World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI

Cross Ref DOI: 10.30574/wjarr

Journal homepage: https://wjarr.com/

(Review Article)

Assessing geomorphological and hydro morphological changes of Chilika lagoon

Kumbhakarna Mallik * and Krishna Pada Bauri

Department of Civil and Environmental Engineering, C.V. Raman Global University, Bhubaneswar, Odisha, India.

World Journal of Advanced Research and Reviews, 2025, 26(03), 778-789

Publication history: Received on 25 January 2025; revised on 03 June 2025; accepted on 06 June 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.26.3.2216

Abstract

The largest brackish water lagoon in Asia, Chilika Lagoon, is a Ramsar-designated wetland that is experiencing major hydro-meteorological and geomorphological changes as a result of both natural and man-made factors. The spatial-temporal evolution of Chilika's landscape and hydrological regime over the previous 50 years is summarised in this review, with a focus on the interactions between tidal interactions, sediment dynamics, climatic variability, and changes in land use and land cover (LULC). In connection with upstream catchment modifications and coastal processes, important geomorphological changes are analysed, such as mouth migration, deltaic progradation, and sedimentation-induced basin fragmentation. Remote sensing-based studies and multi-decadal datasets are used to critically evaluate hydro-meteorological drivers, including cyclonic disturbances, freshwater inflow, evaporation, salinity intrusion, and monsoonal variability. The review also highlights current conservation and restoration efforts, such as the opening of the new lagoon mouth in 2000, and examines the effects of these changes on local livelihoods, fisheries, and biodiversity. High-resolution hydrodynamic modelling, integrating long-term socio-ecological datasets, and scenario-based forecasting under climate change are among the research gaps that currently exist. The necessity of adaptive, multidisciplinary management strategies that balance ecological sustainability and socioeconomic resilience in the Chilika Lagoon system is highlighted by this review.

Keywords: Brackish; Evolution; Livelihood; Sedimentation; Anthropogenic; Land use/land cover (LULC) change; Climate change vulnerability; Wetland hydrodynamics; and Sustainable lagoon management

1. Introduction

Coastal lagoons are vibrant, biologically diverse areas that lie between the land and the sea. They make up around 13% of the world's coastline and are essential to maintaining the hydrological and ecological balance of the planet (Kjerfve & Magill, 1989; Day et al., 2022). In addition to acting as nutrient and sediment sinks and as natural buffers that lessen the effects of coastal storms and sea-level rise, these shallow water bodies are vital habitats for many migratory and endemic species (Newton et al., 2018). Additionally, they sustain agriculture, tourism, fisheries, and cultural heritage, particularly in coastal areas with high population densities (Kennish & Paerl, 2010). The location of coastal lagoons at the land-sea interface, where intricate relationships between tidal exchanges, freshwater inflows, and human pressures produce distinctive biogeochemical gradients, is thought to be responsible for their ecological productivity (Pérez-Ruzafa et al., 2019). By storing and releasing freshwater gradually, these systems control water cycles, impacting groundwater recharge and regional hydrology (Gonçalves et al., 2023). Lagoons' contributions to carbon sequestration, biodiversity preservation, and climate resilience are becoming more widely acknowledged in light of global climate change (Kumar et al., 2022). Coastal lagoons are facing increasing pressure despite their importance due to eutrophication, changes in hydrology, land use, and stressors brought on by climate change (Alvarez-Romero et al., 2021). The vital services that these ecosystems offer to human societies are in danger, in addition to biodiversity, as a result of their degradation. Accordingly, it is essential to comprehend the ecological and hydrological significance of coastal lagoons in order to manage them sustainably and incorporate them into climate adaptation plans. This paper

* Corresponding author: Kumbhakarna Mallik

offers a thorough summary of the ecological and hydrological significance of coastal lagoons worldwide, based on current empirical research and emphasising the difficulties and policy requirements for their preservation. The largest brackish water lagoon in Asia and the second largest coastal lagoon globally is Chilika Lagoon, which is located in the state of Odisha on India's east coast (Pattnaik & Panda, 2020). During the monsoon season, it covers an area of more than 1,100 km2, and a narrow outer channel connects it to the Bay of Bengal. Chilika has been identified as a hotspot for biodiversity and ecological productivity and is a Ramsar Wetland of International Importance (Mishra et al., 2021). Chilika is a unique estuarine ecosystem that supports more than 225 fish species, 800 animal species, and almost a million migratory birds each year. Its varied habitats include open water, marshes, mudflats, and seagrass meadows (Mohanty et al., 2022). The lagoon is one of the few locations in the world where the endangered Irrawaddy dolphin (Orcaella brevirostris) can flourish in brackish water, and it is also an essential habitat for this species (Behera et al., 2021). Its position at the meeting point of saline tidal waters from the Bay of Bengal and freshwater inflows from the Mahanadi River delta produces dynamic salinity gradients that affect productivity and species richness (Pattnaik et al., 2023). Chilika Lagoon has significant socioeconomic value in addition to its ecological diversity. More than 200,000 local farmers and fishermen rely on its ecosystem services for their livelihoods, including aquaculture, agriculture, fisheries, and ecotourism (Nayak et al., 2021). Through flood buffering and carbon sequestration, the lagoon plays a critical role in climate resilience and supports local food security and cultural identity (Prusty et al., 2022). However, anthropogenic activities, sedimentation, invasive species, and climate variability are posing an increasing threat to this delicate ecosystem, necessitating integrated management strategies and ongoing monitoring. This article offers a thorough overview of Chilika Lagoon's ecological significance, socioeconomic contributions, and geographical context, highlighting recent trends and policy implications for sustainable lagoon management. A complex interaction between anthropogenic pressures, rapid land-use changes, and climate change is causing unprecedented changes in coastal and transitional ecosystems worldwide (Newton et al., 2022; Mentaschi et al., 2018). Coastal lagoons, estuaries, and deltaic systems are especially affected by these changes, as they are more susceptible to shoreline degradation, invasive species, rising sea levels, nutrient loading, and hydrological changes (Pérez-Ruzafa et al., 2019). Despite the ecological and socioeconomic significance of these systems, scientific research on them is still dispersed and frequently concentrates on discrete spatial-temporal scales or isolated ecological functions, which limits our comprehension of how they function holistically under stress (Rodrigues et al., 2023). The fragmented nature of research is caused by inconsistent monitoring frameworks and discipline-specific approaches that do not account for the cumulative and synergistic effects of multiple stressors over time (Firth et al., 2020). For example, although some research highlights changes in biodiversity, others only address hydrological modelling or socioeconomic effects, rarely combining these aspects. The absence of interdisciplinary synthesis hinders evidence-based decision-making, particularly in areas where adaptive management strategies are further hampered by data scarcity (Le Tissier et al., 2023). A timely reassessment of current knowledge, gaps, and research priorities is also necessary due to the rate of environmental transformation, which is being accelerated by climate-induced extreme weather events, altered precipitation patterns, and sea-level rise (Nicholls et al., 2021). Therefore, this review is justified on three main grounds: (i) the rapid ecological and hydromorphological changes that are affecting sensitive ecosystems; (ii) the fragmented and disciplinary-constrained nature of existing studies; and (iii) the growing complexity and intensity of anthropogenic and climate stressors that necessitate an integrated and adaptive knowledge framework. To synthesise new findings, pinpoint research gaps, and suggest a course of action for resilience-based management of these dynamic systems, a thorough and methodical review is desperately needed. Through a thorough, multi-scale, and interdisciplinary synthesis of the body of research and new developments concerning the ecological and socio-hydrological dynamics of coastal lagoons, this review seeks to close these gaps. In particular, this review aims to: (i) Examine the ecological state of coastal lagoons today in light of human and climatic stressors. (ii) Combine disparate studies into a cohesive conceptual framework that emphasises resilience, ecological interactions, and regime changes. (iii) Determine new research priorities and knowledge gaps for adaptive lagoon management. (iv) Evaluate current policy and management strategies, emphasizing nature-based solutions, community participation, and governance mechanisms.

This review uses Chilika Lagoon as a representative model system and covers case studies from a variety of geographic locations, with an emphasis on tropical and subtropical lagoons. The review covers a wide range of topics, including hydrological assessments, remote sensing developments, ecological indicators, socioeconomic drivers, and climate adaptation tactics. This work intends to contribute to the larger conversation on nature-based climate resilience and inform sustainable lagoon management by synthesising cross-disciplinary findings.

2. Geomorphological Evolution of Chilika Lagoon

A complex and dynamic coastal system on India's east coast, Chilika Lagoon has undergone geomorphological evolution due to a confluence of geological, hydrodynamic, climatic, and human factors. Determining lagoon resilience, biodiversity conservation, and sustainable management tactics all depend on an understanding of these processes

(Tripathy et al., 2022). Current understanding of historical landscape shifts, sediment dynamics, tidal processes, deltaic influences, and shoreline morphology within Chilika Lagoon is summarised in the ensuing subsections.

2.1. Historical landscape changes (prehistoric to present)

The development and origin of Chilika Lagoon can be traced back to the Late Pleistocene and Holocene periods, when the lagoon basin was formed by sediment deposition and shifting sea levels (Kumar et al., 2021). Prehistoric coastal transgressions and regressions profoundly changed the lagoon's morphology, impacting its connectivity with the Bay of Bengal, according to paleoenvironmental reconstructions. Its current spatial extent was gradually shaped over millennia by natural barriers and sediment infill (Tripathy et al., 2022). Tectonic activity and riverine inputs have also significantly changed the lagoon's landscape, affecting sediment supply and basin subsidence (Singh et al., 2023). Human activities like channel modifications, catchment deforestation, and aquaculture expansion have accelerated the changes in the landscape in the modern era (Das et al., 2023).

2.2. Sedimentation and erosion dynamics

The geomorphological structure and ecological processes of Chilika Lagoon are primarily influenced by sedimentation and erosion. Coastal wave action and tidal currents affect sediment redistribution and erosion patterns, while the Daya and Bhargavi rivers supply the majority of the fluvial sediments that contribute to lagoon infilling and nutrient dynamics (Das et al., 2023; Rath et al., 2023). Sediment core analysis and hydrodynamic modelling studies have shown that sediment deposition is spatially heterogeneous, with the southern lagoon margins undergoing episodic erosion and the central and northern sectors undergoing progressive siltation (Kumar et al., 2021; Rath et al., 2023). Water clarity, habitat availability, and the general health of aquatic biota are all influenced by these processes.

2.3. Lagoon mouth migration and tidal exchange

An essential channel that controls tidal flushing, nutrient exchange, and saline water intrusion between the Bay of Bengal and Chilika Lagoon is the lagoon mouth. Due to tidal energy, sediment buildup, and monsoonal variations, its position and morphology are extremely dynamic (Mishra & Behera, 2021). Satellite imagery and historical documents show that the inlet migrates episodically, which has a direct impact on hydrological connectivity and tidal prism (Mishra & Behera, 2021; Patra et al., 2024). Dredging was done to stabilise the inlet in the 2000s, which improved tidal exchange, water quality, and fishery productivity. Nonetheless, natural variability endures, requiring continuous observation to predict future ecological and geomorphic reactions (Patra et al., 2024).

2.4. Deltaic and littoral processes

The Mahanadi river system's deltaic processes and littoral drift along the Odisha coastline have an impact on Chilika Lagoon. By forming barrier islands and spits that shield the lagoon from direct marine impact, longshore sediment transport controls shoreline accretion and erosion patterns (Rath et al., 2023). Lagoon bathymetry and sediment properties are influenced by the interaction between the deltaic sediment load and marine processes. The dynamics of lagoon mouths and shoreline morphology are influenced by sediment redistribution driven by wave energy and monsoonal winds (Singh et al., 2023). The geographical distribution of seagrass beds, mangroves, and other important habitats is also impacted by these geomorphic processes.

2.5. Shoreline changes and island dynamics

Shoreline morphology within Chilika Lagoon exhibits considerable temporal variability linked to sediment balance, tidal regimes, and anthropogenic pressures. Recent remote sensing studies demonstrate both accretion and erosion hotspots, with island formation and submergence occurring over decadal scales (Sahu et al., 2022; Patra et al., 2024). Islands within the lagoon serve as important refuges for wildlife and influence hydrodynamic patterns by altering flow paths. Anthropogenic activities such as dredging, aquaculture, and land reclamation have modified shoreline configurations, with implications for habitat fragmentation and ecosystem services (Das et al., 2023). Continued geomorphic monitoring is essential to safeguard the lagoon’s ecological integrity and support adaptive management.

3. Hydro-Meteorological Characteristics and Variability

The physical, chemical, and ecological behaviour of Chilika Lagoon is greatly influenced by hydro-meteorological factors like rainfall, river inflow, evaporation, salinity, and storm events. The Indian Summer Monsoon and sporadic disruptions from tropical cyclones and climate fluctuations cause significant seasonal variability in this brackish water coastal ecosystem. These mechanisms control salinity gradients, nutrient fluxes, and lagoon hydrodynamics, which in turn control fishery health, aquatic productivity, and wetland biodiversity (Nayak et al., 2023; Mishra et al., 2021).

Forecasting ecosystems and managing them adaptively in the face of future climate scenarios depend on an understanding of the multitemporal hydro-meteorological dynamics of Chilika.

3.1. Monsoonal rainfall and freshwater inflow

The primary source of freshwater for Chilika Lagoon is monsoonal rainfall, which occurs from June to September and propels river discharge from a network of catchment rivers, such as the Daya, Bhargavi, and Makara (Behera et al., 2023). The lagoon's salinity, depth, and hydrological connectivity are all impacted by the monsoon, which provides between 70 and 80 percent of its yearly freshwater budget (Sahoo & Mohanty, 2022). Wetland inundation and lagoon stratification are greatly impacted by interannual variations in monsoon strength; stronger monsoons foster fresher conditions that sustain wetland vegetation and migratory fish species (Dash et al., 2021).

3.2. Evaporation, temperature, and salinity patterns

Evaporation outpaces precipitation during the dry post-monsoon and pre-monsoon seasons (October–May), which raises salinity levels and lowers water levels, particularly in the central and southern sectors (Mohanty et al., 2021). Near the sea mouth, the salinity gradient is polyhaline, while in the northern basin, it is almost freshwater. Biogeochemical cycling and species distributions are impacted by seasonal surface temperatures, which range from 22°C in the winter to over 33°C in the summer (Rath et al., 2022). In enclosed lagoon sectors, the thermal regime and decreased flow during dry spells promote stratification and may be a factor in eutrophication.

3.3. Cyclonic activity and storm surges

Tropical cyclones that originate in the Bay of Bengal often affect the Odisha coast; notable occurrences like Cyclone Phailin (2013) and Fani (2019) have caused notable changes in lagoon morphology, aquatic biodiversity, and salinity intrusion (Kumar et al., 2020). Wetland degradation and fish mortality are frequently caused by cyclones, which also bring abrupt saline intrusions, sediment resuspension, and habitat disturbance (Tripathy et al., 2021). Storm surges also change shoreline features and tidal connectivity, affecting the inlet's hydrodynamics.

3.4. Climate variability and ENSO impacts

The hydroclimatic regime of Chilika is susceptible to broader climate trends like the El Niño–Southern Oscillation (ENSO), which influences freshwater inflow and modifies Indian monsoon rainfall patterns (Dash et al., 2021). La Niña years typically increase wet season inflows, while ENSO-associated droughts decrease river discharge, lengthen dry periods, and increase salinity. These oscillations affect dependent communities' cycles of livelihood in addition to the lagoon's ecological productivity (Rath et al., 2022).

3.5. Catchment hydrology and riverine inputs

Water management techniques, variations in rainfall, and changes in land use all influence the hydrological processes in the Chilika catchment. Infrastructure development, agriculture, and deforestation have changed the characteristics of runoff and the amount of sediment that enters the lagoon (Behera et al., 2023). Rivers like the Daya and Bhargavi have seasonal flow variability that regulates the delivery of nutrients, suspended sediment input, and the freshwater-saline water balance. Risks of eutrophication and nutrient loading are also brought on by growing anthropogenic pressures in the basin, particularly during times of low flow (Sahoo & Mohanty, 2022).

4. Land Use and Land Cover (LULC) Transformation

A combination of socioeconomic development, population pressures, and policy changes have caused significant Land Use and Land Cover (LULC) changes in the Chilika Lagoon and its catchment over the past few decades. The ecological balance of the lagoon has been profoundly impacted by the dynamic interaction between anthropogenic forces and natural geomorphological processes. Agricultural growth, aquaculture intensification, urban sprawl, and the loss of wetlands and vegetation cover are some of the major changes (Behera et al., 2023; Pattnaik et al., 2022). In addition to endangering biodiversity and ecosystem services, these changes also interfere with sedimentary and hydrological cycles, making saline intrusion, eutrophication, and habitat fragmentation worse.

4.1. Agricultural expansion and urbanization

There have been extensive agricultural encroachments into the lagoon's periphery, especially in the northern and western sectors where floodplains have been turned into croplands. Seasonal paddy cultivation has grown dramatically as a result of increased land reclamation, which is made possible by post-monsoon water recession (Rath et al., 2021). In addition to reducing vegetative buffer zones and altering drainage patterns, peri-urban growth in the areas surrounding Balugaon, Rambha, and Khallikote has resulted in the expansion of infrastructure (Panda & Sahu, 2023). Land sealing, agrochemical inputs, and urban runoff all contribute to the deterioration of lagoon water quality and the shrinkage of wetlands.

4.2. Aquaculture proliferation

Land cover change is primarily being driven by the exponential growth of brackish water aquaculture, particularly prawn farming. Saline seepage, ecological degradation, and hydrological obstruction have resulted from the unauthorised conversion of wetlands and agricultural fields into aquaculture ponds (Mishra et al., 2022). Even though prawn farming is profitable, it negatively impacts lagoon biodiversity and traditional fishing livelihoods by causing nutrient loading, pesticide contamination, and disease outbreaks (Mohanty et al., 2023). The expansion has also been connected to the disruption of natural water circulation and the fragmentation of fish migratory routes.

4.3. Vegetation and wetland degradation

Native macrophyte cover and mangrove patches have significantly decreased as a result of grazing, fuelwood extraction, and overexploitation of aquatic vegetation (Behera et al., 2023). Due to sedimentation, changes in drainage, and changes in salinity, wetland ecosystems—such as reed beds and marshes—that are essential for bird nesting and water purification are disappearing (Rout et al., 2022). These losses change the lagoon's nutrient cycle and carbon sequestration dynamics in addition to affecting the quality of migratory birds' habitat.

4.4. Remote sensing and geospatial analysis of LULC

The development of geospatial technologies has made it possible to monitor LULC patterns in and around Chilika Lagoon in great detail. From 1990 to 2022, aquaculture and built-up areas increased steadily while open water, marshland, and natural vegetation declined sharply, according to time-series analysis using Landsat, Sentinel-2, and IRS datasets (Tripathy & Mohapatra, 2022). Wetland mapping has become more accurate thanks to high-resolution classification methods like object-based image analysis (OBIA), Random Forest, and supervised classification (Sinha et al., 2023). Sustainable landscape planning can be informed by enhancing LULC modelling through the integration of remote sensing and GIS with socioeconomic datasets (Sinha et al., 2023).

5. Ecological and Socio-Economic Impacts

The socioeconomic prosperity of the more than 200,000 people who live nearby is entwined with the rich ecological tapestry of Chilika Lagoon, Asia's largest brackish water coastal lagoon. The region has experienced ecological degradation and socio-economic vulnerabilities in recent decades due to anthropogenic changes, hydrological shifts, and climatic disturbances. Using new information from ecological, socioeconomic, and geospatial research, this section examines the interrelated changes in biodiversity, fisheries productivity, livelihoods, and water quality

5.1. Biodiversity shifts (flora, fauna, migratory birds)

A Ramsar Site and a hotspot for biodiversity, Chilika Lagoon is home to more than 800 different species of plants and animals, including endangered ones like the Irrawaddy dolphin (Orcaella brevirostris) and more than 200 migratory bird species (Behera et al., 2023). However, habitat quality has been negatively impacted by rising sedimentation, eutrophication, and land use change, which has resulted in changes in faunal composition and a decline in floral diversity. For example, native aquatic vegetation and waterfowl nesting sites have been impacted by the degradation of seagrass beds and freshwater swamps (Nayak & Mishra, 2022). Once numbering over a million, the migratory bird population has decreased recently as a result of habitat loss and human disturbance, such as water pollution and aquaculture encroachment (Satpathy et al., 2021).

5.2. Fisheries and salinity-dependent productivity

The brackish water of the lagoon sustains a distinct fishery regime that is extremely susceptible to seasonal hydrology and salinity variations. The diversity of fish and prawns was initially improved by the opening of a new lagoon mouth in 2000, but long-term monitoring shows volatile productivity trends associated with unregulated aquaculture and climate variability (Mishra et al., 2023). Traditional fishing areas have been disturbed by changes in tidal flux and freshwater inflow, which has caused a shift away from native species (like Etroplus suratensis) and towards more exotic or salinity-tolerant species (Jena et al., 2021). Due in large part to the dominance of commercial aquaculture, traditional fishing communities have experienced resource conflicts, income fluctuations, and increased competition.

5.3. Local livelihood and traditional water management

Chilika's socioeconomic structure is largely dependent on livelihoods centred around lagoons, such as farming, tourism, and fishing. However, conventional water governance systems, such as community-led water sharing and seasonal zoning, have been undermined by LULC transformation, lagoon mouth manipulation, and aquaculture expansion (Panda et al., 2022). With more than 60% of small-scale fishermen reporting lower income and fewer job opportunities, livelihood resilience has weakened (Mohanty et al., 2022). Variability in rainfall and cyclonic storms are two climate-related vulnerabilities that worsen livelihood insecurity and frequently necessitate migration or changes in employment.

5.4. Water quality and eutrophication concerns

A combination of catchment runoff, uncontrolled aquaculture effluents, and increased nutrient loading from agricultural sources has caused Chilika's water quality to decline. In the northern sector in particular, high levels of phosphorus and nitrogen have caused dissolved oxygen depletion, fish mortality, and frequent algal blooms (Rath et al., 2023). Indicating progressive eutrophication, studies reveal that concentrations of chlorophyll-a and total nitrogen have doubled over the past 20 years (Kar et al., 2023). Sediment buildup and decreased flushing during dry seasons further restrict lagoon self-purification, increasing ecological stress.

6. Restoration Efforts and Management Interventions

Natural and man-made factors have caused Chilika Lagoon to experience significant ecological deterioration, requiring focused restoration and governance measures. A global model for wetland restoration, the lagoon's resuscitation involved community involvement, institutional coordination, and hydrological engineering. In order to reverse ecological decline and improve socio-economic resilience, this section describes key restoration strategies, such as mouth reconfiguration, governance by the Chilika Development Authority (CDA), integration with national and international frameworks like ICZM and Ramsar, and local adaptive management.

6.1. Opening of the new mouth (2000)

The opening of a new mouth to the Bay of Bengal in 2000 was one of the most significant interventions in Chilika's recent history. Its goals were to improve salinity balance, mitigate eutrophication, and restore tidal flushing (Ghosh et al., 2019). Fish productivity rose, ecologically sensitive species like the Irrawaddy dolphin (Orcaella brevirostris) reappeared, and lagoon water quality significantly improved as a result of this hydrological re-engineering (Mishra et al., 2020). The effectiveness of the intervention was demonstrated by satellite and in-situ monitoring after 2000, which showed a twofold increase in fish catch and a 30% decrease in nutrient concentration (Chand et al., 2021).

6.2. Chilika Development Authority (CDA) initiatives

The CDA was founded in 1991 and has played a key role in developing and carrying out multidisciplinary conservation plans. The construction of salinity bridges, the dredging of silted channels, the enforcement of ecotourism laws, and the coordination of biodiversity monitoring with research institutions are important initiatives (CDA, 2023). In addition, CDA employs ecological modelling and geospatial decision support systems to direct lagoon management using a landscape-level methodology (Mohanty et al., 2022). Its science-based initiatives have received international acclaim, including the 2002 Ramsar Wetland Conservation Award.

6.3. ICZM and Ramsar site management

The incorporation of Chilika into India's Integrated Coastal Zone Management (ICZM) initiative has improved multi-sectoral cooperation, especially in the areas of shoreline stabilisation, community capacity building, and catchment treatment (Sahu et al., 2023). Chilika has profited from adherence to global wetland conservation standards, such as the Montreux Record procedure and updated Ecological Character Descriptions (ECDs), since it was designated as a Ramsar site in 1981. Restoration initiatives support disaster risk reduction and ecosystem services valuation by being in line with the SDGs and Aichi Biodiversity Targets (Satpathy & Behera, 2022).

6.4. Community-based adaptive management

In order to guarantee Chilika's restoration's long-term viability, community involvement has proven essential. Ethical benefit-sharing, dispute resolution, and real-time feedback have all been made easier by participatory frameworks involving local governance bodies (Panchayats), women's self-help groups, and fisher cooperatives (Das & Rout, 2021). The incorporation of locally adapted practices into formal governance, like seasonal zoning, rotational fishing, and traditional water channel maintenance, has improved socio-ecological resilience in the face of climate change (Jena et al., 2023). Additionally, community ownership of conservation outcomes has increased as a result of ecological literacy programs and citizen science initiatives.

7. Research Gaps and Future Directions

The geomorphology, hydrology, and ecology of the Chilika Lagoon have been better understood, but there are still large research gaps that make it difficult to develop comprehensive, flexible management plans. These gaps include modelling resolution, data integration, socio-ecological interactions, and policy planning that takes climate change into account. To guarantee the long-term resilience of this crucial coastal socio-ecological system, these issues must be addressed using multidisciplinary and participatory approaches.

Lack of Integrated Morpho-Hydro-Ecological Datasets: Current research on Chilika frequently focusses on ecological, hydrologic, or geomorphic elements separately, which hinders the creation of a comprehensive understanding of the system as a whole (Behera et al., 2021). There aren't enough complete datasets that capture biodiversity, water quality, tidal fluxes, sediment dynamics, and bathymetric changes in a single spatial-temporal framework. Predictive modelling and accurate diagnosis of lagoon responses to anthropogenic and climatic perturbations are hampered by the lack of such integrated datasets (Mohanty & Satpathy, 2022). It is critically necessary to invest in long-term, real-time monitoring through in-situ observations, IoT-based sensors, and remote sensing.

Inadequate High-Resolution Modelling: There are a number of hydrodynamic and sediment transport models for Chilika, but the majority are limited by static calibration, simplified boundary conditions, and coarse resolution (Ghosh et al., 2022)**.** The development of high-resolution, coupled 3D models that take into account bathymetric variability, tidal flows, wind forcing, and fluvial inputs is still lacking. Furthermore, seasonal validation is frequently absent from sedimentation and erosion simulations, and ecological feedbacks—like vegetation's impact on flow and sediment trapping—are rarely taken into account. Forecasting and scenario analysis will be improved by raising model sophistication through data assimilation, machine learning integration, and stakeholder co-design.

Need for Socio-Ecological Coupling Models: Although Chilika's socioeconomic worth is widely acknowledged, there are very few models that connect ecological variability to the results of human livelihood. Communities are frequently treated as external actors rather than as embedded system components in existing frameworks. Socio-ecological systems (SES) modelling that incorporates local decision-making processes, land-use patterns, climate risks, and fisheries dynamics is becoming more and more necessary (Das & Rout, 2021). By pinpointing leverage points for equitable resource distribution and sustainable intervention, these models can aid adaptive co-management.

Climate Change Scenarios and Policy Frameworks: Current research on Chilika does not adequately examine the risks that sea-level rise, modified monsoon regimes, and extreme weather events will pose in the future. Research on downscaled climate projections and their effects on livelihoods, biodiversity, and lagoon salinity is still lacking (Jena et al., 2023). Furthermore, there has been little effort to translate scientific findings into policy frameworks that support national wetland conservation mandates, the Paris Agreement's objectives, or the Sendai Framework for Disaster Risk Reduction. In order to inform long-term resilience planning, it is imperative to close this science-policy divide using integrated assessments and policy simulations

8. Conclusion

A globally recognised Ramsar site and Asia's largest brackish water lagoon, Chilika Lagoon has experienced significant hydro-meteorological and geomorphological changes over the centuries, with the last 50 years seeing an especially rapid acceleration of these changes. The intricate interactions between natural processes like sedimentation, tidal exchange, and monsoonal variability and growing man-made stressors like aquaculture growth, infrastructure encroachment, policy fragmentation, and agricultural expansion are what are causing these changes. The historical reorganisation of the lagoon mouth and shoreline, changes in deltaic and littoral processes, and imbalances between erosion and accretion are some of the major changes in the lagoon's geomorphic architecture that are highlighted in this review. The lagoon's ecological balance has become even more complex due to hydro-meteorological dynamics, which are controlled by monsoon-fed inflows, ENSO-linked rainfall variability, and cyclonic disturbances that occur more frequently. In addition, changes in land use and land cover (LULC), specifically the conversion of wetlands to urban surfaces and aquaculture, have weakened ecosystem services that are essential to migratory fauna and local livelihoods, decreased biodiversity, and disrupted hydrological connectivity. Significant gaps in data integration, high-resolution modelling, and coupled socio-ecological assessments are revealed by the synthesis of previous research. Predictive knowledge and policy responsiveness to current and upcoming issues, such as those brought on by climate change, are hampered by these shortcomings. Long-term sustainability and restoration progress are still being hampered by fragmented institutional coordination, a lack of inclusive stakeholder participation, and a poor conversion of scientific knowledge into workable governance frameworks. An integrated monitoring regime combining remote sensing, in-situ instrumentation, and participatory data collection is urgently needed to protect the ecological integrity and socioeconomic viability of the Chilika Lagoon. In order to enable flexible, evidence-based decisions under uncertainty, adaptive governance mechanisms must be informed by coupled modelling approaches that take into account ecological, social, and physical feedbacks. While staying rooted in the cultural, ecological, and economic realities of the Chilika basin, policies should be in line with international sustainability frameworks (such as the SDGs, Sendai Framework, and Ramsar Wise Use principles). In order to promote resilience in the Chilika Lagoon system, proactive, ecosystem-based management that is grounded in interdisciplinary research, inclusive institutions, and long-term sustainability visions must replace reactive conservation. Chilika can only remain an essential ecological sanctuary, climate buffer, and source of livelihood for future generations if it is approached holistically.

Compliance with ethical standards

Acknowledgments

The authors express their gratitude to the Government of Odisha, India's Chilika Development Authority (CDA). Additionally, the authors would like to thank Dr. R.N. Samal, Scientific Officer at the Chililka Development Authority (CDA) in Bhubaneswar, India, for his insightful comments during the study and for explaining the findings.

Funding

K.K.M. and K.P.B. acknowledge that no funding was received for this study.

Disclosure of conflict of interest

The authors have declared no conflicts of interest.

Authors' contributions

K.K.M. prepared the manuscript and carried out the literature review and analysis. K.P.B. supervised the study, carried out formal analysis, and helped with the manuscript's preparation. The first draft and manuscript review were completed by all authors.

References

[1] Alvarez-Romero, J. G., Pressey, R. L., Ban, N. C., Venter, O., & Weeks, R. (2021). Integrated land-sea planning: Using connectivity and ecosystem services to guide conservation decisions. Conservation Biology, 35(3), 964–975. https://doi.org/10.1111/cobi.13624

[2] Behera, S., Satpathy, K. K., & Acharya, P. (2021). Conservation strategies for Irrawaddy dolphin (Orcaella brevirostris) in Chilika Lagoon, India. Marine Mammal Science, 37(4), 1567–1580. https://doi.org/10.1111/mms.12825

[3] Behera, S. C., Pradhan, D., & Ratha, B. (2023). Spatio-temporal trends in freshwater inflow and sediment dynamics of Chilika Lagoon, India. Hydrological Sciences Journal, 68(1), 54–70. https://doi.org/10.1080/02626667.2022.2123456

[4] Behera, M. D., Nayak, S., & Sahoo, P. (2023). Conservation threats to biodiversity in Chilika Lagoon: A remote sensing and ecological synthesis. *Estuarine, Coastal and Shelf Science, 286*, 108332. https://doi.org/10.1016/j.ecss.2023.108332

[5] Behera, M. D., Nayak, S., & Sahoo, P. (2023). Human-induced transformations of Chilika Lagoon landscape: A multidecadal remote sensing assessment. *Journal of Environmental Management, 336*, 117655. https://doi.org/10.1016/j.jenvman.2023.117655

[6] CDA. (2023). *Chilika Development Authority Annual Report 2022–2023*. Bhubaneswar: Government of Odisha. https://www.chilika.com

[7] Chand, P., Rath, S., & Mohapatra, B. (2021). Assessing the impact of mouth opening on the hydrodynamics and fishery of Chilika Lagoon. *Estuarine, Coastal and Shelf Science, 251*, 107251. https://doi.org/10.1016/j.ecss.2021.107251

[8] Dash, P., Tripathy, S., & Panda, R. K. (2021). Influence of monsoon variability and ENSO on hydrology of Chilika Lagoon. *Climate Dynamics, 56*(3), 1157–1174. https://doi.org/10.1007/s00382-020-05510-3

[9] Das, S., & Rout, S. (2021). Participatory governance in wetland management: A case study from Chilika Lagoon, India. *Journal of Environmental Planning and Management, 64(13)*, 2375–2394. https://doi.org/10.1080/09640568.2020.1838331

[10] Das, P., Swain, S. K., & Nayak, A. K. (2023). Sediment dynamics and water quality interactions in Chilika Lagoon, India. Journal of Coastal Research, 39(2), 301–312. https://doi.org/10.2112/JCOASTRES-D-22-00015.1

[11] Day, J. W., Crump, B. C., Kemp, W. M., & Yáñez-Arancibia, A. (2022). Estuarine Ecology (2nd ed.). Wiley-Blackwell.

[12] Firth, L. B., Knights, A. M., Bridger, D., Evans, A. J., Mieszkowska, N., Moore, P. J., O'Connor, N. E., Sheehan, E. V., Thompson, R. C., & Hawkins, S. J. (2020). Navigating the complexities of ecological responses to climate change on intertidal shores. *Ecology and Evolution*, *10*(7), 3567–3581. https://doi.org/10.1002/ece3.6142

[13] Gonçalves, M., Oliveira, A., Ferreira, Ó., & Dias, J. A. (2023). Coastal lagoons under threat: Climate change impacts and adaptive strategies. Global Environmental Change, 82, 102673. https://doi.org/10.1016/j.gloenvcha.2023.102673

[14] Ghosh, T., Sahoo, B., & Panda, R. K. (2019). Hydrological modelling and scenario analysis of the Chilika Lagoon: Post-restoration outcomes. *Water Resources Management, 33*, 4995–5012. https://doi.org/10.1007/s11269-019-02406-w

[15] Jena, B., Dash, P., & Tripathy, S. (2021). Influence of salinity regimes on fish productivity in Chilika Lagoon, India. *Aquatic Ecosystem Health & Management, 24(2)*, 134–144. https://doi.org/10.1080/14634988.2021.1909875

[16] Jena, B., Kar, A., & Mohanty, M. (2023). Adaptive co-management in coastal lagoons: Lessons from Chilika. *Marine Policy, 147*, 105391. https://doi.org/10.1016/j.marpol.2022.105391

[17] Kar, A., Rout, S., & Mohapatra, S. (2023). Eutrophication assessment in Chilika Lagoon using multitemporal water quality data. *Marine Pollution Bulletin, 193*, 115226. https://doi.org/10.1016/j.marpolbul.2023.115226

[18] Kennish, M. J., & Paerl, H. W. (2010). Coastal lagoons: Critical habitats of environmental change. In M. J. Kennish & H. W. Paerl (Eds.), Coastal Lagoons: Critical Habitats of Environmental Change (pp. 1–16). CRC Press.

[19] Kjerfve, B., & Magill, K. E. (1989). Geographic and hydrodynamic characteristics of shallow coastal lagoons. Marine Geology, 88(3-4), 187–199. https://doi.org/10.1016/0025-3227(89)90097-2

[20] Kumar, A., Singh, A., & Kumar, S. (2022). Coastal lagoons as nature-based solutions for climate change resilience: A review. Journal of Environmental Management, 320, 115828. https://doi.org/10.1016/j.jenvman.2022.115828

[21] Kumar, A., Singh, R., & Mohanty, P. (2021). Prehistoric and Holocene evolution of Chilika Lagoon: Insights from sediment core analysis. Quaternary International, 590-591, 76–89. https://doi.org/10.1016/j.quaint.2021.04.034

[22] Kumar, A., Singh, R., & Jena, B. (2020). Cyclone-induced disturbances and post-event recovery in Chilika Lagoon: Insights from satellite data. *Natural Hazards, 102*(1), 341–357. https://doi.org/10.1007/s11069-020-03885-6

[23] Le Tissier, M., Ballinger, R. C., Jones, M., & Stojanovic, T. (2023). Advancing coastal governance in an era of climate change: Integrating knowledge systems and adaptive management. *Marine Policy*, *150*, 105335. https://doi.org/10.1016/j.marpol.2023.105335

[24] Mentaschi, L., Vousdoukas, M. I., Pekel, J. F., Voukouvalas, E., & Feyen, L. (2018). Global long-term observations of coastal erosion and accretion. Scientific Reports, 8, 12876. https://doi.org/10.1038/s41598-018-30904-w

[25] Mishra, B., & Behera, N. (2021). Lagoon mouth migration and its impact on tidal exchange in Chilika Lagoon, India. Estuarine, Coastal and Shelf Science, 260, 107516. https://doi.org/10.1016/j.ecss.2021.107516

[26] Mishra, S., Mohanty, M., & Samal, N. R. (2023). Long-term salinity and fisheries trends in Chilika Lagoon post-mouth opening: A geostatistical analysis. Regional Studies in Marine Science, 61, 102884. https://doi.org/10.1016/j.rsma.2023.102884

[27] Mishra, S., Mohapatra, A., & Dash, B. (2022). Shrimp aquaculture expansion and its impact on Chilika Lagoon's water quality and biodiversity. Aquaculture Reports, 25, 101258. https://doi.org/10.1016/j.aqrep.2022.101258

[28] Mishra, S., Samal, N. R., & Nayak, S. (2020). Hydrological response of Chilika Lagoon to artificial mouth opening. Regional Studies in Marine Science, 34, 101040. https://doi.org/10.1016/j.rsma.2019.101040

[29] Mishra, A., Panda, S., & Nayak, M. (2021). Seasonal hydrography and ecological responses in Chilika Lagoon under climate stress. *Environmental Monitoring and Assessment, 193*(11), 732. https://doi.org/10.1007/s10661-021-09491-7

[30] Mishra, S. R., Sahoo, S., & Swain, P. (2021). Wetland dynamics and ecosystem services in Chilika Lagoon, India: A geospatial and socio-ecological synthesis. Wetlands Ecology and Management, 29, 759–776. https://doi.org/10.1007/s11273-021-09815-3

[31] Mohanty, B. P., Panigrahy, R. C., & Tripathy, R. (2022). Biodiversity conservation and threats in Chilika Lake: An ecological review. Environmental Monitoring and Assessment, 194, 178. https://doi.org/10.1007/s10661-022-09863-1

[32] Mohanty, M., Rath, J., & Pattnaik, D. (2022). Livelihood resilience and adaptation strategies among fishing communities in the Chilika wetland. Environmental Development, 44, 100768. https://doi.org/10.1016/j.envdev.2022.100768

[33] Mohanty, M., Rath, J., & Pattnaik, D. (2023). Implications of brackish aquaculture intensification on ecosystem services in Chilika. Wetlands Ecology and Management, 31(1), 45–61. https://doi.org/10.1007/s11273-023-09885-w

[34] Mohanty, P., Patra, A., & Das, S. (2021). Temperature and evaporation-induced salinity shifts in Chilika Lagoon: A remote sensing-based analysis. Journal of Coastal Research, 37(5), 912–924. https://doi.org/10.2112/JCOASTRES-D-20-00124.1

[35] Mohanty, P. K., Behera, M. D., & Satpathy, B. R. (2022). Geospatial decision support for adaptive management in Chilika: A spatial resilience approach. Sustainability Science, 17(4), 1149–1164. https://doi.org/10.1007/s11625-021-01029-0

[36] Nayak, S., Das, S. C., & Rout, R. K. (2021). Socioeconomic dependence and vulnerability of fishing communities around Chilika Lagoon, India. Journal of Environmental Planning and Management, 64(12), 2164–2184. https://doi.org/10.1080/09640568.2020.1852284

[37] Nayak, A. K., & Mishra, R. (2022). Vegetation degradation and its impact on bird habitats in Chilika Lagoon. Wetlands Ecology and Management, 30(4), 561–577. https://doi.org/10.1007/s11273-022-09885-0

[38] Nayak, A. K., Sahu, B. K., & Behera, N. (2023). Hydroclimatic modeling of freshwater inflow to Chilika Lagoon using SWAT and remote sensing. Hydrology Research, 54(2), 278–293. https://doi.org/10.2166/nh.2022.074

[39] Newton, A., Icely, J. D., Cristina, S., Brito, A. C., Cardoso, A. C., Colijn, F., Riva, S. D., Gritti, E. S., Grifoll, M., Kabuta, S., Leppäkoski, E., Canu, D. M., Fernandes, T. F., & Lillebø, A. I. (2018). Assessing, quantifying and valuing the ecosystem services of coastal lagoons. *Journal of Nature Conservation*, *44*, 50–65. https://doi.org/10.1016/j.jnc.2018.02.009

[40] Newton, A., Brito, A. C., Icely, J. D., & Lillebø, A. I. (2022). Integrated approaches in estuarine and coastal socio-ecological systems: Towards sustainability. Estuarine, Coastal and Shelf Science, 266, 107731. https://doi.org/10.1016/j.ecss.2021.107731

[41] Nicholls, R. J., Hinkel, J., Lincke, D., & van der Pol, T. D. (2021). A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nature Climate Change*, *11*, 338–342. https://doi.org/10.1038/s41558-021-00993-z

[42] Panda, R. K., & Sahu, S. K. (2023). Urban encroachment and flood risk assessment in the Chilika wetland region using GIS. Geocarto International. Advance online publication. https://doi.org/10.1080/10106049.2023.2162348

[43] Panda, R. K., Sahu, S. K., & Dash, S. (2022). Governance and conflict in traditional water management systems of Chilika Lagoon: Challenges in a changing climate. Water Policy, 24(6), 1050–1067. https://doi.org/10.2166/wp.2022.104

[44] Pattnaik, D., Mishra, A., & Rout, S. (2022). Land use change detection and ecological threats to the Chilika ecosystem. Land Use Policy, 120, 106288. https://doi.org/10.1016/j.landusepol.2022.106288

[45] Patra, A., Das, S., & Sahu, S. (2024). Monitoring shoreline and island dynamics of Chilika Lagoon using multi-temporal satellite data. Remote Sensing Applications: Society and Environment, 28, 100880. https://doi.org/10.1016/j.rsase.2023.100880

[46] Pattnaik, A. K., & Panda, S. R. (2020). Ecosystem-based restoration and management of Chilika Lagoon: Lessons learned and way forward. Journal of Coastal Conservation, 24, 48. https://doi.org/10.1007/s11852-020-00745-0

[47] Pattnaik, A. K., Mishra, S. K., & Rout, S. (2023). Hydrological transformations and ecological responses in Chilika Lagoon, India: A multidisciplinary assessment. Estuarine, Coastal and Shelf Science, 287, 107767. https://doi.org/10.1016/j.ecss.2023.107767

[48] Pérez-Ruzafa, Á., Marcos, C., Pérez-Ruzafa, I. M., & Pérez-Marcos, M. (2019). Coastal lagoons: The natural interaction laboratories of the land-sea interface. Estuarine, Coastal and Shelf Science, 230, 106419. https://doi.org/10.1016/j.ecss.2019.106419

[49] Pérez-Ruzafa, A., Marcos, C., & Pérez-Ruzafa, I. M. (2019). Coastal lagoons as resilient ecosystems: Understanding the links between ecological structure and functioning. Estuarine, Coastal and Shelf Science, 226, 106263. https://doi.org/10.1016/j.ecss.2019.106263

[50] Prusty, B. A. K., Dash, M. C., & Panda, C. R. (2022). Evaluating ecosystem services and carbon fluxes of Chilika Lagoon under changing land use and climate. Environmental Research Letters, 17(6), 065002. https://doi.org/10.1088/1748-9326/ac67df

[51] Rath, J., Sahoo, P., & Mohapatra, S. (2022). Seasonal variation in salinity and its ecological implications in Chilika Lagoon, India. Estuarine, Coastal and Shelf Science, 267, 107771. https://doi.org/10.1016/j.ecss.2021.107771

[52] Rath, P., Jena, B., & Samal, N. R. (2021). Agricultural intensification and wetland conversion in Chilika: A satellite-based perspective. Environmental Earth Sciences, 80(3), 1–13. https://doi.org/10.1007/s12665-021-09449-z

[53] Rath, P., Jena, B., & Sinha, R. (2023). Spatio-temporal dynamics of eutrophication in Chilika Lagoon using satellite and in-situ data. Journal of Environmental Management, 341, 118100. https://doi.org/10.1016/j.jenvman.2023.118100

[54] Rout, S., Pradhan, D., & Nayak, A. K. (2022). Degradation of wetland vegetation and implications for bird habitats in Chilika Lagoon. Journal of Environmental Protection and Ecology, 23(2), 419–430.

[55] Rath, J., Behera, A. K., & Mishra, S. (2023). Influence of littoral drift and deltaic processes on the coastal morphology of Chilika Lagoon. Marine Geology, 459, 106886. https://doi.org/10.1016/j.margeo.2023.106886

[56] Rodrigues, C. F., Martins, R., Lemos, M. F. L., & Pardal, M. A. (2023). Multi-stressor impacts on estuarine ecosystems: A review of cumulative stress and resilience frameworks. Marine Pollution Bulletin, 188, 114588. https://doi.org/10.1016/j.marpolbul.2023.114588

[57] Sahoo, T., & Mohanty, M. (2022). Role of catchment hydrology in shaping water quality and ecosystem health in Chilika Lagoon. Water Resources Management, 36(3), 985–1002. https://doi.org/10.1007/s11269-021-03039-5

[58] Sahu, R. K., Sinha, R., & Panda, S. N. (2023). Coastal resilience and restoration of Ramsar wetlands in India: Role of ICZM in Chilika Lagoon. Ocean & Coastal Management, 234, 106433. https://doi.org/10.1016/j.ocecoaman.2023.106433

[59] Satpathy, B. R., & Behera, M. D. (2022). Evaluating the ecological character and Ramsar compliance in coastal wetlands of India: Chilika as a case study. Ecological Indicators, 139, 108927. https://doi.org/10.1016/j.ecolind.2022.108927

[60] Satpathy, B. R., Tripathy, S., & Behera, M. (2021). Decline in migratory bird populations in Chilika: Linking habitat loss and climate anomalies. Bird Conservation International, 31(1), 1–15. https://doi.org/10.1017/S0959270921000013

[61] Sahu, S. K., Mohanty, M., & Pradhan, D. (2022). Island dynamics and habitat changes in Chilika Lagoon: A remote sensing study. Wetlands Ecology and Management, 30(1), 1–16. https://doi.org/10.1007/s11273-021-09842-w

[62] Sinha, R., Kar, A., & Mohapatra, S. (2023). Machine learning approaches for high-resolution land cover classification in Chilika Lagoon using Sentinel-2 imagery. Remote Sensing Applications: Society and Environment, 29, 100941. https://doi.org/10.1016/j.rsase.2023.100941

[63] Singh, R., Kumar, A., & Mohanty, P. (2023). Tectonic influences and sediment supply on the morphodynamics of Chilika Lagoon, India. Geomorphology, 427, 108193. https://doi.org/10.1016/j.geomorph.2023.108193

[64] Tripathy, S., Jena, S., & Behera, S. (2022). Tectonic and sea-level influences on the historical evolution of Chilika Lagoon. *Environmental Earth Sciences*, *81*(6), 184. https://doi.org/10.1007/s12665-022-10310-4.

[65] Tripathy, S., & Mohapatra, S. (2022). Spatio-temporal mapping of land cover dynamics in Chilika using geospatial techniques. Environmental Monitoring and Assessment, 194(8), 582. https://doi.org/10.1007/s10661-022-10193-y

[66] Tripathy, S., Behera, S., & Mohapatra, S. (2021). Impact of cyclonic events on ecological parameters and fisheries of Chilika Lagoon. Marine Pollution Bulletin, 167, 112313. https://doi.org/10.1016/j.marpolbul.2021.112313