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Environmental aspects and their effects on blackish water lagoon management and ecosystem sustainability: A case study of Chilika Lagoon, India

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Abstract

The geomorphology, hydrodynamics, and ecological balance of blackish water lagoons are significantly shaped by environmental factors like wave action, tidal currents, longshore drift, and relative sea level rise. These factors also have a direct impact on the management and long-term sustainability of these lagoons. This study looks at shoreline dynamics and related environmental effects in the Chilika Lagoon in India as a representative case. Natural episodic events like waves, tides, currents, and global sea level rise are all responsible for the Chilika Lagoon's dynamic coastal environment's constant reshaping. This study specifically examines shoreline lateral displacement, recognising that volumetric sediment changes are not captured by this method. Because of the high-energy interactions between wave action, tidal currents, and longshore drift along the coastal front, lateral movement of the shoreline can result in either accretion or erosion. This study evaluates the shoreline configuration changes of Chilika Lagoon and surrounding coastal areas over a 42-year period using the Digital Shoreline Analysis System (DSAS) of the U.S. Geological Survey. The analysis shows that, with some notable exceptions in certain depositional zones like Palibandha, the western flank of the new mouth inlet, the section from the old mouth to Harchandi Temple, and the stretch from Pentukota to Konark beach, the majority of the region shows net erosional trends. Shoreline retreat can reach 40.29 meters in the northeastern lagoon sector, which is closest to the present new mouth and shows the highest rates of erosion. A secondary line of barrier bars is now visible due to the frontal barrier spit breaching, which is the cause of this erosion. At the Rushikulya River's mouth, a comparable erosional pattern is visible. However, with a maximum advancement of 11.69 meters, the western side of the new mouth inlet exhibits notable accretion. The dynamic behaviors of the lagoonal inlets affects these morphological changes, with longshore drift and wave energy concentration becoming more dominant due to the Rushikulya River's reduced sediment supply. The foreshores of the Chilika Sand Spits and the Puri township coast exhibit moderate shoreline changes. These are mostly caused by high water levels during the monsoon season and wave breakers created by seasonal winds. Coastal retreat and sediment loss have been made worse by the lack of notable post-event recovery after the effects of cyclones Phailin and Hudhud. Gornitz et al. (1994) developed the Coastal Vulnerability Index (CVI) method to measure coastal vulnerability. This method incorporates a number of factors, such as shoreline change rate, mean tidal range, mean wave height, slope, relative sea level rise, and coastal geomorphology. Relative sea level rise stands out as the most important factor influencing vulnerability among these. A relative sea level rise of roughly 0.77 mm/year is indicated by data from the Paradip station (NOAA-PSMSL, 2015). The study area's CVI values, which are based on these parameters, show notable spatial variability in coastal risk throughout the Chilika region, ranging from 2.64 (very low vulnerability) to 21.45 (high vulnerability).

Keywords: Geomorphic changes; Episodic events; Shoreline; Coastal vulnerability; Accretion; Lagoon management; Ecosystem sustainability; Digital Shoreline Analysis System (DSAS); Coastal Vulnerability Index (CVI)

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1. Introduction

Worldwide, coastal lagoons are important ecosystems for both ecology and economy, especially those with blackish water that combine freshwater and marine influences (Patra et al., 2021; Kjerfve et al., 2020). According to Liu et al. (2023), their unique hydrological and biogeochemical processes support fisheries, maintain rich biodiversity, and deliver essential ecosystem services like nutrient cycling and carbon sequestration. These lagoons' ecological integrity and sustainable management are threatened by a number of environmental stressors, such as pollution, sedimentation, climate change, and hydrological changes (Smith et al., 2022; Zhao et al., 2024). Such vulnerability is best illustrated by Chilika Lagoon, the largest brackish water lagoon in India and the second largest in Asia. Its intricate hydrodynamics are influenced by seasonal freshwater inflows, tidal exchanges via numerous inlets, and human activities such as dredging and land use changes. It is located along the east coast of Odisha (Dash & Sahu, 2023). These elements have an impact on biological productivity, sediment transport, and water quality, which in turn affects the ecological balance of the lagoon and the livelihoods it sustains (Mishra et al., 2022). Water exchange between the lagoon and the sea is essential for controlling salinity, sedimentation, macrophyte growth, and the recruitment of marine species—all of which influence biological changes and fisheries productivity, according to research conducted over the years. Fishery yields and biodiversity declined as a result of the silting and shifting of Chilika's inlet in the 1980s and 1990s. A new inlet was opened in September 2000 to combat this, and as a result, the area's biodiversity has improved, fish catches have increased, weed infestation has decreased, seagrass has recovered, and dolphin and migratory bird populations have increased. Notwithstanding these encouraging developments, stakeholders continue to voice ecological worries and socioeconomic difficulties that could worsen in the absence of efficient management. Lagoon sustainability is ensured by integrated management strategies that strike a balance between socioeconomic development and environmental conservation, according to recent studies (Kumar et al., 2023). Developing adaptive management strategies requires a better grasp of the interactions between environmental factors, including sediment dynamics, nutrient inputs, and salinity gradients. There are still gaps in assessing the effectiveness of management interventions in blackish water lagoon systems like Chilika and connecting environmental changes to ecosystem responses (Rao et al., 2024). Since the early 20th century, researchers from a variety of fields have studied this lake's water quality, plankton, benthos, fish and fisheries, including aquaculture, and the nesting habits of resident and migratory birds, reptiles, and mammals. A wealth of literature about many facets of the lake had been amassed as a result of decades of research. The scientific data that is now available (Jhingran 1969; Mohanty 1988; Biswas 1995; Ghosh and Pattnaik 2005) shows that the lake's ecology has changed over time, especially in the 1980s and 1990s, due to anthropogenic activities like overfishing, land reclamation, gheri culture (pen culture), pollution dumping, and changes in local oceanographic processes. Climate change has also caused floods and droughts in the lake's catchment basin. The loss of biodiversity brought about by environmental deterioration has had an impact on people's socioeconomic and cultural well-being. During the Ramsar Convention in1981, the lake was named a "Ramsar site," or a wetland of international significance. In 1993, it was included to the Montreux records, which list wetlands that are in danger. The siltation of the lake basin and the outer channel, the limited circulation of seawater between the lake and the sea, eutrophication, weed infestation, and a decrease in the recruitment of fish and crustacean larvae from the sea end were the main environmental changes that were of concern. Pollution from household, industrial, agricultural, and aquaculture wastes, overfishing, watershed mismanagement that favors excessive sediment inputs, land reclamation for agriculture, aquaculture, and human settlement, deforestation in the catchment area, unplanned tourism, and fisheries conflict have all made environmental issues worse. As evidenced by the obvious loss of biodiversity, the lake's ecology has in fact substantially worsened (Ghosh and Pattnaik 2005). The production of fish and shellfish decreased from 8669 MT in 1985–86 to 1274 MT in 1995–96 (CDA, 2011). In light of this, the Chilka Development Authority (CDA) was established in 1991 by the Department of Forest and Environment, Government of Odisha, to address the lake's problems and restore it through appropriate management practices.

Chilika Lagoon, located on the east coast of India, is Asia's largest brackish water lagoon and the second largest globally (Mohanty & Otta, 2008; Balachandran, 2006). Its ecological importance stems from rich biodiversity and critical habitats for migratory birds and aquatic species (Madhusmita, 2012). It was designated India’s first Ramsar site in 1981 due to its international ecological significance (Ramsar, 2014). Recent studies highlight a surge in nutrient loading from agricultural runoff, sedimentation, and eutrophication (Ghosh et al., 2006; Ghosh et al., 2023), resulting in shifts in primary productivity and trophic dynamics (Dash et al., 2022). Furthermore, remote sensing data reveals increased turbidity and habitat fragmentation (Mishra et al., 2020; Sahoo et al., 2021). However, interventions such as the artificial inlet (2001) and community-based conservation under the Chilika Development Authority (CDA) have improved salinity exchange and fisheries recovery (Ghosh & Pattnaik, 2005). Recent policy-driven ecosystem restoration, supported by CDA, ICZMP, and Ramsar, emphasizes integrated lagoon management, biodiversity conservation, and alternative livelihoods (ICZMP-Odisha, 2014; Ghosh et al., 2023). Continued real-time monitoring and stakeholder participation remain key to ensuring Chilika’s ecological and socio-economic resilience in the face of climate change and anthropogenic stress.

The review of the above literature on Chilika Lagoon highlighted the following observation on different environmental issues:

- The water quality of the lagoon studied by many researchers for its biological and chemical significance.
- The physiographic conditions of the lagoon are studied by a few researchers to achieve the physiographic settings of the lagoon and its evolution under the impact of process dynamics.
- Many authors have conducted their survey on fish and fisheries management of Chilika Lagoon and to analyze the conditions and the capacity of the lagoon to support the livelihood security of fisher folk society.
- Studies are also conducted by some researchers particularly on the degradation of the lagoon in terms of eutrophication, floral and faunal diversity of the largest brackish water lagoon.

However, the environmental status of the Chilika Lagoon, the risk hazard and vulnerabilities of the lagoon margin landscapes and society are not considered in detail by the above researchers. The present article has highlighted the unfolded facts of environmental status of the Chilika Lagoon, the risk hazard and vulnerabilities of the lagoon margin landscapes that can influence the hazards of the coastal society of Puri, Khordha and Ganjam Districts of Odisha. The purpose of this study is to look into how the environment affects the water quality, sedimentation patterns, and ecosystem sustainability of Chilika Lagoon. We evaluate the temporal and spatial fluctuations in important environmental parameters and their consequences for lagoon management using a multidisciplinary approach that combines statistical modelling, field observations, and remote sensing. By offering evidence-based insights into reducing environmental threats and fostering resilience in coastal lagoon ecosystems, our findings advance sustainable lagoon governance. Additionally, the main goals of this research are to: (i) assess the Chilika Lagoon's current environmental conditions and the risks, hazards, and vulnerabilities that are affecting the marginal landscapes of the lagoon as well as the communities that surround it; and (ii) determine ways to achieve sustainable development and long-term ecological resilience of the lagoon environment.

2. Material and methods

2.1. Study area

Chilika Lagoon is the largest coastal lagoon in the Indian subcontinent with an average area of about 1165 square kilometers, (Paul et al., 2014). This lagoon is significant on a local and regional scale and about 5240.35 square kilometers make up the Chilika watershed. This lagoon is situated in the western part of Mahanadi Delta. The Chilika Lagoon watershed includes the city of Bhubaneswar, the capital of Odisha (Figure 1).

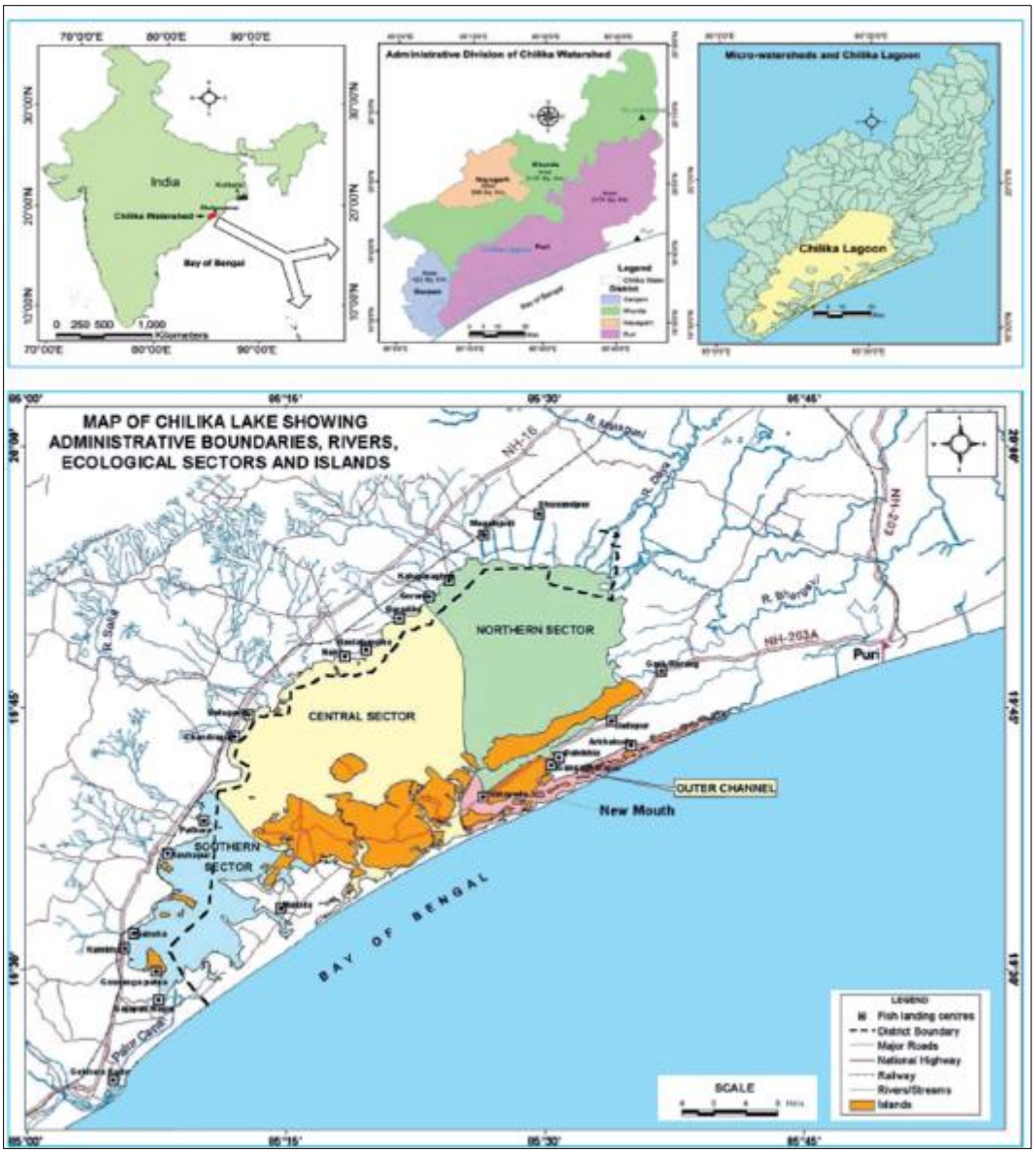

Figure 1 Map depicting the location of the Chilika Basin along the eastern coast of India, derived from ESRI basemaps, Landsat TM imagery, SRTM DEM, and ORSAC (CDA) data

This lagoon consists of Brahmagiri Krushnaprasad, and Kanas Community Development (C.D.) Blocks of Puri District, Chilika and Tangi C. D. Blocks of Khordha District, Khallikote and Ganjam C. D. Blocks of Ganjam District. (Figure 2).

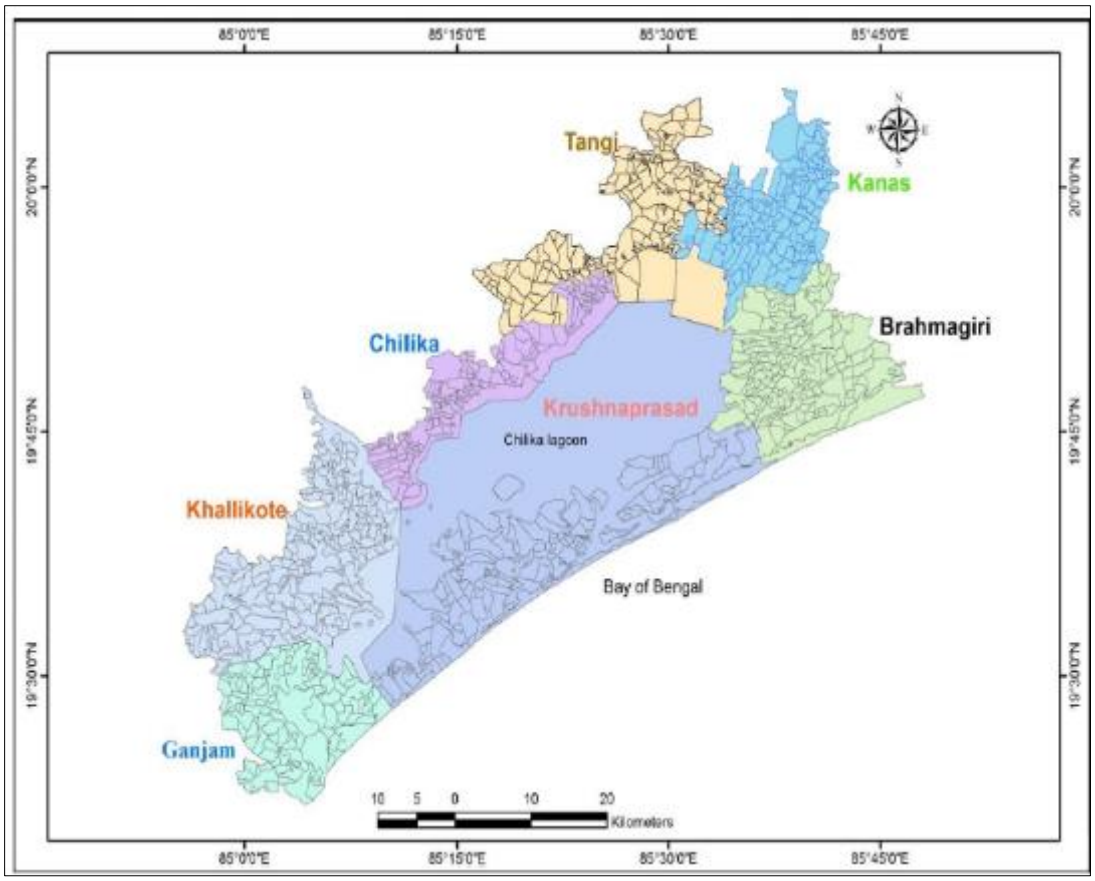

Figure 2 *The* location map of Chilika Lagoon and the adjoining seven Community Development (C.D.) Blocks, as delineated by Odisha Sampad and ORSAC (Odisha Space Applications Centre)

The eastern side of the watershed is alluvial plain with some hillocks, the northwestern, western and southwestern side is enclosed with rocky hills of Charnockite. The lagoon is continuously developing at the western side of the Mahanadi Deltaic plain. The prolonged sedimentation, temporal changes of the sedimentation foci of the Mahanadi Delta, the configuration of the shoreline and longshore drift plays the major role in reshaping the lagoon. Near about 64 km long barrier spit separate the lagoon from the Bay of Bengal. The longshore current of Bay of Bengal regularly reshape the barrier spit. The spit plays a key role to maintain the lagoon water quality and ecology which maintain the livelihood of the lagoon islands and fringe societies. The evolutionary process of Chilika Lagoon is highlighted by many geologists and geomorphologists like Blanford (1872), Venkatarathnam (1970) and Rao et al. (1995). Marine regression process in the Holocene epoch was the important factor for the origin of lagoon (Venkatarathnam, 1970 and Paul et. al., 2014). Sediment from the rivers and longshore drift influence in shaping the lagoon morphology. A major source of sediment of this area is from Mahanadi and Rushikulya Rivers. Various complex systems make the lagoon environment more lively. The lagoon water varies from fresh to brackish and the freshwater mainly flushed by Mahanadi distributaries from the northeast and saline water mainly flushed by tidal inlets from the south. The physical and the chemical properties of the lagoon water changes seasonally. Owing to the accumulation of favorable physical and chemical condition the lagoon water becomes favorable for aquatic biota. The local as well as the regional environment and the economy of the surrounding area are influenced by the rich biota of the lagoon. The settlement around the Chilika mainly consists of fishing and farming communities. Local economy and livelihood of people are mainly controlled by the capture and culture of the fish, crab and prawn species of the lagoon and its area. The area of the Chilika Lagoon is decreasing slowly by filling of clastic and biological sediments. The lagoon ecology is being degraded gradually which influence the societal degradation of the lagoon dependent society. A lagoon may face many healthy and degraded ecological phases by turn. Various natural causes degraded the lagoon but it recovers its healthy ecology naturally. Ecology of Chilika Lagoon has been faces various types challenges of natural and anthropogenic impacts. Closing and opening of tidal inlets, mixing of seawater, supply of fresh river water, river sediments, availability of nutrients, flora and fauna and climatic condition controls the natural system of the lagoon. In the last few decades, Chilika has been suffering from multiple problems such as inlet closing, low rate of saline water mixing, high rate of sediment flow into the lagoon, population pressure on lagoon watershed, the invasion of reed etc. These problems cause the low production of aquatic resources. Besides these, population pressure and an increasing commercialization of fish production causes

the lagoon deterioration. Illegal competition between fisher and non-fisher communities caused bloodshed which creates the lagoon society unpeaceful.

2.2. Methodology

The coastal portion of the Puri township and the foreshores of the Chilika sand spits showed moderate shoreline changes. These changes are mostly caused by large wave breakers produced during the monsoon season, which are impacted by higher water levels and more wind stress. Significantly, the increased force of recent cyclonic storms—Phailin and Hudhud—without a recovery period has accelerated coastal retreat by aggravating the erosion of shoreline sediments. The study uses the Gornitz et al. (1994) methodological framework, which incorporates a number of physical variables, to evaluate coastal vulnerability. These consist of mean tidal range, mean wave height, shoreline erosion/accretion rates, slope, relative sea level rise, and coastal geomorphology. The most important factor affecting vulnerability among these is relative sea level rise. The region's relative rate of sea level rise, according to data from the Paradip station, is roughly 0.77 mm/year (NOAA-PSMSL, 2015). A thorough assessment of the coastal areas around the Chilika Lagoon's vulnerability to environmental risks is made easier by this multi-parameter approach.

2.2.1. Coastal Vulnerability Index (CVI): Mapping and Assessment

Assessment was conducted using ArcGIS software, which served as the primary platform for spatial data processing, analysis, and map generation. ArcGIS tools such as Reclassify, Raster Calculator, Zonal Statistics, and Symbology were used to standardize input variables, compute the composite CVI scores, and classify vulnerability levels across the coastal zone. Additionally, Digital Elevation Models (DEMs) were processed using ArcGIS's Spatial Analyst extension to extract elevation and slope data, while shoreline and land use layers were digitized and analyzed using vector editing tools. The use of ArcGIS allowed for the integration of multiple datasets, accurate spatial alignment, and the creation of high-quality vulnerability maps essential for decision-making in coastal planning and risk management. Furthermore, the Geoprocessing tools within ArcGIS, such as Buffer, Clip, and Extract by Mask, were utilized to define the study area boundaries and isolate relevant features from broader datasets. The Reclassification tool played a crucial role in assigning vulnerability scores to each variable based on predefined thresholds, allowing for uniform comparison across different parameters. To visualize the spatial distribution of vulnerability, the final CVI raster was symbolized using classified color gradients, enhancing the interpretability of the results. Additionally, the Layout View in ArcGIS was used to prepare professional-quality maps with essential cartographic elements, including legends, scale bars, north arrows, and titles. The comprehensive capabilities of ArcGIS enabled the seamless execution of the CVI methodology from data preparation to final map output, ensuring accuracy, reproducibility, and clarity in the analysis of coastal vulnerability.

2.2.2. Geospatial Mapping of Coastal Regulation Zones

The methodology for delineating the Coastal Regulation Zone (CRZ) involves a combination of satellite imagery interpretation, geospatial analysis, and field verification to accurately identify ecologically sensitive areas and zones regulated under the CRZ notification. High-resolution satellite data such as IRS or Sentinel imagery is used to demarcate the High Tide Line (HTL), Low Tide Line (LTL), and coastal features including mangroves, mudflats, estuaries, and backwaters. Using GIS software like ArcGIS, a buffer of 500 meters from the HTL is generated to represent the CRZ boundary, as per the guidelines of the Coastal Regulation Zone Notification issued by the Ministry of Environment, Forest and Climate Change (MoEFCC). Land use/land cover classification, along with topographic maps and tidal data, supports the identification of CRZ categories (CRZ-I to CRZ-IV). The mapped zones are further validated through ground truthing and cross-referenced with existing cadastral maps and government records to ensure legal and ecological accuracy. This integrated approach ensures that development activities along the coast comply with environmental regulations while preserving the fragile coastal ecosystem.

3. Results and discussion

3.1. Assessment of Shoreline Dynamics and Coastal Vulnerability

The lateral shifting of shoreline may cause the accretion or erosion process. The concentrated energy of waves and tidal currents along with the intense longshore drift in the shorefront areas is responsible for erosion and accretion on the shoreline.

Figure-3 represents the coastal vulnerability index which indicates the physical vulnerabilities of Chilika Lagoon environment and its surroundings. The areas of sand spits, islands and low-lying tidal flats are highly vulnerable in comparison with the Chilika Lagoon water bodies which are moderately vulnerable due to the fluctuations of water cover areas during the landfall of cyclones and the occurrences of the flood. Other areas of moderate vulnerability are

extended over the northeastern portions of the deltaic flood basins of Devi and Daya Rivers because of the occurrences of the monsoonal flood. If the rate of the sea level rise becomes steady and constant, then these areas may be inundated in future and may be affected by the frequency and magnitude of hazards. However, the remaining portions of the northern part of the Chilika Lagoon are less vulnerable due to their higher elevations from the lagoon water body. The analysis using the DSAS software (USGS) indicates the changing shoreline configuration of the Chilika and the adjoining areas. The study shows that the major portion of the shoreline of the study area are erosive in nature and only the small portion of Palibandha, western side of new mouth inlet, old mouth to Harchandi Temple and Pentukota to the Konark beach area are depositional. The maximum erosion of the shoreline has been recorded on the northeastern side of the present new mouth of the Chilika with 40.29 m in last 42 years as the frontal barrier spit of the new mouth washed out and the second series of barrier bar have been exposed in front of the shoreline. The same scenario has been observed in the case of the mouth of the Rushikulya River spit. The maximum accretion of 11.69 m observed at the western side of present new mouth inlet. The high values of new mouth areas are the result of inlets dynamisms of the lagoonal systems; on the other hand, the reduction of sediment discharge of Rushikulya river mouth into the coastal zone provides the scope for the concentration of longshore drift currents and significant wave breakers. The moderate shoreline changes are recorded along the foreshores and on the shores of Chilika sand spits and the Puri township area. Such moderate changes are resulted from significant wave breakers in the monsoon period by wind stress effects and high-water levels. The erosion of the sediment from the shore front position is accelerated due to the intensified magnitude of the recent 2 cyclonic storms (Phailin and Hudhud) without having specific recovery phase. The vulnerability of the coastal areas can be estimated using the method of Gornitz et al., (1994).

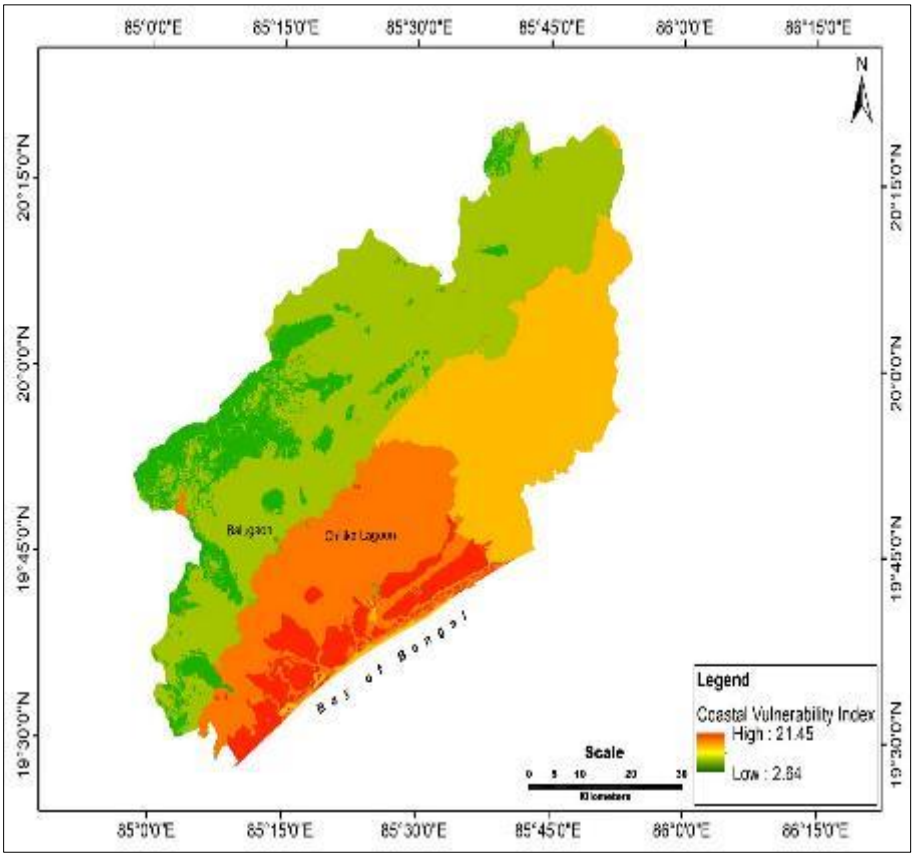

Figure 3 Show the spatial distribution of coastal vulnerability levels around the Chilika Lagoon in 2024, derived using the Coastal Vulnerability Index (CVI) and geospatial analysis techniques (Source: USGS and geospatial technology applications)

The major variables used for the estimation are geomorphology, coastal slope and relative sea level rise and shoreline erosion/accretion rate, mean tide range and mean wave height. Among these variables the relative sea level rise is the most important factor for vulnerability assessment. The relative rate of sea level rise is about 0.77 mm/year near the Paradip station (NOAA-PSMSL, 2015). The result shows the Coastal Vulnerability Index (CVI) of the study area varies between 2.64 (very low) to 21.45 (high-risk) (Figure 3).

3.2. Approach to minimize stakeholder conflicts over resource allocation

Chilika Lagoon and the fringe area is a complete resource unit with different types of users. The conflict arises from the demand for the particular resource among the different stakeholders. For the particular resource a specific type of stakeholder is responsible for using and maintaining that resource. The major stakeholders are the CDA, different government organizations like fishery department, forest department, OTDC etc and also the local villagers; who have the customary right to the Chilika Lagoon for their livelihood. The conflict arises due to the amount of sharing the resources among the different stakeholders. Due to the increased demand of the societal development all the stakeholders need to use the resources in the optimum limit. Because of the decrease of the aquatic resources of the Chilika competition among the stakeholders are increased, which create instability and resource depletion which furthermore create a clash between different stakeholders. To minimize the problems resources, have to be used in a sustainable way. ICZMP-Odisha is trying to minimize the conflicts between different stakeholders and provides livelihood options to the backward society of the Chilika fringe and island areas.

3.3. Coastal Zone Governance through Integrated Approaches

Sustainable management of coastal resources is essential for ecological balance and socioeconomic development of Chilika fringe area. Spit, sand dune, estuary, beach, wetland, backwater and island are the very sensitive geomorphic feature which influence the lagoon ecology. The lagoon area is replete with a wide range of seagrass, salt marsh, mangrove, waterfowl, fish, prawn, crabs and some rare, vulnerable and endangered species. A large number of fishermen are engaged in coastal fishing. The Integrated Coastal Zone Management (ICZM) project is an integrated approach and coordinating activities of various stakeholders for the sustainable usages of the coastal natural resources maintaining the natural environment of Chilika. The vision of ICZM is to maintain and safeguard the ecological integrity of the lagoon by augmenting scientific study and lagoon monitoring. The ICZM project has the following components to maintain and regulate Chilika coastal environment

- Formulation of Integrated Coastal Zone Management Plan for the lagoon environment
- Coastal erosion and associated oceanographic processes study
- Disaster vulnerability assessment
- Biodiversity conservation and ensure livelihood security
- Pollution measurement and environmental quality management
- Improvement and conservation of cultural and archaeological assets

3.4. Fostering Sustainable Tourism Through Eco-Conscious Management

Tourism is one of the fastest growing industries in the world. It is the main source of income for many countries. It also offers various jobs which help the local economies of the many countries. Tourism can also cause problems, such as, ecological degradation, loss of cultural heritage and social displacement etc. To overcome these problems sustainable tourism such as nature-based tourism and ecotourism is the better way of development. According to IUCN the ecotourism is “Environmentally responsible travel to natural areas, in order to enjoy and appreciate nature (and accompanying cultural features, both past and present) that promote conservation, have a low visitor impact and provide for beneficially active socio-economic involvement of local peoples”. Chilika also suffers from mass tourism activities. Harmful effects of tourism are clearly observed in Satapada, Mirzapur, Gabakunda and Barkul. Mangaljodi ecotourism is a managed tourism place which is free from environmental degradation. The lagoon area is replete with a wide range of seagrass, salt marsh, mangrove, waterfowl, fish, prawn, crabs and some rare, vulnerable and endangered species. A large number of fishermen are engaged in coastal fishing. The Integrated Coastal Zone Management (ICZM) project is an integrated approach and coordinating activities of various stakeholders for the sustainable usages of the coastal natural resources maintaining the natural environment of Chilika. The Integrated Coastal Zone Management (ICZM) project is an integrated approach and coordinating activities of various stakeholders for the sustainable usages of the coastal natural resources maintaining the natural environment of Chilika. The vision of ICZM is to maintain and safeguard the ecological integrity of the lagoon by augmenting scientific study and lagoon monitoring. The ICZM project has the following components to maintain and regulate Chilika coastal environment:

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3.5. Environmental Management for Promoting Sustainable Tourism

Tourism is one of the fastest growing industries in the world. It is the main source of income for many countries. It also offers various jobs which help the local economies of the many countries. Tourism can also cause problems, such as, ecological degradation, loss of cultural heritage and social displacement etc. To overcome these problems sustainable tourism such as nature-based tourism and ecotourism is the better way of development. According to IUCN the ecotourism is "Environmentally responsible travel to natural areas, in order to enjoy and appreciate nature (and accompanying cultural features, both past and present) that promote conservation, have a low visitor impact and provide for beneficially active socio-economic involvement of local peoples". Chilika also suffers from mass tourism activities. Harmful effects of tourism are clearly observed in Satapada, Mirzapur, Gabakunda and Barkul. Mangaljodi ecotourism is a managed tourism place which is free from environmental degradation which attracted many national and international nature lovers situated at the northeastern fringe of Chilika. There is a potential scope for the development of nature tourism, ecotourism, wildlife tourism and heritage tourism in an around the Chilika Lagoon. However, there are some restrictions of CRZ I, CRZ III and CRZ IV for the extensive development of such tourism activities in the lagoonal environment. The ecological, social and physical carrying capacities of tourism destinations may be estimated from time to time to control or reduce the over development of tourism related activities. There is a possibility of the tourism environment conflicts in future if tourism destinations may develop in uncontrolled ways with the violation of CRZ Rules. In any sustainable tourism development, the CRZ Rules, Island Protection Rules, Forest Act and Wetland Act should be considered to prevent the over development in the sensitive environment of the coastal lagoon.

3.6. Livelihood Diversification Options for Fishing Communities

The livelihood activities like fishing, pasturing, agricultural and other activities have been found in Chilika surrounding area. But the main livelihood in the lagoon fringe areas depends on the fishing and the farming. As the water depth and the quality have been deteriorated gradually, the amount of fishes reduced which raise a clash among the traditional livelihood maintaining villagers for the fishing area. Due to the increase of the commercial fishing the traditional fishermen are facing problems. Seasonal variation of the fish catch also affects their livelihood. For that reason the traditional fishermen have to choice alternative livelihood like tourism boating, pasturing in the marshy grassland, poultry farming and animal husbandry, forest product collection etc. but sometimes these are not sufficient and profitable for maintaining their livelihood. That's why many of the young of the fishermen communities have migrated outside states for the sustenance of their family. Population growth rate in the study area is relatively higher than the state average. To support the increased population the pressure on land is increased. Production beyond the carrying capacity creates land degradation and soil erosion in the lagoon and the lagoon surrounding areas. Land degradation decreases the production, so it is necessary to diverse the farmers and fisherman to other profitable occupations to decrease the pressure from the lagoon and lagoon fringe land. According to FAO "Diversified livelihoods are also a feature of household strategies, with members of fishing households often being involved in different economic sectors to smooth the effects of resource variations". The Government of Odisha, ICZMP and the CDA promoting the alternate livelihood activities among the local villagers through funding and training activities for animal husbandry, milk production, handicraft (mats, bags, baskets etc. making), fish processing, fish food preparation, poultry farming and orchard farming, weaving, mericulture and bee keeping etc.

3.7. Spatial Mapping of Coastal Regulation Zones and Their Violations in the Chilika Lagoon Area

For regulation of activities in the coastal area of India, the Ministry of Environment and Forests, Government of India issued Coastal Regulation Zone (CRZ) notification in 1991. Coastal stretches of seas, bays, estuaries, creeks, rivers and backwaters which are influenced by tidal action (on the landward side) are included in the Coastal Regulation Zone notification (Ministry of Environment and Forests, 2011).

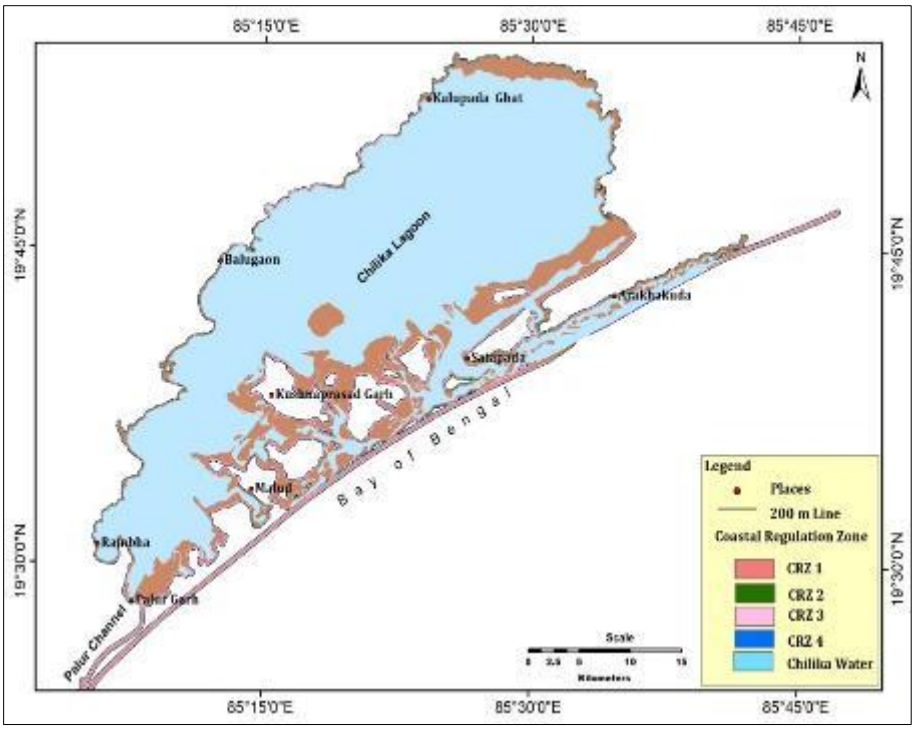

Figure 4 Coastal Regulation Zones (CRZ) delineation for the Chilika region as per CRZ Notification, 2024 (Source: Ministry of Environment and Forests, Government of India; geospatial analysis based on CRZ guidelines)

The present study shows that CRZ I is extended to the shore front positions of islands and spits, as well as the inner shores of the lagoon in a few places. The Chilika region's Coastal Regulation Zones (CRZ) are delineated in Figure 4 in compliance with the CRZ Notification, 2024. The Ministry of Environment and Forests, Government of India, provides the datasets and official CRZ guidelines that are used to derive the zoning through geospatial analysis. The regulatory boundaries that are essential for land-use planning, coastal conservation, and the sustainable management of the lagoon ecosystem are highlighted in this spatial representation. The areas between HTL and 500m inland surface are very much sensitive to the location of different geographical habitats (salt marshes, other grasses, mangroves and macrophytes). However, the CRZ I is violated in few places of the lagoon (Satapada, Mirzapur and Arakhakuda etc.) by tourism development, land use changes by the local communities and other infrastructural development (Figure 4). The CRZ II of the Chilika Lagoon fringe area is occupied by five urban centers. The region extends from HTL to 100m landward side or width of the creek whichever is less, on the landward side of the tidal influence channels and lagoon water bodies. However, the influxes of the waste and untreated sewage waters of the urban areas are directly discharged into the lagoon fringe areas. These materials are again washed out into the lagoon water bodies by seasonal increased cover area and discharge of the western catchment rivers into the zone. For this reason of such mixing the eutrophication is extensive in the lagoon bed (Figure 4). The shoreline of Chilika to the west and southwest as well as to the north and northeast are characterized by a rural environment of fisher folk communities within the area of CRZ III (500m landward side of HTL) for the spread of hazards in the form of storm tides, storm surges and predicted sea level rise. Though the tidal effects are poor in the western and southwestern part but it is very significant on the north and north-eastern part of the lagoonal shore and other hazards disturbed the areas during the landfall of cyclones and occurrences of river floods (Figure 4). The CRZ IV is restricted in between LTL and HTL. As the tidal range is 1 m during monsoon and 0.2 m in the non-monsoon months the CRZ IV is much narrowed in occurrence particularly along the northeastern shores of the lagoon and sand spits. The CRZ IV supports the intertidal belt of the lagoon dominated by mangroves and salt marshes. Certain areas of the CRZ IV are violated by the excessive fishing activities and overuse of natural resources (Figure 4). The CRZ V is extending from LTL of the sand spit to 12 nautical miles that is mainly used by navigators and fisher folks. However, the CRZ V also extended to the sides of the outer channel of Chilika Lagoon in which it is extended from the LTL to the channel beds. The over activities may pollute the environment of the CRZ V in this region (Figure 4).

3.8. Managing Land Use for the Conservation of Coastal Habitats

Man acts as a major force of change on earth. It transforms land to provide food, shelter and other products for daily living. Land use is being transformed regularly in the habitable parts of the earth. Land transformation by man directly

affects the physical, chemical and biological systems of that area. Unscientific land transformation affects the productivity and habitat destruction thereby affecting the human civilization. In spite of having much importance of it, at the time of making a decision regarding land use the potential ecological and the societal effects are not a matter of great consideration. According to European Space Agency an ecological perspective should be incorporated into land use management. Coastal lagoon habitats like freshwater, saline water, tidal flat, dune, rocky outcrop, sandy lagoon bed, clay lagoon bed and mangrove etc. are very sensitive to land use transformation. The coastal habitats of the Chilika Lagoon are very much diverse and significant in maintaining the coastal biodiversity, lagoon water quality and sediment accumulations. The coastal habitats have physical functions (morphologic and sedimentologic), chemical functions (pollution trap), biological functions (species richness, the home of waterfowls), hydrological functions (temporary water reservoirs and groundwater recharging) economic functions (fishing and tourism) and social functions (development of human civilization) in the coastal lagoonal environment. Therefore, initiations should be taken by CDA and ICZM committee of the state to preserve the above coastal habitats for the natural balance of the environment. As the habitats are destroyed behind the outer channel portions the effects of previous cyclones were very significant in the lagoon near the new mouth areas.

3.9. Evaluating Temporal Changes in Water Quality of Chilika Lagoon

The quality of water controls the aquatic lives. Micro and macro plant and animal species of the lagoon are directly and indirectly influenced by water quality parameters such as volume, velocity, vertical and horizontal movement, residence time in lagoon, temperature, salinity, conductivity, pH, turbidity, dissolved oxygen, dissolved organic carbon, dissolved inorganic carbon, particulate organic carbon, dissolved inorganic nitrogen, dissolved inorganic phosphorous, other nutrient, air-water gas exchange and micro and macro-organisms etc. Changes of these parameters which affect the aquatic species directly or indirectly. The organism has some ability to be adjusted with the changing parameters but the extreme condition is harmful to aquatic species. Therefore, the water quality should be monitored for the sustainability of the lagoon. All-important water quality parameters should be monitored regularly with the appropriate and scientific method and the results should be analyzed properly. The surface runoff, river discharge and precipitation input the water in the lagoon and through the tidal inlet channel and subsurface flow from the Bay of Bengal water input output restored the balanced condition of lagoon water. The water level of the lagoon increased about 1m from the average level in the monsoon season and decreases in the months of April-May. Rivers and tidal inlets should be monitored regularly and water quality parameters should be measured. Anthropogenic activities like fishing, transportation and tourism should be monitored to protect water quality. Water quality directly related to the fish production of the lagoon which controls the economy and livelihood of the lagoon fringe society. The Chilika Development Authority has established the Wetland Research and Training Center at Chandraput near Balugaon in 2002. This center is studying limnology, marine biology, hydrology, coastal influence on the lagoon, flora fauna weeds, sediment transport, wave climate, tidal influence, lake bathymetry, meteorology and lake ecosystem with the help of 30 sophisticated sensors spreading all over the lagoon which telemeters the real-time data to Wetland Research and Training Center. Results of the automatic water quality monitoring station have been used for analysis to maintain the sustainable condition.

3.10. Lagoon Environmental Recovery Through Cycles of Inlet Mouth Opening and Closure

The tidal inlet is an important controlling factor in the lagoonal system. It also controls the mixing of lagoon water with the saline water of Bay of Bengal. At the time of high tide, the saline water enters into the lagoon and at the time of low tide lagoon water exits. This process may lead to water balances in Chilika Lagoon ecosystem. This inlet also allows the marine fishes, juveniles into the lagoon and helps some mature lagoon fishes (catadromous) to go to the sea to lay eggs. Normally, water and sediment enter into the lagoon through surface runoff, groundwater flow, rivers and streams and flood and water exits through the inlet channel and evaporation. These inlets are unstable and shifting towards the north east. Inlets are opened either naturally (mainly in the time of high energy phase) or artificially. The inlet mouth should maintain regularly by different means such as dredging. Several previous study shows that the tidal inlet mouth has been shifted from Manikpatna to the end of the outer channel. According to the Survey of India toposheet of 1862, the inlet was found in front of Arakhakuda village but the Landsat MSS image of 1972 shows the presence of three inlets within Arakhakuda to the end of the outer channel region. The ETM+ image of 1999 shows that the inlet mouth of Chilika has shifted towards the end of the outer channel of 10 km northeast from inlet mouth of 1862. The earlier studies shows that the mouth was about 1.60 km wide in 1780 but after 40 years it was choked and in 1825 artificial mouth had been opened (O'Malley, 1908). In 1999 water exchange decreases because of the only a single mouth is silted up. In 1999 the water exchange process decreases at the end of the outer channel region. Then artificial mouth has been cut in front of Sipakuda village which also makes the lagoon environment healthy and increase the fish production. This mouth is being shifted towards the northeast at the rate of 222 m/year during 2000 to 2014 (Figure 2). This mouth should be maintained to control the salinity of lagoon that influences the lagoon ecology, fish productivity and regional economy.

4. Conclusion

The vulnerability assessment shows that the islands of Chilika along with their habitats are highly in danger in comparison to the other areas of the lagoon. To monitor shoreline dynamics, fishery productivity, environmental degradation, and adherence to coastal regulatory frameworks in and around the Chilika Lagoon, coastal zone management authorities have conducted extensive assessments. The Integrated Coastal Zone Management (ICZM) Authority, Coastal Zone Management (CZM) bodies, tourism departments, and rural development organisations have all launched a variety of strategic interventions in response to these findings in order to promote ecological restoration and enhance the socioeconomic resilience of the communities that depend on the lagoon. The Chilika Lagoon's ecological integrity and the sustainability of the livelihoods dependent on its coastal resources depend on the Coastal Regulation Zone (CRZ) Rules being implemented effectively and enforced. To improve conservation, control resource use, and lessen conflict among various stakeholders, an environmental zoning-based approach to lagoon management is highly advised. This integrative framework will play a pivotal role in achieving long-term ecological stability and equitable socio-economic outcomes for the region. The alternative livelihood practiced by livestock ranching, pasturing, farming, practicing orchards and involvement in the tourism process may support the economy and environment of the local people. The environmental regulations with relaxation and revision of by laws can promote the nature tourism and heritage tourism in and around Chilika Lagoon. The Chilika Development Authority should play a role with the aid of ICZM funding to improve the economy and environment of the coastal society of Odisha State.

Finally, the modern technology with innovative ideas can help to continue the monitoring processes of the environment. The assessment of the carrying capacity of the lagoon also can help the society to maintain their occupations and economic activities and for better sustainable management of coastal resources for future generations.

Compliance with ethical standards

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Authors' contributions

K.K.M. conducted experimental testing, data collection, data analysis, and manuscript preparation. K.P.B. provided study supervision, performed formal analysis, and contributed to manuscript preparation. All authors participated in drafting the initial version and reviewing the manuscript.

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