civil Engineering, Centurion University of Technology & Management, Odisha
[2]SPANDAN, a non-government organization, Odisha
Correspondence for materials should be addressed to SPM (email: 2sibamishra@gmail.com)

Abstract
Chilika, the world's 2nd largest brackish water lagoon of Meghalayan origin had active ports, drains, and dense mangroves that have deteriorated drastically since the 18th century, confronting warm periods, the little ice age (LIA), and oscillating Indian summer monsoon rainfall (ISMR). The present study investigates the systematic unveiling of the cachet of past Chilika by scientific searches, and historical sneezes. The palynological, radiocarbon dating, paleo sediment, and phenology records from various searches and ground realities are correlated. The existing proxies are available in past histories and archeological findings. The remains of vegetation are compared with past mangroves, inland taxa, strand lines, and the tidal Inlet (TIs). They are interrelated with existing Survey of India (SoI) maps of 1930, 1963, and 1983, with GIS maps of 2022 after mosaicking, and georeferencing. The warm and dry periods, weak ISMR, LIA, anthropogenic interventions in the adjoint hydraulic system, regional mean sea level (RMSL) changes, and the strand line shifts, have made the BoB retrogress or transgress and transformed the coastal landform/ vegetation pattern since 1000YBP. The loss of maritime activity, mangrove losses, lagoon characteristics changes, and tidal inlet positioning has affected the lagoon's salinity and ecosystem. The unbalanced sedimentary budget and extreme climates have deteriorated the Lagoon's eco-health leaving today the fishing and tourism uses only. Consequently, lagoon users, especially fisherfolks, are marginalized, socio-politically exploited, and economically retrograded. Sustainable Development Goals (SDGs) 1,2, 8, 13, to 15 must be well attended to augment the flora, fauna, environment, and socio-economic status of the lagoon users.

Keywords: Anthropogenic; Greater-Chilika; Salinity; Tidal inlet; South Mahanadi Delta

Introduction
Asia's largest brackish water body, Chilika ((19° 28'N to 19° 54'N, and 85° 06' E to 85° 39' E), lies on the South Odisha coast. Its shape and size changed under the transgression and retrogression of the adjacent Bay of Bengal (BoB) and lodges next to the South Mahanadi Delta (SMD). Its evolution dates to the pre-Holocene (Greenlandian) period. The coastal water body along the east coast (EC) constantly varies in storage volume (average 4 km3) that flows from inland drains, BoB through Tides, and littoral drift. The lagoon has varying dimensions in the length of 63.4 km, width of 32.2 km(past) to ≈20 km (present), and depth of 4.2 m (floods) to 0.38 m (summer) respectively. (Chakravarty et al., 2008; Mishra, 2015).

Lagoon formation started as a chain of barrier islands by the late Pleistocene sediments [>12K] years before the present (YBP). The gulf transformed into a lagoon due to the retrogradation of BoB during the Roman warm period of the Meghalayan period (4200YBP). It started from the Rambha Hills toe (Eastern Ghats Belt Hills range). Afterward, the spits were interconnected and closed along the coastline forming a canopy by the SMD rivers the Daya and Bhargavi.

There exist two parallel channels emerging from the body of the Lagoon. The outer channel (OC) from the central sector at Magarmunha. The Bhobania Nadi from the northern sector connected to OC at Manikapatna. The Palur channel (about 30km long) is connected to the southern sector and is now depleted. The present 32km long barrier spit OC is hardly 500 -1000YBP. The lagoon is fed from the Mahanadi system through anastomosed drainage channels (D/Cs). They are the Sunamunhi, Kania Nallah (East Kania, South Kania, Bali Nadi, and Boxy Kania's), Chhamu, etc., Fig 1(a), the 2nd order distributaries of the Bhargavi.

Present Flow and Sediment entry

The Chilika has a regular mix and circulation of bay water (waves and tides) and inland flow (52d/cs), mixed both horizontally and vertically. The average sediment entering the lagoon annually is ≈1MMT/annum. The SMD local d/cs and 6-7% of the Mahanadi River flow to the lagoon via the Daya and the Bhargavi. They contribute an average inflow of runoff and sediment of ≈61%, (850Cumec), and 75% of the total annual sediment flowing through Chilika. The local d/cs of SMD are Nuna, Ratnachira, Makara, Sunamunhi, etc. (Fig. 2). The *western catchment* contributes~39% (536Cumec) of flow through drains Salia, Kansari, Kusumi, Janjira, Tarimi, etc. About 90-95% of inland sediments entered were flushed away to the Bay, (Fig. 3), (Chandramohan et al., 1994; Chakrapani, 2005; CDA report, 2012-13; Mishra et al., 2013; Mishra et al., 2015).

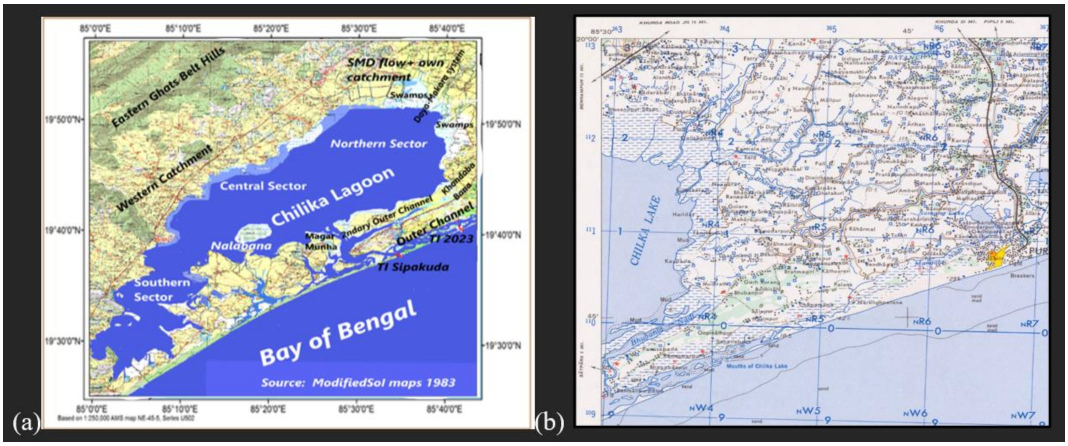


Fig. 1(a). The Index map showing Chilika Lagoon along the South Odisha coast, India (Source: Https//;//ZENODO.ORG/Record for 1" map and the maps 1980 onwards source SoI site); **Fig. 1(b).** The rivers and d/cs draining to the northern sector of the lagoon (SOI-1963 maps)

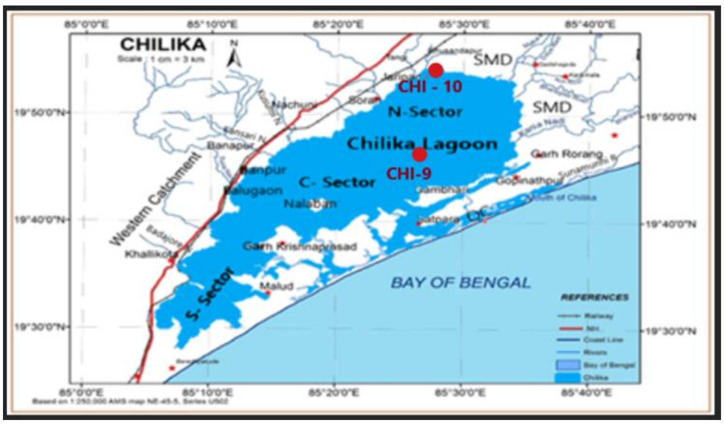


Fig. 2. The drainage system from SMD and its catchment decanting to the Chilika lagoon

Climate

A savanna-type (AW) tropical climate enforces its downpour in the basin through Southwest (SW) (June to Sept) and North East (NE) monsoon (Nov -Dec) with an average rainfall of 1300mm in an average of 73 rainy days. The Lagoon enjoys a maximum temp ~40°C and an optimal minimum of ~14°C. During SW-monsoon the wind velocities range from 5.3 to 16 m/sec, S-ly to SW-ly, and during NE-monsoon the wind speed varies NE-ly with low wind speed, (Sarkar et al., 2012; Tomy et al., 2022). Presently the lagoon area is suffering from late monsoon, erratic rainfall (less in June), anthropogenetic turmoil, and a rise in average day temperature with high humidity.

Present woes and recovery action plans

The Chilika was ranked as the first largest Indian wetland of international importance in 1981 by the Ramsar Convention, providing livelihood of ≈1.5million fisherfolks of ≈132 villages in Puri, Khordha, and Ganjam districts, Odisha in 2012 (CDA report, 2008). The lagoon later ecologically deteriorated due to anthropogenic activities, climate change, sedimentation, and weed proliferation. It was included in the red list in 1991, (CDA report 2011-13). The eco-health was in jeopardy as the average annual aqua catch was depleted from ~8MMT (1985) to 1.5MMT in 1996. The average water spread area was reduced from 1045 km^2 to ~ 800 km^2. The tidal inlet (TI) was shifted to Motto village in the extreme north of OC in 1996. It was about to close, hindering circulation and lowering the salinity. Transformation of the lagoon into a freshwater lake like Koleru Lake in Andhra Pradesh was apprehended, (Mishra et al., 2014 and 2020; Mohanty et al., 2015; CDA Report 2011-13).

To ameliorate the deterioration, after study from various angles, a direct tidal inlet was dredged and opened on 23rd Sept. 2000. To allow a flushing flow of 2830cumec in SMD, the Naraj barrage constructed at the apex of the SMD operated from 2003. Consequently, the salinity/circulation improved, the Motto inlet closed (2004), the ecology was upgraded, and hydrodynamics were sustained improving the lagoon aqua catch. But after 8 years, the dynamics iterated by opening TI at Gabakund on 1st Aug 2008, during a BoB deep depression. The old dynamics such as the northerly shift of TIs, their closing/opening, and eco-health started repeating, (Kankara et al., 2020; Mishra et al., 2021; Mishra, 2022).

Review of literature

The Chilika was initially a gulf, later turned into a lagoon by the creation of barrier spits from the SE fringe of Rambha hills, to begin with by the sediment carried by the sediment of SMD rivers mainly, (Sahu et al., 2014; Mishra et al., 2015; Behera et al., 2023; Acharya et al., 2023). The history and geography of the Chilika and the movement of the tidal inlet to the north are well studied by various authors (Mishra et al., 2014; Sahoo et al., 2016).

The barrier spits started from the south (Rambha Hills), later the water retained in the estuarine low-lying areas is transformed into a sub-bay occupying 1500sqkm by the coastal process of submergence, and emergence (Stevenson, 1958; Phleger, 1969; Mishra, 2022). The sub-bay formed a leaky lagoon and was later converted to a restricted or choked lagoon based on the number of inlets. Sediment activities of geological, hydrological, ecological, and meteorological oceanic processes are the causes of the formation and transformations of such water bodies. About 13% of the coast in the world occupies lagoons ranging from<0.01 km^2 to>10000Km^2 and started forming from fag end of the Pleistocene epoch, (Kjerve et al., 1989; Mahapatra et al., 2013; Mishra et al., 2019; Acharya et al., 2023). The lagoon was part of a Sub- Bay or gulf in a coastal setting before 3.0k years BP westerly bounded by Eastern Ghats Hills, having an area of about 1500sqkm, (Sadakata et al., 1996 and Mishra et al., 2021) (Fig. 1).

The sediment transport by the inland riverine system has been estimated by many researchers globally (Holeman, 1968; Syvitski et al., 2009) and along the East coast of India. (Pradhan et al., 2017; Mishra, 2020). About 90-95% of inland sediment with inland flow joins the northerly offshore drift current, (Syvitski et al., 2009, Chakrapani, 2005; Mishra et al.,2020; Kar et al., 2021). Chilika has a high blue carbon seagrass ecosystem (2.018±0.673 M gC/ha worth ≈ 30.19×10^6 INR assessed in 2020 and should have efficient management climate change bearings, (Bedulli et al., 2020; Kaladharan et al., 2021). The plunging sediment, sewage, pollutants, erosions, geologic deposits, littoral drift, organic putrefaction, and agricultural runoff to the Lagoon favoured the growth of seagrasses and phytoplankton by nonpoint pollution (correlation between BOD and PO_4, (Barik et al., 2018). It is pertinent to know the formation and vegetative history, dynamic behavior, geography, physiognomy, and geomorphology of the lagoon. Chalk out action plans to save the deteriorated lagoon to transform it into a lake.

The objective of the study

The development of mangroves in the creeks and drainage channels of the lagoon must be rejuvenated. The lagoon and its periphery in Puri/Khordha district need to be investigated with anthropogenic transformations. The tidal inlet dynamics and the retrogression or progradation of the BoB coast depend upon changes made by the climate, temperature, regional sea level, and anthropogenic activities. Some ameliorative measures and hydraulic interventions are needed to save the lagoon from its physical, vegetative, and socio-political deterioration.

Little attempt was made to have a conjoint study from all aspects except the Chilika Development Authority (CDA), a Govt. setting. The SOI TOPO maps of 1930, and 1983 and GIS maps of 2022 were compared to assess the real geophysical changes in landforms, and ecosystems. The ground truthing of various landcover and land uses and anthropogenic interventions to the dynamics of the flow system interpreted with the literature findings, being interpreted and correlated with research findings like Pollen studies and carbon dating to establish the research gaps. A solution to the restoration of the deteriorated eco-health of the lagoon needs to consider all aspects.

Methodology

After the formation of the Survey of India (SoI), the Topo Map was available from 1930 onwards on a 1:50000 scale but presents the real field data. The oldest TOPO map is compared with maps created later in 1983 or 2005 with the 1930 Topo Sheets. The change in Land use and land cover are compared and physical changes are ascertained to assess the changes that have occurred from 1930 to 1983. The problem encountered in the availability of small-scale maps and the difficulties in getting the map of Chilika in one sheet. The maps are obtained after mosaicking and georeferencing.

After the availability of GIS images from the satellites has made the task easier to get the maps. From Google, and USGS Earth Explorer the image of the Chilika lagoon and its periphery has been considered and used for shifting of TIs, and their positions along the outer channel are ascribed and compared with previous maps.

Various researchers have worked on the History, geology, sedimentology, hydrodynamics, anthropology, Paleobotany, etc. during various stages and ages of the lagoon. The present proxies and records available are compared to take unanimous planning decisions to rejuvenate the lagoon and give it a sustainable eco-health and a stable earth science system.

Tidal inlets, player to the dynamics

The lagoon has squatted its coastal length from 70km before 1700AD to 64.0km today. The maximum width was from 32km to 20km, the average flood spread area was from 1165sqkm to 1010sqkm, and the minimum water spread area to 800sqkm from 906Km^2 in the year 2012. The average depth was 0.9 to 1.5 meters except at places > 3 meters. The bed of the lagoon at places remains a few meters lower than the average high tide level of BoB. The TIs are shifting north but loiter around the spit in front of Manika Patna. Heavy flood flow and intensified storm surges compel to shift of the TIs centrally loitering around falling points of the Bhobania River, (Fig 2, a, b & c). The TIs in the barrier spit of the lagoon shift north regularly and the closing/opening of TIs at intervals are status quo dependent. A mouth in 1780 was reported to be 1.5 km wide but it was reduced to 750m after forty years. Later it was dredged for the trespassing of boats for navigation and daily fishing activities but later constricted, (Hunter, 1872).

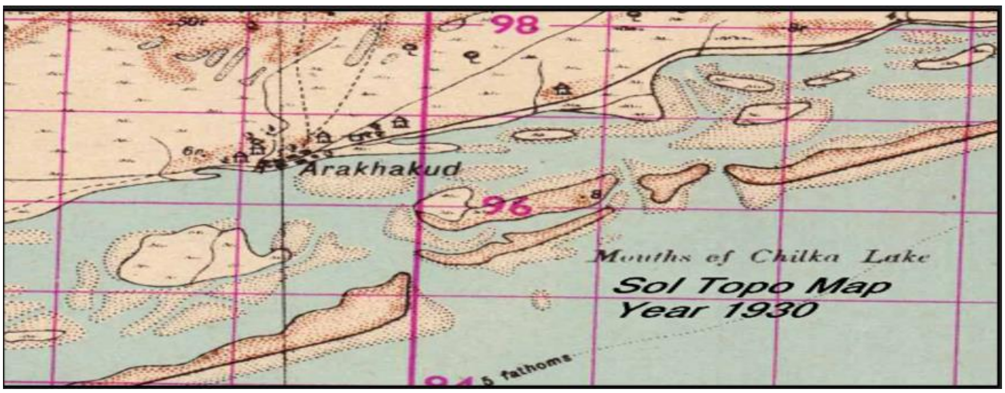


Fig 2(a). Position of the natural mouth of Chilika Lagoon 1930 (at Arakhakuda) (SoI map)

The constriction of the TI towards the fag end of the 20th century hindered the circulation process and affected salinity status and the lagoon's health deteriorated, the fish catch was reduced, the tourism trade degraded, and the eco-health was tarnished. Stakeholders started migrating and marginalizing for livelihood.

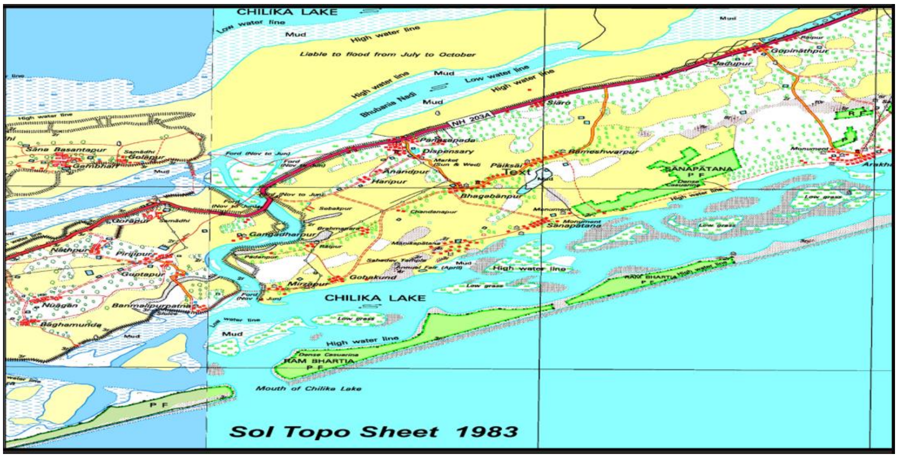


Fig. 2(b). Position of the Tidal inlets of Chilika Lagoon 1983 (at Arakhakuda) (SoI map)

For the refurbishment of the deteriorated ecosystem, the Govt of Odisha dredged a direct mouth at Sipakuda in 2000, a barrage at delta head (Naraj), dredged or renovated all the obstructed channels including the Palur canal connecting Rushikulya estuary. The direct TI of 450m cut was near Sipakuda but widened gradually.

Naturally, the positioning for TIs is oscillating between Manika Patna to Arakhakuda, being Bhobania Channel at the center. From a field study of the barrier spit, it is ascertained during extreme climates, the TIs jump to Hatikhola (Rambhartia) during floods or the village Motto in dry periods.

Fig. 2(c). The Position of Tidal inlets in the OC of Chilika Lagoon near Arakhakuda

Downsized lagoon

Rao et al. (1996) reported that the greater Chilika was extended to 1500 km^2 parts of the Kanas, Satya Badi, and Puri Sadar blocks of the Puri district later squeezed to the present condition. The lake was varying in depth and water spread area seasonally and BoB disturbances. Depth remains 0.3 m to 0.8 m in summer, whereas, the depth rises to 1.8 m to 4.2 m during floods.

Terrestrial Physiognomy Chilika

The Chilika Lagoon has six types of topographic landforms and 3zones. They are a) Daya-Bhargavi alluvium (recent to old); b) Tidal flats, and saline marshes, c) islands and isles with mud flats, iv) mangrove creek and swamps, (v) Area covered by Nala grasses, phytoplankton, ipomoeas/ hyacinths in the outer lagoon, (vi) sand barrier spits, tidal inlets, and dunes, (vii) Water spread area of the lagoon. The three zones are sandy beaches, partly rocky, and the rest mudflats. The southwest coast lies in mountainous ridges are rocky covering Kalijai, Soleri hills, Chadheihaga, etc.; mudflats/swamps in the north and central sector covering Badagotha, Nalabana, Mangalajodi, etc, and sandy beaches are the coastal barrier spit zones.

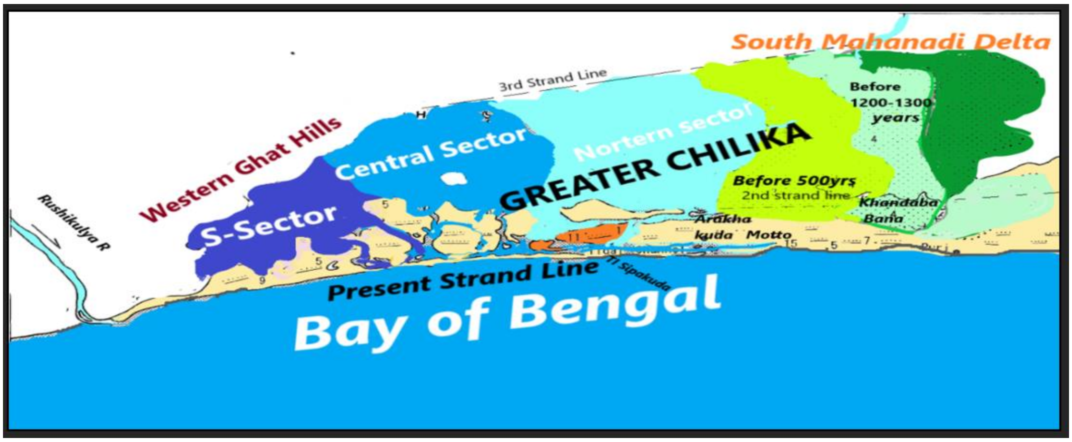


Fig. 3. Dimension of the lagoon through ages (greater Chilika to present status), field studies.

The OC separates the bay from the lagoon representing the inland presently, about 500-1000YBP. The Bhobania R. extends up to Hasimpur, less than OC's length. OC was formed due to the retrogression and transgression of the coast. The pear-shaped lagoon body of the lake has been classified into four ecological sectors, the OC, North, Central, and South sectors based on salinity, circulation, inflow, and depth. The OC is fragile and maintains the salinity of the lagoon through TI's, (Arya et al., 2006). The Lagoon has a local western Catchment of area ~2800 Km2 and a local SMD catchment area of ~1777 km2, (Fig. 3).

Formation of the lagoon

The northern Hemisphere passed through three warm periods from the beginning of the Holocene during 12.81KYBP, (Greenlandian warm period), followed by a strong Indian summer monsoon (ISM) until the end of Northgrippian warm period (8.2KYBP) with some intermittent dry periods. The climate and ISMR have remained constant from the Meghalayan period (4.2kYBP to the present. There were intermittent volcanic activities, warm periods, and the little ice age (LIA) observed from 700 to 250YBP, with a weak ISMR during the 18^{th} and 19^{th} century AD, (NASA) Fig. 4(a).

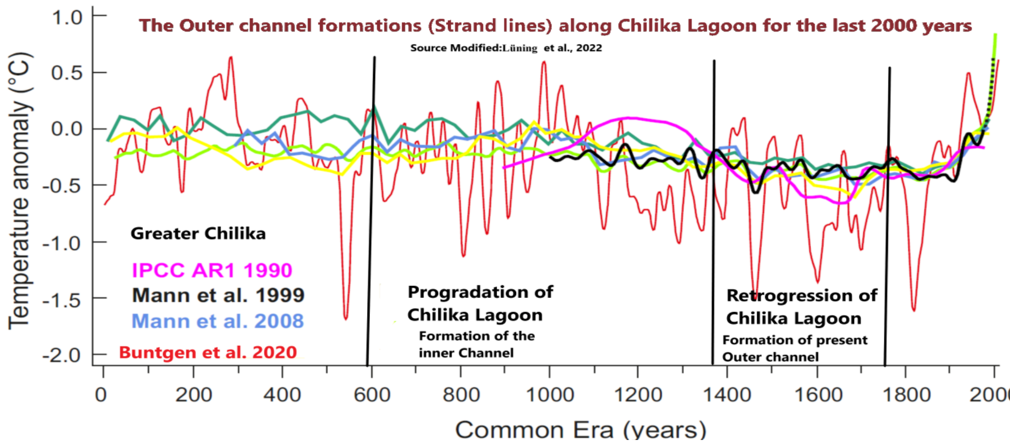


Fig. 4(a). The Temp. anomaly linked with stages of Chilika (Lüning et al., 2021)

The Regional Sea Level Rise

During the Greenlandian Period, the major lagoons along the east coast of India faced two congenital stages. The foremost stage formation was before 12300 years BP (Post-Pleistocene period or Greenlandian interglacial stage) when the Regional Sea Level Rise (RSLR) was 8 ± 2 m above present (Unikrishanan et al., 2006; IPCC 5th AR, 2013; Mishra et al., 2022; Hazra et al., 2022). The second stage is approximately before 5100 years BP, during the Northgrippian period (mid-Holocene) when RSLR is >5m above the present level. Later, During Meghalayan Period the ISMR was very weak during the Holocene climate optimum there was a fall in RSLR to 2-3m (Mann et al., 1999 & 2002; Mishra, 2018; Seikh et al., 2019; Jackson et al., 2023). There was a change in the water level of the lagoon during the Medium Warm Period before the LIA 1000 to 600YBP due to alternate cold/warm, and dry/wet events, (Luning et al., 2022; Mann et al., 1999 and 2008; IPCC CC, 2001; Buntzen et al., 2020) (Fig. 4b).

The increase in inflow (Halosteric) and sea surface temperature (SST) (thermosteric), are the dominant players for the regional sea level rise (RSLR). The Lagoon water level has a rising tendency of thermosteric change of 1.62 ± 0.85 mm/year (from 2004 to 2010), and a Halosteric rising trend of -0.59 ± 0.28 mm/year (Wang et al., 2017, Ghosh et al., 2017). These interim RSL fluctuations (progression and retrogression) were instrumental in the formation and modification of Barrier spit and the positioning of TIs. A shell of Ostrea Virginiana obtained datable to 3750 ± 200 YBP from the southwestern edge of a spit, (Venkat Ratnam, 1970; Pattanaik, 2021; Mishra et al., 2022).

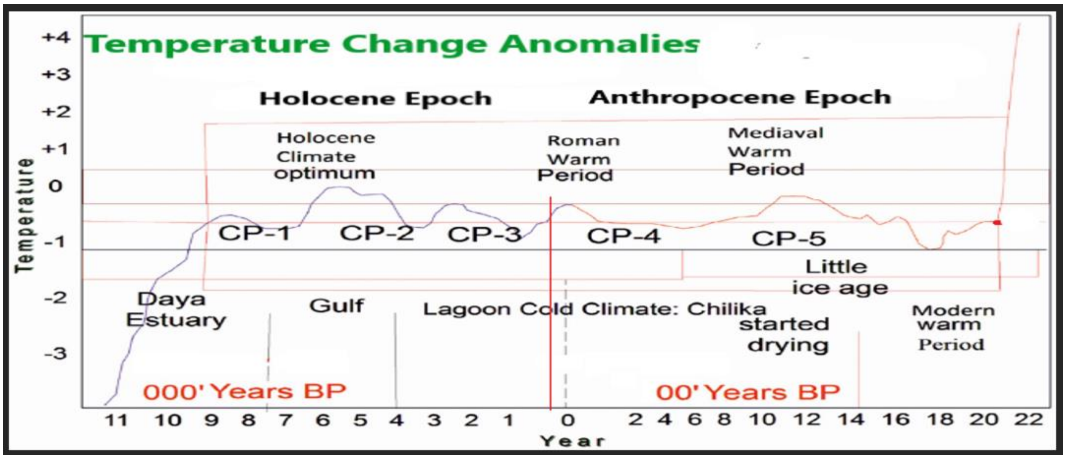


Fig. 4 (b). The etymology of the Chilika Lagoon through the Holocene to present

Lithostratigraphic studies

Various Litho-stratigraphic studies of sediments from the core received identified as CHI to CHI 9 of Chilika Lagoon (Venkat-Ratnam 1970). The Radiocarbon dating, Luminescence, and Palynological studies at various locations of the lagoon by various researchers are in Table 1)

Geography of Chilika Lake

The lagoon is bordered by many zigzag coast perpendicular/parallel active/defunct drainage channels in the north. The rivers of the south Mahanadi delta (SMD) origins such as Buxi-Kania, South Kania, North Kania, Bali-Nai, Chhamu (Now defunct) and Makara, etc., joining a coast parallel river Sunamunhi which is joining the lagoon. They were mangroves dominated due to the temperature anomaly & ISM and mangrove associates mangroves till 1.2-1.0KYBP. The Lagoon accommodates ever-deforming 203 islands/isles depending upon the orientation and positioning of the TIs. The islands and swamps are Parikud, Nuapada, Nalbana, Mangala Jodi, Kalijai, and Chadheihaga, The Chilika is the Daya R. estuarine amphitheater.

ISM intensities with ages

There were strong ISM activities and high intensities of ISMR and higher sediment inflow into Chilika, during the entire Greenlandian period and mid-Northgrippian period (~7.8 ka to ~ 5.1 ka B.P.) from the Mahanadi System. Later during the weakest ISM, Chilika received less ISMR and sediment inflow. Later Chilika got a strong ISMR from about 2 to 1 KYBP (Mishra et al., 2012).

Ancient marine trade and voyages

In ancient days, the connectivity and trading between West and East were mainly through specially built ships (Vessels) before the Vedic age (Greenlandian era, about 8000 YBP). Proxies reveal that ports and harbors along the Chilika coast were used for shipbuilding, ship repairing, or ship shelters during storms and high waves. Ports along the Chilika coast were used for filling food and drinking water for the voyage, jewel stones, and costumes for trade (Mishra et al., 2012).

Table 1. The formation years of various places of the Chilika Lagoon by various studies

SN	Place	Km From Satapada	14C data result in years of BP	Years of Formation	Remarks
1	Luminescence dating (OC) (300-40YBP)	≈3km to 30km	>2.5m depth spit built; ≈40 YBP before	300YBP	Depositional, (Murray et al., 2006)
2	19° 43′ N,85.37°E (Near Satapada)	00	538±5	500years	The inner channel & near NH 203A;
3	Chilika southern sector (Prayagi)	34km	792 ± 2 Ma	spit sand over EGB Hill rock	(Dobemier, 2003)
4	Radiocarbon-dated Holocene sediment (OM & SM study)	Entire Chilika	Strong ISM Greenlandian, 10.4 –9.0 ka; Weak ISM, ≈ 4kMeghalayan;	ISM strong 1.2 to 1.1 KYBP, ITCZ shift from west to east India	In Anthropocene, the ISM was erratic, due to Insolation. (Szczęsny, 2016 and Amir et al., 2021)
5	Golabai Sasan;(enotes. Com / topic/ChilikaLake	Archeological studies	multi-stage boat-building activity	4.3 2.3, 1.6, 0.9 KYBP	Cover Neolithic, Chalcolithic, iron age, Patra, 2015
6	Litho-stratigraphy sediment studies	Sediment core CHI9	0m-36m; 36-100m; 100-700m 700-780m	grey silt; Grey &black; Grey Dark/ light grey	Khandelwal et al., 2008
7	Carbon dating studies	Southern sector	Anthracite formed	3750± 200 years	(Dobemier et al., 2003)
8	Luminescence dating (OC) (300-40YBP)	≈3km to 30km	>2.5m depth spit built ≈40 YBP prior	300YBP	Depositional Spit, (Murray et al., 2006)

OM: Organic matter; ISM: Indian Summer monsoon; OC: organic carbon, KYBP: Thousand years before present

Harbor activities

Archeological explorations at Golabai (20°17′N and 85° 32′ 54″ E), 10kms to the North to the West coast of the lagoon, the bank of the Malaguni River was a place of shipbuilding in three phases Neolithic phase(1600BCE), Chalcolithic (1400 to 900 BCE) and iron age (900 to 800 BCE). Further, the radiocarbon dating of artifacts is datable to 2000 to 2500 years BP (Mahalik, 2004). Archaeological findings talk about the boat-building architecture of Chilika during 4200YBP in the Greater Chilika (Patra et al., 1993).

Several ports existed at Ganja, Kantiagarh, Palur, Prayagi, Manikapatna, Sanapatna, Badapatna, Arakhkuda, Banjiapatna, Boitkud, and Khal kata Patna (Kush Bhadra R. mouth), are the harbors, on the Puri coast during the 16th century, (Tripathy, 2007), Fig 6(a). Previously the ports were inaccessible due to dense mangroves, later it was degraded/exterminated and replaced by saltpans, grasses, sedges, amaranth, and inland taxa giving the port easy accessibility that enhanced port activities. (The Orissa of the ancients: Full text of Orissa, British Library) Fig. 6(b).

The administration

The southern region of Chilika Lagoon was famous for its glorious maritime trade during Kharavela, the king of Kalinga, (209BC to 170BC). The lagoon, part of Kalinga Jana Pada (c. 1100 – 200BCE) was ruled by the Orissa Kings, and Britishers under Madras Presidency, before independence until the medieval period (1435-1576AD) by Gajapati, Bhoi, and Chalukya dynasty. The Moghuls (1576 to 1751AD), Marathas (1751-1803AD), and later Britishers (1804 to 1947AD) ruled over the people of the lagoon area.

Table 2. Chilika Lagoon and BoB, and maritime trade activities years before present (YBP)

(YBP)	source	Statement	Proxies/ History/Legends	Source
4300 to 2900 YBP (3 phases)	Archeologic excavations	Boatbuilding & repair (famous)	Golabai Sasan; Neolithic, Chalcolithic, & Iron Age	(Patra, 1992-93)
2300 YBP	Copper covered boats	Boat building & repairing	Large, Fast moving, well-protected, technic	(Mohanty, 2011)
3500-3200 YBP	Rig-Veda (literature)	Jatakas, & Greek, Roman literature	Pakura, Paloura (Palur) within Chilika Lake	(Mahalick, 2004)
2130 to 2150 YBP	Cenkuttuvan; AP literature	Gupta period Chilika -Gajbahu I Srilanka)	The sea voyage from Tamluk (West Bengal) to Amra- panini (Ceylon)	(Mahalick 2004)
2339 to 2320 YBP	Chanakya in "Arthsastra"	Mauryan dynasty	Maritime trade through Chilika	(Britannica 2023)
2230 BCE–after 2193 BCE	Lord of the Sea (Mahodhipati)	Kharavela; Maha-meghavahana	Chilika; a major harbor for maritime & trade	(Ghadei, 2009)
1500YBP; Post Gupta period	Manjusri Mulakalpa	Sanskrit text "Mahajan"	Bay of Bengal as "Kalingadresu	(Tripati, 2008)
1000YBP; Post	Brahmananda Puran	Maritime events and trading via Chilika	Voyages to Java, Rome, China, Malaya, Ceylon, the Indonesia islands	(Tripathy,2007)
1727 and 1736	In Novel and poems	Nilasaila" & "Niladribije,	Lord Jagannath shifted to an Island Gurubai	(CDA report, 2008)
480 to 75YBP	Bhoja dynasty Golabai, the harbor	Madalapanji; the chronicle of Lord Jagannath	Constructed Boita's and the construction ethics found in Juktikalpataru	(Abhilash, 2021)

Fishing rights

The British settlement, Odisha - 1897-98 report about the fishery rights of the Chilika fishermen community but under to be enjoyed by Zamindari estates Khallikote, Parikud, Mirza Taher Baig, Suna Bibi, and the Chaudhary families of Bhingarpur and the Khas mahal of Khordha on a lease basis to the local fisherfolk. The Britisher constituted 25 Primary Fishermen Cooperatives (1926-1953). The prawn culture and brackish water fishing in the Chilika became lucrative. The Tata entered the fishing arena. The leasing system collapsed in 1991 when PWD tendering and auction procedures were introduced. On challenge, the honorable High Court (HC), Odisha, directed the Government (GoO) to formulate a rule that would safeguard the interests of traditional fisherfolk. The order remained dormant till 1993. Chaos/protests built up and the outcrop was the Soran riot. To date, the GoO issued a notification banning the lease of Chilika for prawn culture.

Confronting Extreme Events Chilika Lagoon

Climate change is so imposing that in the last two decades, at least 10 intensive and devastating cyclonic storms slam or pass very close to the Chilika domain as a hotbed. These cyclonic storms are of category SCS (Severe cyclonic storms), Very Severe cyclonic storm (VSCS), Extreme SCS, and Supper cyclonic storms like category-4 in 1999, Philine, Hudhud, Titili, Phani slammed in and around the Chilika coast and many passed in the vicinity of the coastal reach like Amphan, and

Yaas, etc. Chilika faced two dry phases i.e., 1995 to 1999 and 2014-2017. Each storm slamming Chilika causes devastation to its stakeholder, ecosystem, flora, fauna, and avifauna.

a b c d

Fig. 5(a) Ancient wells of earthen ring wall at Manikapatna **Fig. 5(b)** 20th-century Berhampura mangrove plants: **Fig. 5(c)** 13th-century Bhabakundaleswar Temple, Manikapatna; **Fig. 5(d)** The stone anchor worshiped as "Siva" at Ramachandrapur hills near Kusumi R.

Fig. 6(a). Boat Building, & stone anchor; **Fig. 6(b).** Mangroves at Manikapatna (22.08.2008)

Avifauna

Chilika Lagoon is housed in the Palearctic path of the migratory avifauna and transforms into a hub in the winter season. About 1.13 mi avifauna of 184 various species are housed in the 1100 km2 of the lagoon Chilika Lagoon as of December $4^{th,}$ 2022 (1.09 mi guest birds of 105 varieties and 0.4 mi native birds of 79 various species (Down to earth, dt. 05.01.2023). Many birds have permanently settled in the outskirt swamps and water bodies in the periphery of the lagoon for safe habitation, enough food, and a favorable climate. Special species like Dalmatian, Pelican, Gadwall, and Northern Pintail contributed the most to the surge, followed by Eurasian Wigeon, Northern Shoveler, Tufted Ducks, and Red Crested Pochard, are housing in Chilika, concentrated in Nalbana, and Mangala Jodi bird sanctuaries.

Tourism

Travel is the legal right of each human. Kalinga, (Udra or Utkal) was a maritime state in the Indian subcontinent rightly named Kalinga as "Lords of the Sea" by the great poet Kalidas in his epic "Raghuvanshi". The ports were dead during the little ice age. Later from the 17th century, the lake was used for fishing and thoroughfare from land to sea. In 1956, after the implementation of the "tourism acts", the lagoon started overcrowding with tourists from the domestic and foreign front from tourists coming to Puri, Bhubaneswar, and Gopalpur are tempted to visit the Chilika.

Fig 7(a): The rocky coast in the south (foot of Soleri hills); Fig 7(b): the northern swamps & muds Arakhakuda Fig 7(c): The Drainage system joining from the Northern fringe, Fig 7(d): The nursery for mangrove plantations at Arakhakuda, Chilika.

Mangroves, the blue carbon ecosystem

Mangroves are bio-indicators. For the survival of mangroves, essentialities are coastal environment, creeks, backwater ingression and regression, clayey sand, and the least anthropogenic interventions. The Mangrove colonies were sporadically widespread but inconsistent all through the east coast of India. Mangroves and some mangrove associates like *Avicennia* sp., *Acanthus ilicifolius*, and *Excoecaria agallocha* of the tropics are seen in the sea-river interaction zone.

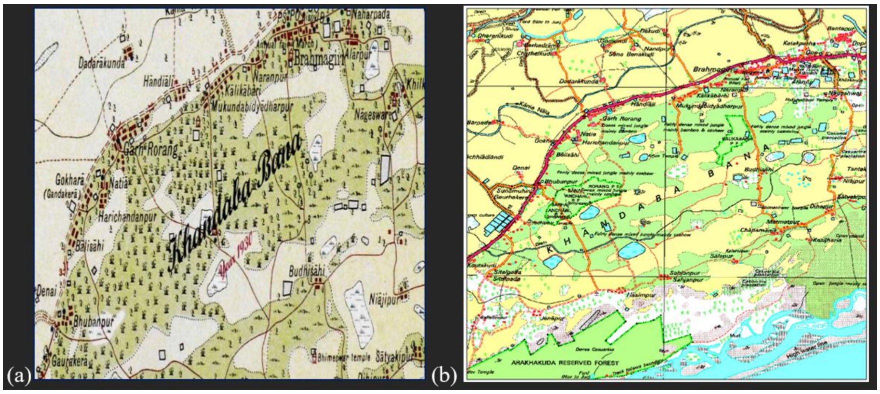


Fig 7. (a). Thick Mangrove and associates in the NW corner of Chilika (SoI Topo, 1930); **Fig 7. (b).** Thick Mangrove and its associates in the NW corner of Chilika (SoI Topo, 1983)

Out of six categories of mangroves in India, the mangroves in and around the Chilika Lagoon are deltaic and estuarine mangroves. The distributed species of mangroves and associates found in the Mahanadi Delta (Chilika area) are different from mangroves found in the adjacent Brahmani Baitarani Delta, Sundarbans of WB, and northern Odisha (Balasore) (Sarkar et al., 2012).

Fig. 7(c). Khandababana from Hara Chandi (2023); **7(d).** Backwater in tides Sunamunhi R. (2023)

The Chilika has been transformed from 300YBP to 2000YBP due to Post Holocene, and Anthropocene warm periods. The lacustrine system had fewer mangroves, more inland taxa, more sedimentation, continuous downsizing, the least maritime activity, and nonstop deterioration of eco-health. From 1000YBP to 1700YBP, the mangroves were in a flourished state during BoB regression. Later the dense mangroves became sparse and disappeared.

The Chilika was crowded with ships, merchants, and merchandise up to the mid-Meghalayan period from post Greenlandian period, the ISM was strong, there was Chilika Gulf gradually gave rise to the chain of dunes and the shallow sweet water estuary started converting to a saline pool at the maximum water level named greater Chilika. The levees of creeks, d/cs were full of backwater and were fully covered by dense core mangroves and their associates. Until post-Pleistocene, the greater-Chilika, a vast estuarine area ranging from Brahma Giri, Kanas up to the Rushikulya R.

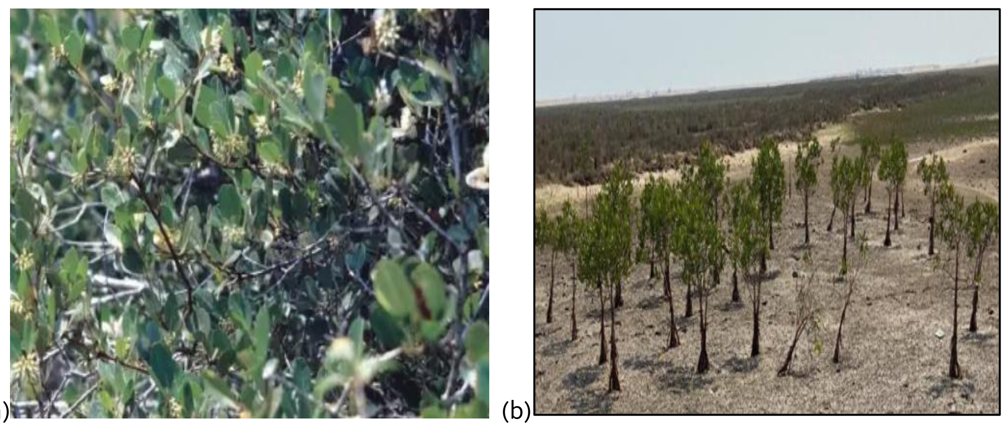
(a)  (b)

Fig. 8(a). The luxuriant mangroves on the Kush Bhadra River coast **Fig. 8(b).** The degraded mangrove plants Chilika

The mangroves were sporadically widespread until the last millennium but peripheral mangroves along with hinterland/ubiquitous taxa, are found within 2-3km of hinterland close to the coast. Development of a blue carbon ecosystem was attempted by GoO through CDA (Manika Patna), and ICZM projects (Arakhakuda) for 94.12ha to develop core mangroves but it is observed that the growth rate is low (only ≈10ha) and the plantation becomes rarely encouraging. But it is found that the Khandababana is in the northern corner close to the Hara Chandi temple and found a green corridor of hinterland taxa, sparse availability of core mangroves, (Fig 7 (a-d)).

Table 3. Mangrove history in and around Chilika in KYBP (Asha Khandelwal, 2008)

Area (sector)	Depth (m)/ Formation	Mangrove present	Status of flora	Inference of geo-bio-Hydro status
CHI-9 Heart of Lake, C-sector	7.8m; 13KYBP	13KYBP	freshwater Taxa; start of brackish water conditions	Low land; Estuary of the Daya R.
	Tarantian period of	4.5KYBP	Mixed Mangrove & its associates	ISM strong, late Northgrippian period
	Pleistocene	3.0KYBP	Proliferation of mangroves	Early Meghalayan, lagoon transformed
		2.5KYBP	Mangroves sullied; overruled by Mangrove-associates, freshwater taxa	Greater Chilika downsized, Mud and mud flats in N- Sect
Rambha, S-sec, EGB hills	4.3m; 3.47 KYBP	3.5-3.0KYBP	For 500yrs core mangroves flourished &dominated	Early Meghalayan period; ISM weaken
		3.0-2.1	mangroves Core degraded & periphery flourished	Spit in the southern sector was stable
		2.1-1.7	Mangroves and associates inland taxa overcame	Mid-Meghalayan period; ISM weaker
		1.7-1.4	Salt-tolerant inland forests prevailed	Weak ISM; start of LIA; Chilika drying
Huma salt pans formed		1.4-0.7	Mangrove Forests lost; Low land high wave marooned swamps formed	Medieval warm period, ISM weak; present condition;
Balugaon (S-Sector)	5.5m	3.13-1.93	Core mangroves/associates flourished than dominated	Medieval Warm Period, ISM weak
		1.93-1.13	Core mangroves degrade; M-associates developed	LIA period, Odisha maritime at the apex
		1.13-Present	Mangrove lost; Associates more with inland taxa	LIA & modern warm Period, OC formed
Bhobania R. (N-Sector)	4.85m	3.0-2.4 KYBP	Mangroves Flourished; filled estuary swamps	Meghalayan period; ISM moderate
		2.4-2.0	Core mangroves declined,	Lagoon cold climate
		2.0-1.4	Core mangroves lost replaced by M-Associates	Naval trade peak, Path to enter Chilika
		1.4 - Present	Mangroves & associates are sparse in Khandababana	Sea trade failed; TIs & lagoon shallowed
Solari &Chandra pur (S-Sector)	3.0m/ 2.0KYBP	2.0-1.5KYBP	Core and outskirt mangroves dominated	Roman warm period, weak ISM, Saline
		1.5-1.0 KYBP	(a) Solari: Core mangroves failed & infringe sustained	Little Ice Age; modern warm period
			(b) Chandrapur: Mangroves decline; Inland taxa sustained	The lagoon was in full oceanic activity
		1.0 to present	Solari: mangroves sparse Chandrapur-mangrove lost.	Huma salt pan increase as at present

The mangroves that are sparsely available in and around Chilika are *Officinalis* L. of group Avicenniaceae, *Rhizophora apiculate*, of family Rhizophoraceae, and *Excoecaria agallocha*, etc. The mangroves associates found in Chilika and its periphery are Cocos, Pandanlls, Borasslls, Palmae, Cerhera, Terminalia, etc. and *Fabaceae cressa cretica*, *Excoecaria agallocha*, *Acanthus ilicifolius*, *Derris indica*, etc. but sporadically dispersed indicating the past existence of mangroves. The area covered by mangroves at Arakhakuda, Puri is 94.12ha as per Mangroves planted in Chilika's periphery, (Published TOI, Ramnath R.V., TNN news on 21.01.2015, and Gupta et al., 1999).

The mangrove growth flourished between ≈4150 YBP and ≈2550 YBP in the Chilika area, indicating warm, strong ISMR and humid climatic Meghalayan settings. After 2550YBP, the mangroves re-flourished and persisted for three centuries as the Regional Sea Level was stable with an almost fixed strand line. Later gradually mangroves were degraded and replaced by mangrove associates and midland Taxa (Pandey et al., 2014).

Aquafauna Chilika Lake

The lake also had a rich fishery resource for the lagoon users. The sweet water fishes are found in the northern sector, brackish water fishes in the central and southern sectors, and a combination of marine/brackish water fishes in the central sector and the outer channel. The enumeration with identification of aquafauna was 138 species in 1918 (Jones et al., 1954[1]) which has been increased to 336 species (261 fin-fish + 28 prawns + 34 crabs) in 2008 (Sarkar et al., 2012, and Suresh et al., 2018), which has been reduced to 317 species in Feb. 2023 (Fish Species in Chilika Lake/Lagoon). These species comprise 207 genera, 88 numbers of families, and 23 orders. Two of them are endemic, Gobiidae, and exotic cichlid species (*Oreochromis mossambicus*), (Burma et al., 2023). The threatened species found in the lagoon are Ten Pounder, Milk-fish, and Bream. For the years 2017, and 2018) 16657.28 MT of fish landed which was about an 18.4% rise in comparison to the year 2016 (14,067.5MT) as per CDA health card 2017 and 2018.

Faunal diversity

Fishing Cats (Vulnerable), dugong (Vulnerable), Eurasian Otters (Vulnerable), Irrawaddy dolphin (Endangered), green sea turtle (Endangered), blackbuck (Near Threatened), Spoon-billed sandpiper (Critically endangered), Chilika limbless skink (Critically endangered) and 24 mammalians, 37 reptiles, and amphibians are in the red list of International Union for Conservation of Nature (IUCN). The population of Dolphins (Irrawaddy, Striped, Humpback, Spinner, Bottlenose, and Finless) has improved. It was 544 in 2021 which increased to 726 in 2022. The Irrawaddy Dolphins have reduced from 162 in 2021 to 151 in 2022 but they are endangered species as per IUCN, as per Chilika Lake Odisha, 2023 updated Government of Odisha (GoO).

Geology

The domain of Chilika Lagoon was originally attached to the EGB-Rayner block during Rodania assembly isolated, later moved southward, and collided with the Western Australia plate. This region is supplemented by the presence of sub-horizontal stretching of lineation, prominent lineament pattern, distribution of Mesozoic faults along and off the Mahanadi delta, and the existence of two opposite sets of sheer fabrics found in the domain. (Chatterjee, 2008 and Bose et al., 2016).

Discussion

The 2.5m height barrier spit of the outer channel from various studies reveals the top layer and bottom layer formation were about 60 to 350 YBP, (Murray et al., 2006; Mishra et al., 2019). The lagoon is deteriorating drastically since the 18th century, confronting three warm periods, the little ice age (LIA), and oscillating Indian summer monsoon rainfall (ISMR). (~8.2 to ~ 4.2KYBP; ~4.2 to ~1.20KYBP; ~1.2 to ~ present KYBP). Inland sediment influx and siltation was the cause of lost navigation history and past mangrove in and around Chilika (Mishra et al., 2017).

Implementation of the SDGs, agenda 2030 in 2030 due to the pandemic COVID 19 has lagged far back to rank 120 out of 192 adhering nations by 2022. The social sector SDG 1, SDG 2, and SDG 6, the environmental sector SDG 13 to SDG 15, and the economic sector SDG 8 should be given more importance for reducing poverty and hunger, addressing climate change by mangrove plantation to combat extreme events from the land and oceanic end, and finally enhance livelihood resources for the flora, fauna, and stakeholders depending upon the lagoon Chilika.

The navigation and port activities have ceased for the last 400 years BP. The present shallow OC formation is contemporary to the LIA that depleted the TIs and made the lagoon shallow. Human activities intervened in the lagoon and its feeder basins/channels until 1850, like many hydraulic structures in the upper basins, the 6-lane roads (NH-216), the denudation of peripheral hills, quarrying activity, industrialization, and urbanization. The eco-health of the lagoon has deteriorated by weed proliferation, sedimentation, tourism activities, and over-exploitation of the resources in and around the lagoon (Mishra, 2019).

The deteriorated ecosystem was rejuvenated by noticeable circulation, and salinity as the result of the dredged mouth opened at Sipakuda on 23rd Sept 2000. The rising salinity, reduction of phytoplankton cover, increase in migratory birds, and aqua catch (1.5MMT to 16MMT) are observed. The TI near Motto village finally closed in 2004 due to the operation of Naraj. The shift of official TI was an average rate of shift 240m/ year to the northern direction was observed. In 2008, a new mouth was opened at Gaba Kund as an impact of a deep depression in BoB on 8th August. But during the last 50 years, Mirzapur TI's opening is exceptional. Later the tidal inlets shifted north opening/closing of TIs during Bay disturbances became regular. At present the lagoon has three mouths in a cluster at Arakhakuda proving the northern shift. The reconstruction of the South Mahanadi Delta and anthropogenic intervention is adding to the sedimentation and downsizing of the lagoon, (Mishra et al., 2015).

There is an increase in guest birds and Irrawaddy dolphins from 2019 onward due to COVID-19 disasters, restricted poaching, restricted eco-societal movement, zero political chaos and warfare between Russia and Ukraine, innovative ecotourism development, and resources improvisation for its unique ecosystem. But Anthropogenic interventions in the hydraulic system within the basin, and discharge of terrigenous sediments, eutrophication, and IAS species infestation have deteriorated its eco-health. The judicious management of the Naraj Barrage at the apex of the delta provides 2830Cumec flood flow in the Kuakhai system, at regular intervals to maintain the flushing flow to the lagoon, brushing off the aquatic weeds, and barring the sedimentation of the lagoon.

To sustain the life of the lagoon for a long period, there should have an attempt for the catchment treatment plan, forestation, closing of all Prawn Gherries, encouraging public awareness, and least liquid sewage disposal from urban areas must be banned by rule. Monitoring the water quality and applying green technology to sustain the lagoon. The blue carbon system (Mangroves) must be encouraged to reduce CO_2 in the area to save the ecosystem.

Indian summer monsoon (ISM) was strong and active. Global climate variability in and around the Chilika Lagoon areas studied emphasize the presence of mangrove taxes in a backwater estuarine environment during the Northgrippian to Meghalayan period (~7.8ka and 4.2 ka BP) during the Holocene Epoch. This indicates the dominance of C3 vegetation (Crop plantations), suggesting a warm climate, strong ISM, and setting cropping pattern changes (Sangvi et al., 2010). The socioeconomic impact on the marginalized and migrated stakeholders due to hydraulic interventions over the last two decades including the major fisherfolk.

Conclusion

The Chilika lagoon is trailing its character, rich ecosystem, and panoramic views due to the hydrologic/anthropogenic interventions within and its associated South Mahanadi Delta (SMD) since the end of the Little Ice Age (17^{th} century). Earlier Chilika was deep enough for use as a harbor and had appropriate outlets for plying of vessels. Siltation of Chilika and shallowing of spits due to littoral drift, and depletion of mouth could not maintain the hydraulic regime as was during the greater Chilika period. Weak successors of the local kings, weak economy and invasion of neighboring states have also reduced maritime activities of the lake onwards. Combining history, legends, mythology, geography, anthropology and geomorphology, it is inferred that the age-old large semi-marine lagoon may convert to a shallow freshwater body in the future. It may mingle with fast-growing urbanization and industrialization. Our progeny shall read about the lake in their text as swamps like Samanga, Tampara Lake, and Sar Lake exist nearby or Koleru lagoon in Andhra Pradesh. It is high time to protect its environment by beach nourishing, proper hydrologic, and hydraulic management, and raising public awareness to protect the natural paradise for the future.

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SPM, SKM and KCS conceived the concept, wrote and approved the manuscript.

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