

Water quality in Sambhar Lake: Recent advances and future prospects

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Abstract

Sambhar Lake, India's largest inland saline wetland and a Ramsar site, is vital for both ecology and the economy, serving as a key habitat for migratory birds and a major centre for salt production. Over the past two decades, the lake has suffered from serious water quality decline due to unchecked human activities such as industrial pollution, illegal bore-wells, unregulated salt extraction, and encroachment, all worsened by climate variability and reduced rainfall. Scientific studies have tracked rising salinity, nutrient loading, heavy metal contamination, and biological changes, with modern tools like remote sensing and GIS improving monitoring. These environmental stresses have led to a drop in bird diversity and mass mortality events. Despite some policy and conservation efforts, enforcement and community involvement remain weak. The review stresses the urgent need for integrated, multidisciplinary strategies—combining hydrological restoration, pollution control, ecotourism, and innovation—to restore Sambhar Lake's ecological and economic health for the future.

Keywords: Sambhar Lake, saline wetland degradation, migratory bird habitat loss, salt production and environmental impact, integrated lake restoration strategies

Introduction

Sambhar Lake, located in the Indian state of Rajasthan, is the largest inland saline wetland in the country and holds significant ecological, cultural, and economic value. Spread over approximately 230 square kilometers, the lake is a Ramsar Site of international importance, recognized for its rich avifaunal biodiversity, particularly as a habitat for migratory birds such as flamingos, pelicans, and storks (Yadav *et al.*, 2007) [16]. The lake's hypersaline nature supports a thriving salt industry that contributes substantially to the local economy. However, in recent decades, Sambhar Lake has faced severe degradation in water quality due to both natural and anthropogenic factors, raising serious concerns among environmentalists, scientists, and policymakers (Sinha, & Raymahashay, 2004) [12].



Fig 2: Sambhar Lake, Rajasthan (Google Earth)

The water quality of any wetland system is a crucial determinant of its ecological health and functional sustainability. For Sambhar Lake, the increasing pressure from salt extraction, illegal borewell drilling, industrial pollution, and encroachment of catchment areas has resulted in altered hydrology, increased salinity, eutrophication, and contamination by heavy metals and other toxicants. Concurrently, the region's arid climate, coupled with erratic monsoon patterns and reduced inflow from seasonal rivers

such as the Mendha, Rupangarh, Kharian, and Khandel, has exacerbated the situation. These environmental stressors have not only reduced the lake's water spread and depth but have also impaired its ability to support aquatic life and bird populations (Bhat *et al.*, 2015) [2, 3].

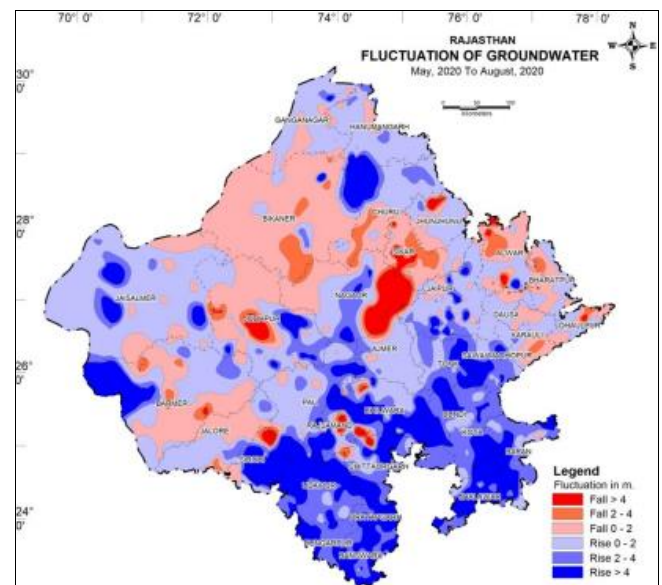


Fig 1: Water Level Fluctuation- May to August 2020

Over the period from 2000 to 2020, several scientific investigations have been undertaken to evaluate the water quality of Sambhar Lake using both conventional field-based analyses and modern tools such as remote sensing, GIS, and ecological modeling. These studies have focused on the physical and chemical parameters of the lake, including Total Dissolved Solids (TDS), pH, salinity, turbidity, dissolved oxygen (DO), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and nutrient loading (notably nitrates and phosphates) (Kajale, & Deotare, 1997) [6]. More recent research has also

3. Heavy Metal Contamination

The World Health Organization and AERB have different guideline values for uranium, with the World Health Organization assuming up to 30 µg/l can be tolerated in

drinking water and the AERB setting the limit at 60 µg/l for drinking waters. Measurement of uranium levels in aquatic environments is crucial for environment safety (Bhat, & Sharma, 2015) [2, 3].

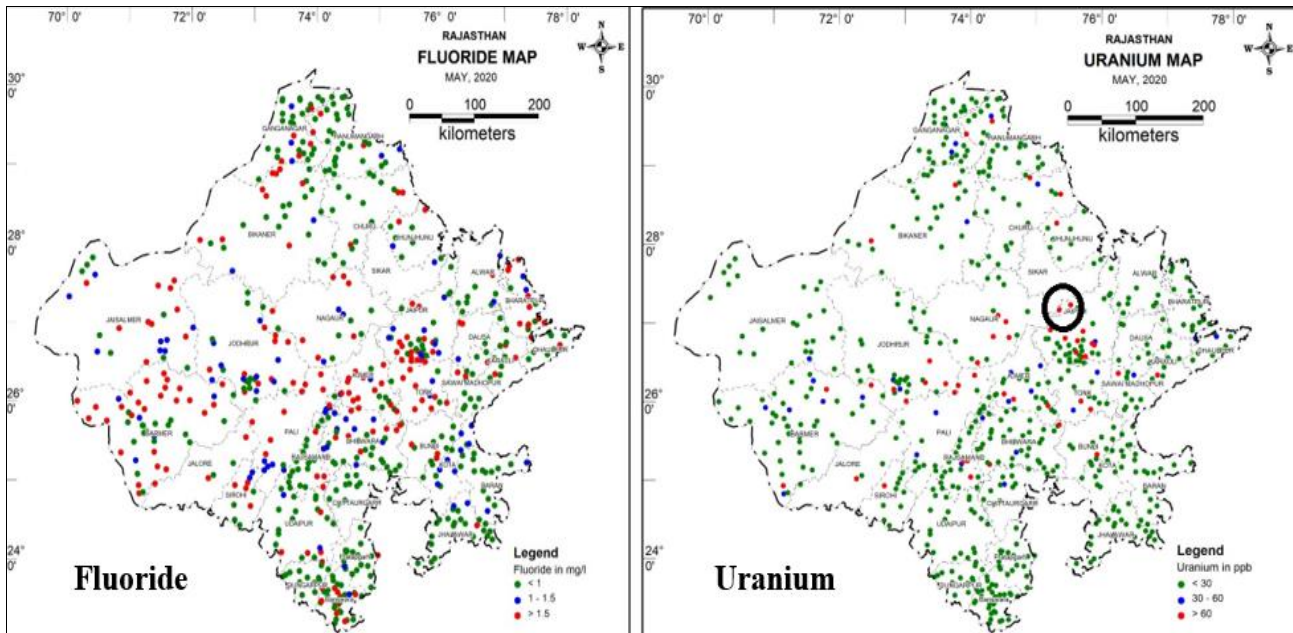


Fig 3: Distribution of Fluoride and Uranium in May 2020

Sambhar Lake, has faced increasing environmental threats, particularly heavy metal contamination, over the past two decades. Rapid industrialization, unregulated salt extraction, and discharge of untreated effluents have contributed significantly to the accumulation of toxic metals such as lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), and zinc (Zn) in the lake's water and sediments. Cherekar, & Pathak, 2016 [4], have reported heavy metal concentrations exceeding safe limits prescribed by environmental standards, posing serious ecological and health risks. The concentrations of arsenic in water samples of Rajasthan state ranged from 00 to 53.389 ppb. In water sample of Kharbaro in Bikaner district having 53.389 ppb maximum value of arsenic (Cherekar, & Pathak, 2016) [4].

These metals, introduced through runoff from nearby salt refineries, vehicular emissions, and industrial waste, bioaccumulate in aquatic organisms and disrupt the lake's fragile food web. Flamingo deaths and declining aquatic biodiversity in recent years have been linked to such contamination. Moreover, local communities involved in salt production and brine harvesting are exposed to chronic health hazards due to prolonged contact with polluted water. Despite several government interventions, monitoring and enforcement remain weak. Effective management demands regular water quality assessments, industrial regulation, bioremediation efforts, and greater public awareness to safeguard Sambhar Lake's ecological integrity and the livelihoods it supports (Arun *et al.*, 2014) [1].

4. Ecological Impacts

Sambhar Lake, plays a vital role in supporting migratory bird populations, salt production, and the fragile desert ecosystem of Rajasthan. However, deteriorating water quality over the past few decades has led to serious ecological consequences. The lake's hypersaline nature, once a stable ecological feature, has been severely impacted by unregulated salt extraction, reduced freshwater inflows,

and pollution from nearby settlements and industries (Cherekar, & Pathak, 2016) [4].

One of the most visible ecological impacts is the decline in avifaunal diversity. Sambhar Lake is a Ramsar site known for hosting thousands of flamingos, pelicans, and other migratory birds. The 2019 mass mortality of over 20,000 migratory birds was attributed to avian botulism triggered by poor water quality and low oxygen levels (Vicente, 2020) [13]. Habitat fragmentation due to illegal bunding, encroachment, and hydrological alterations has further stressed the ecosystem. Thus, the ecological impacts of declining water quality in Sambhar Lake are multifaceted, affecting species diversity, ecosystem functioning, and livelihoods. Without immediate conservation efforts and sustainable water management practices, the lake's ecological integrity and global environmental significance may be permanently compromised (Singh *et al.*, 2020) [11].

Recent Advances in Monitoring and Assessment

1. GIS and Remote Sensing Applications

In recent decades, GIS (Geographic Information System) and remote sensing technologies have emerged as powerful tools to monitor, assess, and manage the lake's environmental health effectively. Remote sensing provides multi-temporal satellite imagery that captures changes in lake area, water spread, turbidity, and salinity patterns. Studies using Landsat, MODIS, and Sentinel data have revealed a consistent decline in water levels and an increase in dry patches around the lake periphery. GIS techniques enable spatial analysis of land use changes in the Sambhar catchment, mapping illegal salt pans, blocked feeder channels, and nearby urban encroachments. Integrating GIS with remote sensing allows generation of thematic maps, such as water quality zoning, pollution hotspots, and vulnerability assessment layers. Digital Elevation Models (DEMs) have further supported hydrological modeling,

drainage pattern analysis, and watershed delineation (Bhat and Sharma, 2015)^[2, 3].

Overall, GIS and remote sensing applications offer cost-effective, scalable, and non-invasive approaches for long-term monitoring of Sambhar Lake. These tools not only enhance our understanding of spatial and temporal dynamics but also support informed decision-making for sustainable lake restoration and wetland conservation. Strengthening satellite-based monitoring, coupled with local data collection, is essential for preserving the ecological and economic functions of Sambhar Lake.

2. Physico-Chemical Modeling

Physico-chemical modeling has emerged as a vital tool to analyze and predict the lake's water quality, offering insights into the complex interactions between natural processes and anthropogenic influences. Several studies utilized models like the Water Quality Index (WQI), Principal Component Analysis (PCA), and QUAL2K to evaluate parameters such as salinity, pH, Total Dissolved Solids (TDS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and heavy metal concentrations (Bhat, & Sharma, 2015)^[2, 3].

High salinity and alkaline pH levels (8.2–9.5) have been consistently recorded, linked to evaporation and salt production processes. Modeling revealed seasonal fluctuations in BOD and COD, indicating the impact of organic load from nearby settlements and saltpan waste. The WQI model helped in classifying water quality zones—most falling under poor to very poor categories. PCA was used to determine dominant pollution sources, pointing to salt industry discharge, brine extraction, and minimal freshwater inflow as primary contributors (Sinha, & Raymahashay, 2004)^[12].

Spatial mapping using GIS-based models showed shrinking lake boundaries and increased salinity hotspots, which correlated with water extraction points and unregulated borewell activities. QUAL2K simulations provided useful data for policy formulation by predicting scenarios under different restoration strategies, such as regulated inflows and reduced pollution loads (Vijay *et al.*, 2016)^[14].

3. Biological Monitoring

Biological monitoring has emerged as a vital tool in assessing the ecological health of Sambhar Lake, India's largest inland saline wetland. Traditional water quality assessments based on physicochemical parameters are now being complemented by biological indicators, providing a more comprehensive understanding of ecosystem changes. Over the past two decades, researchers have used plankton diversity, macroinvertebrate populations, and avifaunal behavior as key bioindicators. Changes in phytoplankton and zooplankton communities—such as a dominance of cyanobacteria and decline in diatoms—signal nutrient enrichment and potential eutrophication. Macroinvertebrate diversity has also declined, indicating deteriorating habitat quality and oxygen depletion. Moreover, the mass deaths of migratory birds like flamingos in recent years have been linked to high salinity, microbial toxins, and reduced prey availability due to water quality degradation. Molecular and microbial studies, including the detection of pathogens and harmful algal blooms (HABs), are being increasingly utilized to identify biological risks. These biological assessments provide early warnings of ecological

imbalance, offering crucial data for timely intervention and conservation strategies. Integrating biological monitoring with remote sensing and GIS technologies can enhance long-term water quality management and help protect the ecological integrity of Sambhar Lake (Kulshreshtha *et al.*, 2020)^[7].

Anthropogenic Pressures and Climate Variability

Unregulated salt extraction, construction of illegal borewells, and encroachment by private salt industries have drastically reduced the lake's water inflow and increased salinity beyond natural thresholds. Discharge of untreated domestic wastewater, agricultural runoff, and solid waste from nearby towns further contaminates the lake, introducing nitrates, phosphates, and heavy metals into its fragile ecosystem (Kulshreshtha *et al.*, 2013)^[8].

Climate variability compounds these pressures. A consistent decline in rainfall, higher evaporation rates, and prolonged dry spells—observed over the past two decades—have led to shrinking water levels and increased concentration of pollutants. Reduced freshwater input also disrupts the ecological balance, affecting migratory bird habitats and increasing the risk of mass die-offs (Bhat *et al.*, 2015)^[2, 3].

These combined impacts have altered the lake's hydrochemistry, affecting pH, dissolved oxygen, and nutrient dynamics. Without immediate intervention, Sambhar Lake faces irreversible degradation. Sustainable management, restoration of feeder streams, regulation of saltpan activities, and adaptive climate strategies are urgently needed to preserve the lake's ecological and economic value.

Future Prospects and Recommendations

1. Restoration and Conservation Strategies

Sambhar Lake, India's largest inland saline wetland, faces severe water quality degradation due to unchecked salt extraction, reduced freshwater inflow, industrial discharge, and climate change. Restoration and conservation strategies must focus on integrated watershed management and pollution control. Hydrological restoration through desilting Feeder Rivers, removal of encroachments, and regulated water inflow is critical for maintaining the lake's ecological balance. Strict enforcement against illegal borewells and unregulated salt pans is necessary to control brine overextraction and contamination. Pollution control measures, including sewage treatment from nearby settlements and regulation of industrial effluents, should be implemented urgently. Promoting nature-based solutions like phytoremediation using salt-tolerant plant species and constructed wetlands can further enhance water purification. Establishing buffer zones and ecological corridors will help protect aquatic and avian biodiversity (Kulshreshtha *et al.*, 2020)^[7].

Community participation is vital—local salt workers, farmers, and NGOs should be engaged in conservation efforts through awareness programs and sustainable livelihood alternatives. Scientific monitoring using GIS, remote sensing, and biological indicators should guide decision-making. A multi-stakeholder, science-driven, and climate-resilient approach is essential to restore Sambhar Lake's water quality, safeguard its biodiversity, and ensure sustainable salt production and eco-tourism opportunities for future generations.

2. Community Participation

Community participation plays a vital role in improving and maintaining the water quality of Sambhar Lake. Local communities, including salt workers, farmers, and residents, have traditionally depended on the lake for their livelihoods. However, in recent decades, unregulated salt extraction, overuse of groundwater, and pollution from domestic and industrial sources have severely degraded the lake's water quality.

Engaging these communities in conservation efforts is essential for sustainable management. Awareness programs on pollution control, judicious use of water resources, and sustainable salt production can empower locals to become stewards of the lake. Formation of community-based organizations (CBOs), eco-clubs, and self-help groups can enhance grassroots monitoring and reporting of illegal activities (Kulshreshtha *et al.*, 2013)^[8].

NGOs and academic institutions can further support through citizen science initiatives, water testing kits, and environmental education. Participation in government schemes like the National Wetland Conservation Programme (NWCP) can also be promoted. By integrating local knowledge with scientific and regulatory frameworks, community participation can lead to effective, long-term solutions for restoring Sambhar Lake's ecological health and water quality. Sustainable livelihoods and improved environmental stewardship must go hand-in-hand to protect this unique wetland ecosystem.

3. Scientific Research and Innovation

Over the past two decades, researchers have employed innovative tools to monitor and analyze the lake's physico-chemical and biological parameters. Remote sensing and GIS technologies have been instrumental in tracking changes in water spread, salinity, and land use patterns. Hydrochemical studies have revealed rising levels of total dissolved solids (TDS), heavy metals like lead and chromium, and nutrient enrichment leading to eutrophication.

Advanced modeling tools such as the Water Quality Index (WQI) and QUAL2K have helped quantify pollution levels and simulate future scenarios. Microbial assessments using DNA-based methods and phytoplankton diversity indices offer new insights into biological health and pollution sources. Additionally, research into bio-remediation using algae and aquatic plants shows promise for eco-friendly restoration. A multidisciplinary approach combining technology, ecology, and policy will be essential to safeguard Sambhar Lake's ecological integrity and support sustainable development in the region (Vijay *et al.*, 2016)^[14].

4. Ecotourism and Sustainable Development

Ecotourism presents a promising path for sustainable development while promoting lake conservation. By attracting bird watchers, nature enthusiasts, and researchers, ecotourism can generate income for local communities and create incentives to protect water resources and wildlife habitats. Sustainable tourism initiatives—such as guided bird-watching tours, nature education centers, and salt heritage trails—can raise awareness about the lake's environmental challenges. Importantly, ecotourism must be planned to avoid ecological disturbance and include strict waste and water management practices. Local communities,

particularly salt workers and traditional artisans, should be actively involved in tourism planning and benefit-sharing to ensure equitable growth. Linking water quality improvement with ecotourism development creates a cycle of positive feedback: cleaner water enhances wildlife presence, which in turn attracts more tourists, funding further conservation (Meena, & Bareth, 2020)^[9].

Conclusion

The water quality of Sambhar Lake has undergone significant degradation that driven by unchecked anthropogenic activities, declining freshwater inflow, industrial encroachment, and climate-induced changes. Research over the past two decades has identified alarming trends in rising salinity, eutrophication, heavy metal contamination, and ecological imbalances, including the decline in migratory bird populations. While advancements in water quality assessment—such as GIS-based remote sensing, hydrochemical modeling, and biological monitoring—have improved understanding, actual conservation actions remain limited. Involving local communities and stakeholders in lake conservation, promoting ecotourism, and adopting innovative remediation technologies are essential steps toward sustainable lake management. Strengthening scientific research and enforcing environmental regulations can help reverse ecological damage and revive Sambhar Lake's unique saline ecosystem. A coordinated, multi-stakeholder approach—blending traditional knowledge, modern science, and policy intervention—is imperative for safeguarding the lake's ecological and economic values for future generations.

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