# Hydrological Dynamics and Ecological Consequences of Sambhar Lake through Multi-Satellite Approach to Wetland Monitoring

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**Abstract**: The largest inland saline lake in India, the Sambhar Lake is significant ecologically as well as economically, and has been encountering marked hydrological shifts primarily from climatic change and anthropogenic activities. This study aims to quantify these hydrological changes and assess their ecological consequences to inform effective management strategies for Sambhar Lake. Utilizing high-resolution Sentinel-2 satellite imagery and Google Earth Engine (GEE), we analyzed transitions in water coverage and quality from 1984 to 2021. We employed spectral indices such as Total Suspended Solids (TSS), Turbidity, and Chlorophyll-a to evaluate fluctuations in water quality. Analysis showed an increase in permanent bodies of water while areas of variable seasonal water reflect a dynamic hydrological state determined by environmental and anthropogenic induced disturbances. The study uncovered temporal spikes in turbidity and TSS content, placing special emphasis on the monsoon seasons, alluding to sediment inflows and eutrophication threats. Chlorophyll-a concentrations exhibited seasonal surges indicative of algal blooms. This integrated, multi-decadal assessment provides new scientific evidence to guide policymakers and conservationists in developing targeted, sustainable management actions for Sambhar Lake and other vulnerable saline wetlands.

**Keywords:** Anthropogenic Effects; Birbitat; Climatic Variability; Hydrological Dynamics; Inland Saline Lake; Ramsar Site; Water Quality; Wetland Conservation; Wtland Monitoring

## 1. Introduction

Sambhar Lake, Rajasthan's largest salt lake, is a Ramsar site due to its global ecological importance[1)]. Historically, it was inhabited by diverse migratory and resident bird populations, was biologically rich, and used for salt production[2)]. As a result of increasing human pressures such as urbanization, over-exploitation of water resources, and agricultural growth, and climatic variability, the lake has experienced drastic hydrological transformations in the last few decades[3)]. Besides disturbing the biological well-being and hydrological balance of the lake, these changes also endangered the economic well-being of the cities dependent on its resources. To guarantee its environmental functions and passing through global conservation obligations, the Ramsar site gives utmost importance to careful monitoring and sound management measures[4)]. For the purpose of establishing hydrological alteration in India's largest inland saline lake, Sambhar Lake, Sen (2024) took a decade's worth of data into account. Based on 1991-2023 rainfall and remote-sensing data, the study identified that the coverage area of the lake water had been reducing in some years. Hydrological models show that recent extreme events (such as the 2019 flooding that caused a die-off of thousands of pelicans) were outliers, and future changes in water levels will probably stay within manageable limits. This work underlines the necessity of long-term monitoring to detect gradual wetland shrinkage and determine risks to wetland health[5)]. Hird et al. (2017) realized the next generation of wetland mapping using multi-source data fusion on the GEE cloud platform. Using (numerous) terrain (DEM-derived) metrics plus satellite imagery, they also developed a

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boosted‑tree model in R to predict wetland occurrence across 13,700 km² of Alberta. All models showed high accuracy (Area Under Curve ≈0.90) and agreement (85%) with the official wetland inventory when the continuous output was classified into binary wetland map. Specifically, the highest disaggregated weights in the RF were topographic indices (e.g. wetness and position indices), although subsequent improvement was found when multi-season Sentinel optical and SAR imagery were included in the model. This study highlights how cloud computing and free satellite data facilitate large-scale performance monitoring of wetlands at high resolution with relatively few field data –ageneral approach scalable for regional to national wetland assessments[6]. Seyed Mousavi & Akhoondzadeh, 2023 proposed a simple yet powerful approach to map water area in the extensive Shadegan Wetland (Iran) using Sentinel-2 imagery on GEE. They performed a histogram threshold method to classify water pixels based on the calculated Modified Normalized Difference Water Index (MNDWI) for each image and compared the results with that of a Random Forest classifier. Aiming at the period between 2019 and 2021, this study automated open water extraction and seasonality analysis on wetland extents. This approach — fusing high-res multispectral data with cloud computing — allowed rapid assessment of how an internationally important marsh has changed over the years and the seasons. Such remote-sensing approaches are becoming more common in monitoring wetland transitions in near-real time and informing conservation actions in data-poor locations[7]. Shariati & Hemami (2024) investigated the ecological impacts of the rapid decline of Lake Urmia, a highly saline Ramsar lake which has seen most of its volume drain since 2000. And they discovered that 2000 was a critical breakpoint, when heading for declining water levels and rising salinities caused a collapse in waterbird populations. Employing long-term bird census data (1970–2018) and statistical models (breakpoint analysis, CCA), the study found a close coupling between lake water presence and the abundance of migratory flamingos, pelicans, and shorebirds. The majority of waterbird species declined in tandem with the lake's retreat, reinforcing that water level changes "underlie the dynamics of the lake's waterbird assemblages." Significantly, even modest refilling of the lake had lopsidedly positive, widespread effects on bird numbers. This case illustrates how climate change and upstream water diversions (the drivers of Urmia's desiccation) can destroy wetland biodiversity — but also that partial hydrological restoration could swiftly benefit wildlife[8]. Wang and Yésou (2018) note that "remote sensing can render the process of understanding these sensitive and complex floodpath lakes and wetlands as well as their interactions with their surrounding environment in an increased resolution and scale." Their work highlights the need to combine cutting-edge remote sensing technologies to monitor and model the changing water levels and surface areas of these ecosystems[9]. Yussupov and Suleimenova (2023) further demonstrate the applicability of remote sensing to desertification monitoring. Their research emphasizes how these technologies are able to monitor continental scale land cover change as susceptible to desertification processes and provides observations needed to verify that the land is managed sustainably. This accuracy can significantly benefit the agricultural and industrial sectors, where understanding ecological changes is critical in avoiding environmental degradation[10]. For a more practical use case, Sae-ngow et al. (2024) used UAVs to measure tree heights for carbon stock evaluations on family woodlands. The results of their work, which contrast remote sensing data with the more conventional field survey, show how the accuracy of remote sensing may increase the precision and efficiency of data gathering in carbon cycle studies using innovative semiautomatic technologies[11]. Al Falah et al. (2023) used diatom stratigraphy to document floods from the Tuntang River, Central Java. The study exemplified that sediment core analyses supplemented with remote sensing data can yield historical records of flooding which are essential for flood management and mitigation measures in vulnerable regions[12]. More research on inland saline lakes worldwide highlights similar hydrological and ecological challenges. For instance, studies by AghaKouchak et al. (2015) and Shariati and Hemami (2024) on Lake Urmia (Iran) have documented severe water loss and rising salinity, largely due to drought and water diversion, leading to significant declines in migratory bird populations and overall ecosystem health[13][14].

In the Great Salt Lake (USA), Wurtsbaugh et al. (2017) showed that reduced inflows from upstream water withdrawals and climate variability have resulted in record-low water levels, increased salinity, and shrinking habitats for birds and brine shrimp[15]. The Aral Sea in Central Asia, as analyzed by Micklin (2016), represents a dramatic example where large-scale river diversion has caused catastrophic shrinkage, habitat collapse, and severe ecological and socio-economic impacts[16]. Collectively, these studies emphasize that inland saline lakes are highly vulnerable to both climatic and anthropogenic pressures, underscoring the need for integrated monitoring and management—insights that are highly relevant for Sambhar Lake and similar wetlands. Despite considerable international attention on wetland conservation, critical scientific challenges remain unresolved for Sambhar Lake and similar inland saline ecosystems. First, there is an absence of long-term, high-resolution assessments that capture how both climate variability and anthropogenic activities have altered hydrological regimes and water quality over several decades. Second, prior studies have seldom established direct links between these hydrological changes and their ecological consequences, especially for migratory and resident bird populations that are sensitive to fluctuations in water availability and habitat condition. Third, the interactions between water coverage, water quality (such as turbidity, TSS, and chlorophyll-a), and biological responses within saline wetlands remain poorly understood due to fragmented or short-term monitoring efforts. These unresolved scientific and technical issues impede effective management and conservation of Sambhar Lake.

This study directly addresses these gaps by combining multi-decadal satellite-based hydrological analysis, high-resolution spectral water quality monitoring, and evaluation of ecological outcomes for key avian species. By integrating these approaches, the research provides new insights into the mechanisms linking hydrological change, water quality dynamics, and biodiversity, thereby offering a scientific basis for improved conservation strategies in Sambhar Lake and other threatened saline wetlands.

Along with these many existing research using remote sensing to monitor ecosystems has not adequately focused on inland saline wetlands like Sambhar Lake, which are uniquely impacted by both natural and anthropogenic factors[13-17]. While general hydrological assessments have been performed, there is a notable lack of studies that combine high-resolution satellite imagery with detailed spectral analysis to understand the precise dynamics of these environments. Additionally, the direct impacts of hydrological changes on the biodiversity, especially migratory and resident bird populations at Sambhar Lake, remain underexplored. This study aims to fill these gaps by employing a multi-satellite approach to analyze hydrological dynamics and ecological consequences, thereby contributing to saline wetland management and conservation strategies. This study aims to quantify the hydrological shifts and transitions at Sambhar Lake over recent decades using a multi-satellite data approach. The primary focus is on assessing the temporal variations in water coverage, distinguishing between permanent, seasonal, and ephemeral water bodies. Additionally, water quality parameters, such as TSS, turbidity, and Chlorophyll-a concentrations, will be evaluated to understand ecological health. This study is novel in that it provides the first integrated, multi-decadal assessment of Sambhar Lake that combines long-term hydrological analysis (using the JRC/Global Surface Water dataset) with high-resolution Sentinel-2–based water quality monitoring and direct evaluation of impacts on key migratory bird species. Unlike previous research, this approach allows for a holistic understanding of how hydrological transitions are linked to ecological outcomes. The practical importance of this work lies in its direct application for wetland conservation strategies: by establishing scientifically robust links between hydrological changes and biodiversity, our findings provide actionable insights for local stakeholders, conservation managers, and policymakers. The methodology and results presented here can serve as a model for monitoring and managing other threatened inland saline lakes, both within India and globally, thus contributing to broader wetland sustainability efforts. The significance of this research lies in its integrated assessment of both hydrological dynamics and ecological consequences in Sambhar Lake—India's largest inland saline wetland. By combining high-resolution multi-satellite imagery with advanced spectral analysis, this study offers a holistic and unprecedented understanding of how water availability and quality have changed over time, particularly in relation to key migratory bird species that depend on the lake for survival. Unlike previous research, our approach provides detailed temporal and spatial insights into the transitions between permanent, seasonal, and ephemeral water bodies, directly linking these changes to shifts in biodiversity and ecosystem health. These findings not only fill critical knowledge gaps regarding the vulnerability of saline wetlands to both climatic variability and human activities but also provide a scientific basis for targeted conservation and sustainable management strategies. Ultimately, this work contributes valuable methodologies and perspectives for the preservation of Sambhar Lake and serves as a model for monitoring and managing other threatened inland saline lakes globally.

### 1.1. Study Area

Sambhar Lake, in Rajasthan, India, is the largest inland saline wetland and serves as a Ramsar site, situated in the Jaipur and Nagaur districts of Rajasthan, India (26.9°N; 75.1°E). The lake covers a total area of some 230 km². The surface of the lake reaches its maximum area during the end of the wet season, depending on the inflow of water from the summer monsoon, and can be nearly 35 km long and 10 km wide. The region is characterized by low hills and dry plains with up to 400–600 mm of annual rainfall, which occurs predominantly during the southwest monsoon.

This study excluded the human-made lakes; the natural lake including its wetland habitats and the salt pans were selected for this study. Residential and commercial/paved area were distinguished from water, were excluded from water body determination and area measurements, and were not considered in this analysis to maintain focus on the ecological component.

Sambhar Lake and its wetlands are globally recognized for supporting large populations of migratory and resident waterbirds, especially during winter. The extensive salt pans surrounding the lake reflect the region's long-standing economic dependence on salt extraction, which continues to influence both local livelihoods and hydrological processes.

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**Fig. 1:** Location map of Sambhar Lake in Rajasthan, India

## 2. Methodology

### 2.1. Data Sources and Study Area Delineation

The analysis of Sambhar Lake's hydrological and ecological dynamics was conducted using multi-source satellite datasets processed via Google Earth Engine (GEE). For historical hydrology (1984–2020), annual water classification images from the JRC/GSW1_4/YearlyHistory dataset (derived from Landsat) were filtered by a validated shapefile of Sambhar Lake. This ensured that only natural lake areas and true wetlands were included, while excluding artificial water bodies, salt pans, and built-up zones. Water pixels were then classified as seasonal (Class 2, sporadic water presence) or permanent (Class 3, perennial coverage).

For water quality assessment (2015–2023), Sentinel-2 MSI imagery was used due to its high spatial and spectral resolution. Only pixels within the lake ROI were analyzed. The processing sequence for both datasets involved atmospheric correction, cloud masking, and masking to include only the defined ROI.

The total surface area of each water class was calculated by first counting the number of masked pixels per class, multiplying by the pixel area to obtain total area in square meters, and then converting to square kilometers as shown in Eq. (1)

$$Area\ (Km^2) = \frac{Sum\ of\ masked\ areas\ (m^2)}{10^6} \quad (1)$$

### 2.2. Hydrological Change Analysis

Long-term water body dynamics were assessed by processing the JRC/GSW images in GEE for each year. Pixels were separated into seasonal or permanent classes using binary masking based on the JRC classification. The total area for each class was computed according to Eq. (1). This allowed for temporal analysis of water coverage trends, with annual and decadal changes in both seasonal and permanent water area identified. Composite maps and time-series plots were generated to visualize transitions (e.g., from permanent to seasonal) and to detect patterns such as contraction or expansion of water bodies.

### 2.3. Water Quality Assessment

The ecological health of Sambhar Lake was analyzed by estimating three key water quality parameters from Sentinel-2 imagery: Total Suspended Solids (TSS), Turbidity, and Chlorophyll-a (Table 1). All images were atmospherically corrected and cloud-masked. Calculations were performed only for water pixels within the lake ROI. Total Suspended Solids (TSS) were estimated using the ratio of Sentinel-2 Red to Green bands, applying the empirical model in Eq. (2):

$$TSS = 0.118 \times \left(\frac{B4}{B3}\right)^{1.54} \quad (2)$$

Turbidity was calculated using an established band ratio formula, as shown in Eq. (3):

$$Turbidity = 228.1 \times \left(\frac{B4}{B3}\right) - 95.83 \quad (3)$$

Chlorophyll-a concentration was estimated using the Normalized Difference Chlorophyll Index (NDCI), computed from the Red Edge and Red bands of Sentinel-2, as shown in Eq. (4):

$$NDCI = \frac{B5-B4}{B5+B4} \quad (4)$$

All indices were calculated for each image and then aggregated into monthly and yearly averages to capture both seasonal variability and long-term trends.

To enhance interpretability, a moving average smoothing algorithm was applied to all time series. This reduced short-term fluctuations and clarified underlying trends, as represented in Eq. (5):

$$Smoothed\ Value = \frac{1}{n}\sum_{i-0}^{n-1} Data_i \quad (5)$$

## 2.4. Data Processing and Visualization

All data processing and computation of hydrological and water quality indices were conducted within GEE using automated, reproducible scripts. Area calculations for seasonal and permanent water classes relied on pixel counting and spatial masking, while all water quality indices were computed after restricting analysis to water-only pixels within the defined ROI. Trend analysis and smoothing procedures ensured that both abrupt changes and gradual transitions were captured effectively. Visual outputs—including geospatial maps and time-series graphs—were generated to illustrate hydrological and ecological dynamics for both scientific interpretation and stakeholder communication.

By integrating hydrological and water quality analyses, this study provides a comprehensive understanding of the changing water dynamics at Sambhar Lake. The methodology ensures reproducibility and facilitates future monitoring efforts, allowing stakeholders to make informed decisions for conservation and management.

# 3. Results

## 3.1. Hydrological Changes and Water Body Dynamics at Sambhar Lake

The analysis of temporal satellite imagery revealed significant variations in water coverage at Sambhar Lake over the study period. As illustrated in Figure 1, some regions experienced an expansion in water extent, while others showed a reduction. The observed decrease suggests potential drying trends, reduced inflows, or increased water extraction, whereas the increase in water coverage may be attributed to rainfall patterns, surface runoff, or conservation measures. Areas with no significant change indicate stable hydrological conditions during the observed period. These fluctuations highlight the sensitivity of Sambhar Lake to seasonal and anthropogenic influences, emphasizing the need for continuous monitoring.

**Table 1:** Spectral Indices Used for Water Quality Assessment at Sambhar Lake

| Index | Bands Used | Purpose |
|---|---|---|
| TSS | B3, B4 | Quantifies suspended particles and water clarity |
| Turbidity | B3, B4 | Measures water cloudiness due to suspended matter |
| Chlorophyll-a | B4, B5 | Assesses algal biomass and nutrient levels |

The transition between different water body classifications is depicted in Figure 2, showcasing shifts in hydrological states over time. Some regions previously categorized as seasonal water bodies have transitioned into permanent water bodies, indicating improved retention and prolonged water availability. Conversely, certain permanent water bodies have transitioned into seasonal or lost water bodies, signifying increased water stress likely due to reduced inflows, higher evaporation, or human activities such as groundwater extraction. Additionally, new seasonal and ephemeral water bodies have emerged, reflecting short-term hydrological fluctuations that may result from altered drainage patterns, temporary flooding, or increased surface runoff.

The seasonality analysis presented in Figure 3 provides further insights into water retention patterns across different regions of Sambhar Lake. Some areas exhibit permanent water presence, serving as stable aquatic habitats, while others retain water for varying durations, indicating seasonal or ephemeral water bodies. The presence of short-lived water bodies suggests a reliance on monsoonal rainfall and seasonal hydrological variability. These observations underline the dynamic nature of the lake, where climatic factors and human interventions influence water availability and persistence.

Analysis of the "Permanent Water Area by Year" and "Seasonal Water Area by Year" datasets reveals notable trends. Over time, the permanent water area has shown a gradual increase, suggesting enhanced retention capacity due to improved conservation strategies, groundwater recharge, or favorable climatic conditions. However, the seasonal water area demonstrates fluctuations, with some years experiencing expansion and others contraction. These variations highlight the impact of seasonal precipitation, temperature changes, and water extraction activities on the lake's hydrology.

### 3.1.1. Water Quality Analysis Based on Spectral Indices

Time-series trend analysis of Chlorophyll-a concentration, Total Suspended Solids (TSS), and Turbidity helps to yield useful information regarding the seasonal and long-term trends of water quality in Sambhar Lake. These parameters are very important markers of the ecological status of the lake, processes of sediment transport, and biological productivity. The fluctuated values in these parameters indicate the impact of seasonal forces, hydrological

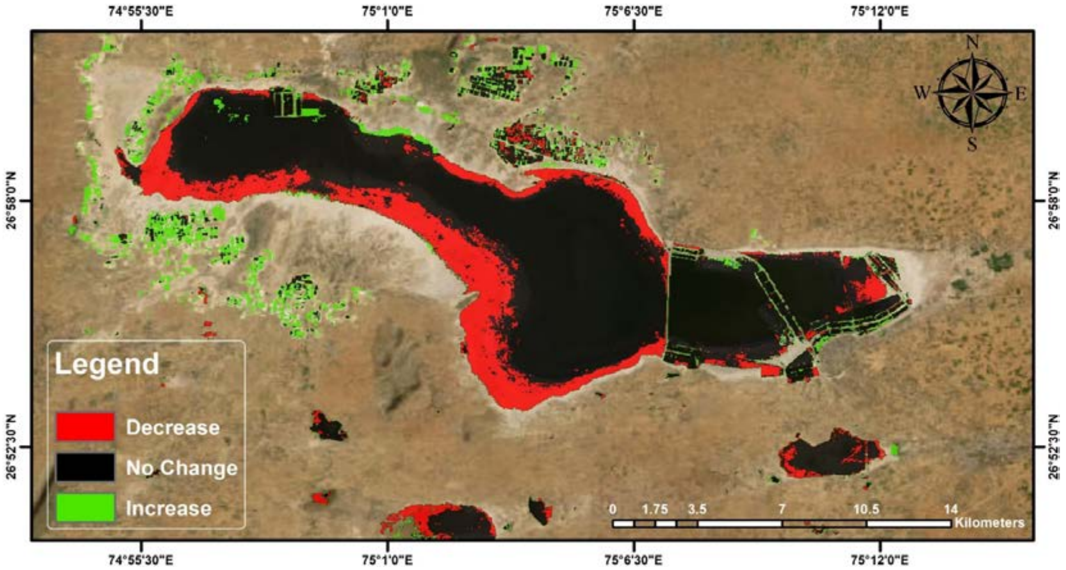


**Fig. 2:** Changes in water extent at Sambhar Lake, highlighting areas where water coverage has increased, decreased, or remained stable over the study period

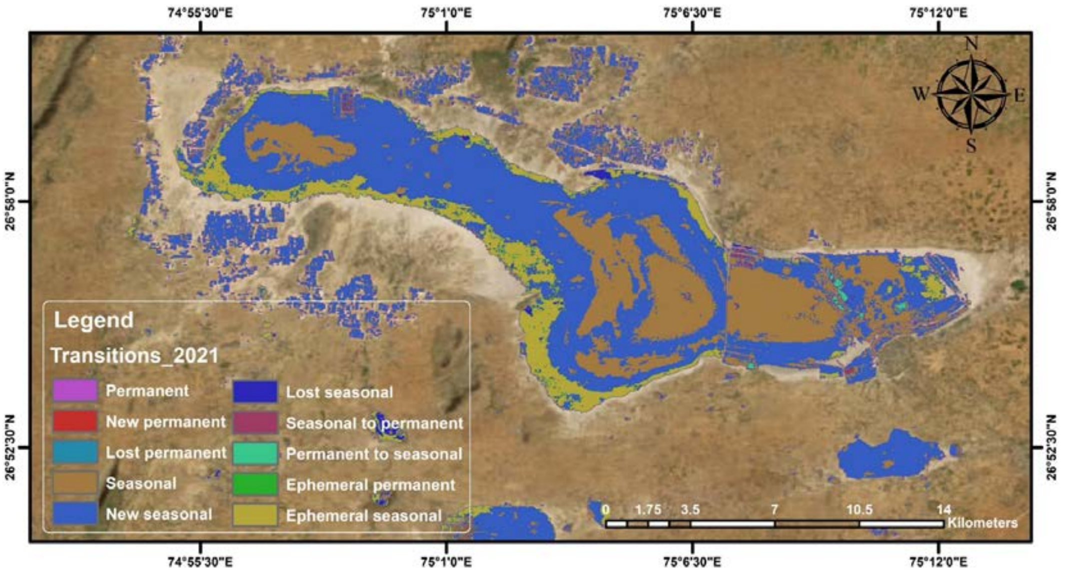


**Fig. 3:** Water body transitions in Sambhar Lake, illustrating shifts between permanent, seasonal, and ephemeral water bodies over time

fluctuation, and human influence on suspended sediment load, nutrient movement, and water clarity.

The Turbidity time-series (Figure 4) is extremely volatile, representing variation in water clarity via suspended particles. Higher turbidity is associated with higher sediment resuspension and surface runoff, and lower values with particle settling or decreased external input. Maximum seasonal turbidity would be caused by monsoonal runoff, pumping higher suspended loads of material, and wind-blown suspended sediments into the lake's shallower parts. Turbidity is raised by human activities such as the release of industrial effluent and salt mining. Higher long-term turbidity may have adverse impacts on aquatic organisms such as reduced penetration of light, inhibition of photosynthesis, and potential decline in water quality.

The TSS time-series (Figure 5) is also consistent and confirming the suspended solids and water clarity relationship. High TSS is linked to high sediment transport during high sediment transport times due to reasons like seasonal inflows, erosion, and overland flow from the surrounding catchment. Evaporation concentration in dry times can also cause further decreasing water clarity. The TSS variant refers to active erosion and sediment processes and is of great importance in nutrient dynamics and biological productivity[14)]. High TSS can alter the ecosystem balance of the lake by regulating oxygen levels, water clarity, and aquatic ecosystems.

The periodic maxima in time-series Chlorophyll-a concentration (Figure 6) are reflective of seasonal maxima

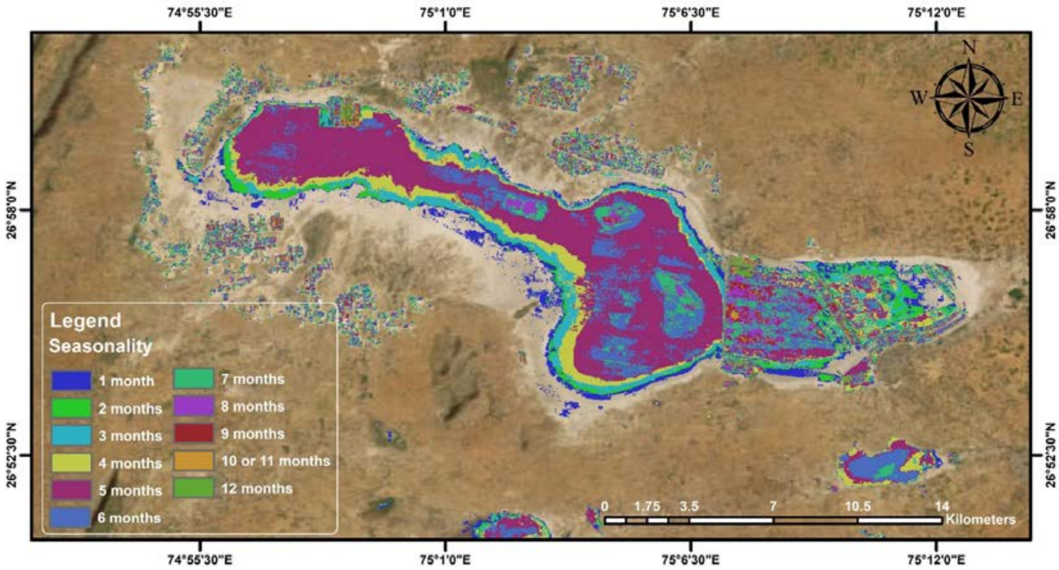


**Fig. 4:** Seasonality analysis of Sambhar Lake, indicating the duration for which different regions retain water throughout the year

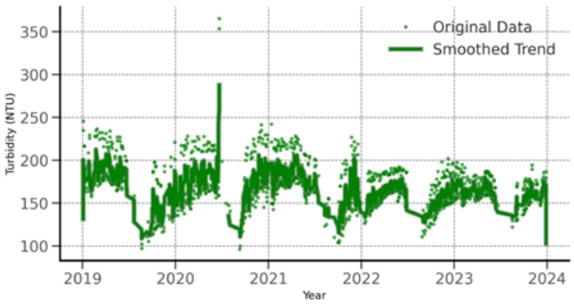


**Fig. 5:** Time-series analysis of Turbidity at Sambhar Lake, illustrating changes in water clarity and sediment load over time

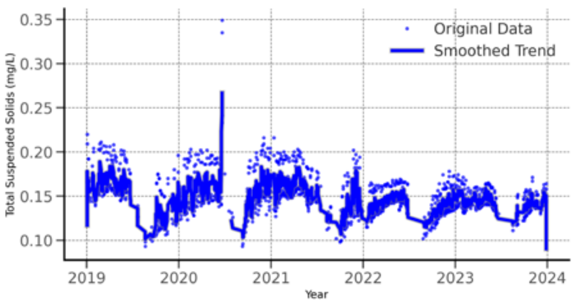


**Fig. 6:** Time-series analysis of Total Suspended Solids (TSS) at Sambhar Lake, depicting variations in suspended particulate matter

in algal biomass. The increases in chlorophyll content reflect eutrophication, resulting from organic matter inflows and agricultural runoff[18)]. Enhanced sunlight exposure and warmer temperatures in certain months may trigger algal growth and formation of algal blooms. The seasonal declines in Chlorophyll-a levels indicate natural die-off phases, potential dilution effects from increased water inflows, or biological consumption by zooplankton and other aquatic organisms. Periodic algal blooms may

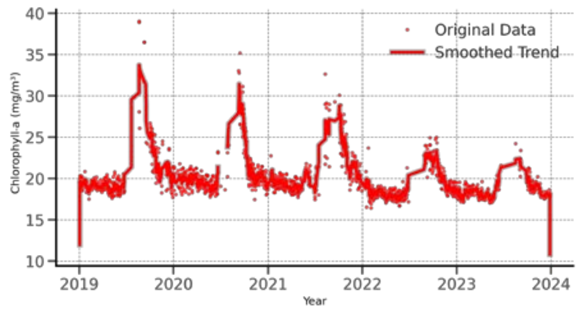


**Fig. 7:** Time-series analysis of Chlorophyll-a concentration at Sambhar Lake, highlighting fluctuations in algal biomass over time

lead to water quality degradation by promoting oxygen depletion and affecting aquatic biodiversity.

## 3.2. Trends in Permanent and Seasonal Water Areas at Sambhar Lake

The past decades of history of seasonal and perennial bodies of water within Sambhar Lake illustrate highly variable hydrology. These document an expression of long-term directions of climatic forcing, hydrological process, and likely anthropogenic forcing within water holding potential and availability within the region.

The plot of permanent water area (Figure 7) shows extreme inter annual variability with changes in water cover oscillations varying in direction. The record implies phases of contraction and expansion, which are perhaps due to changes in precipitation, recharge by groundwater, and human influences such as water abstraction for industrial or agricultural use. In spite of the periodic irregular increases, overall trend line does not stray far from level, which means that while there are periodic periods of water storage in the lake, there is no corresponding long-term increase in permanent water storage. Recent trend towards steep incline in permanent water area is perhaps associated with greater conservation practice, climactic weather patterns, or greater hydrological connectivity in the lake system. But periodic fluctuation is evidence that long-term water storage responds to external climatic and hydrologic forcing. The permanent water area graph (Figure 8) shows a contrasting trend, that is, the overall increase in seasonal water cover with the flow of time. The trend of the observed trend's trend line shows a rising growth curve, which indicates that the lake has been having more regular seasonal water cover in the recent decades (Figure 9). The increase is attributable to increased monsoonal rainfall, increased surface runoff storage, or land cover changes towards increased water storage. The very high seasonality of water area as expected results from the dependence of such water bodies on the regime of rainfall, evaporation, and contribution from surface inflow. Maxima in seasonal water area will reflect years of heavy monsoon rains, while minima will reflect dry years with limited water supply.

These observations point toward dynamic hydrology of Sambhar Lake where permanent and seasonal water bodies exhibit high temporal fluctuation. Relative permanence in permanent water areas signifies ever-lasting presence of water, and increasing trend in seasonal water bodies suggests wetland growth perhaps meritorious to local biodiversity and ecosystem process. However, the difference between two parameters reflects sensitivity of the lake towards climatic oscillation, water management operations, and any likely anthropogenic stress.

Hydrological examination of Sambhar Lake has determined significant spatial and temporal variation in the area of water cover. Examination delineates zones of expanding water storage, possibly because of rainfall and water retention, and zones of contracting water cover, conceivably significance-bearing because of probable drawdown of groundwater, evaporation, or anthropogenic interference. Transition analysis reflects the conversion of a portion of the seasonal bodies of water to permanent, illustrating augmented retention, whereas some portion of

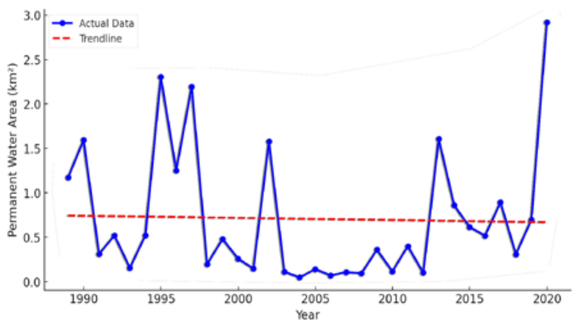


**Fig. 8:** Permanent water area over the years at Sambhar Lake, illustrating fluctuations and overall trend stability with occasional peaks in water retention

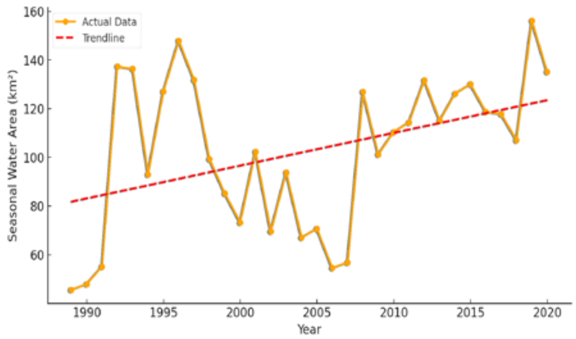


**Fig. 9:** Seasonal water area over the years at Sambhar Lake, showing an increasing trend in seasonal water retention, suggesting enhanced wetland persistence over time

the permanent areas is in the process of becoming seasonal or have disappeared, illustrating water tension and extraction pressure.

Seasonality analysis indicates variations in water persistence, with some areas retaining water year-round, and others depending primarily on monsoonal inflows. Permanent water area trend is one of spikes with rare peaks, indicating episodic retention by climatic and anthropogenic processes. Seasonal water bodies trend positively, but with more improved wetland conditions due to increased surface runoff and precipitation regimes.

Water quality parameters exhibit considerable fluctuations. Turbidity levels fluctuate with sediment inflow and resuspension, peaking during monsoon-driven runoff and industrial activity. TSS trends mirror these patterns, indicating significant sediment transport affecting water clarity and ecological balance. Chlorophyll-a concentrations exhibit seasonal peaks, reflecting algal biomass fluctuations influenced by nutrient loading and hydrological changes.

### 3.3. Impact of Hydrological Changes on Key Bird Species at Sambhar Lake

Sambhar Lake, important wetland ecosystem and traditional wintering site for many migratory birds, has undergone severe hydrological changes in the past decades. Anthropogenic activities have profoundly disrupted avifaunal diversity and population trends through increased variability in water retention, fluctuations in salinity, and habitat loss (Table 2).

To investigate their response to these hydrological changes we focus on five key species, Greater Flamingo, Lesser Flamingo[28)], Northern Shoveler, Common Pochard and Black-tailed Godwit.

The Greater Flamingo, which winters at Sambhar Lake, has shown a long-term declining trend, primarily owing to habitat loss and pre-early seasonal drying of waterbodies. Normally this species leaves by February, but in water retention years, they leave significantly earlier in the spring and foraging and roosting behaviors are impacted.

**Table 2:** Impact of Hydrological Changes on Key Migratory Bird Species at Sambhar Lake, Including Population Trends and Conservation Status

| Bird Species | Migration Pattern (Seasonal Status) | Population Trend (Site-Specific) | Impact of Hydrological Changes on Species | Conservation Status |
|---|---|---|---|---|
| Greater Flamingo (Phoenicopterus roseus) | Winter migratory visitor (arrives ~Aug, departs by Feb-Mar)[19]. | **Declining** long-term (historically fewer than Lesser Flamingo)[19][28]. Absence in drought years, but sharp **increase in wet years** (e.g. >18,000 in 2025)[3][20]. | Highly water-dependent – **leaves early if lake dries** (by Feb in normal years). In **flood years**, can remain year-round. Does not breed at Sambhar due to unstable water levels. Habitat loss from water diversion reduces feeding areas. | IUCN Least Concern[21] |
| Lesser Flamingo (Phoeniconaias minor) | Winter migratory (arrives after monsoon, stays till Mar)[19]; some flocks present year-round if water persists[19]. | **Fluctuating** – historically huge flocks (~18,500 in 1990s)[19], but **declined** with shrinking habitat (arrival markedly reduced in dry years)[22]. **Rebounds** in good years (e.g. ~78,000 in 2025)[23]. | **Strongly tied to water & salinity** – flocks appear only after heavy rains when salinity is lowered and algae bloom[24]. If water is insufficient or too saline, few or none visit (local "arrival declines" observed)[22]. **Mass mortalities** can occur under extreme conditions (botulism in 2019)[3]. | IUCN Near Threatened[25] (population in decline). |
| Northern Shoveler (Spatula clypeata) | Winter migratory duck (common Nov–Feb visitor)[22]. Forms large flocks on open water. | **Declining** during lake's dry phase – only a handful in 2018–19[20]. Suffered a **mass die-off** of ~40,000 in 2019 (botulism)[3]. **Recovering** with water: ~1,981 counted in 2022[22]; ~4,436 in 2025[20]. | **Needs shallow, plankton-rich water** – lake desiccation removed foraging habitat, causing drastic drops in numbers[26]. Stagnant, high-salinity water led to **avian botulism** outbreak in 2019, killing thousands[3]. With restored water, returns in large numbers, but remains vulnerable to water-quality issues. | IUCN Least Concern[27] (globally stable). |
| Common Pochard (Aythya ferina) | Winter migratory diving duck (visits shallow lakes Nov–Feb). | **Declining/vanished** – recorded in mid-1990s, then *absent for ~20 years* at Sambhar[3]). Reappeared only in Jan 2020 when lake refilled (few seen), then missing again in 2021[3]. Trend indicates **local extirpation** during dry decades, with only sporadic return. | **Requires deeper, less saline water** – virtually **absent when lake dried** or too saline. The species returned briefly after **lake water revival** in 2020[3], highlighting that water restoration can bring back lost species. Without sustained water, habitat remains unsuitable for pochards (no refuge in dry years). | IUCN Vulnerable (global decline)[31]. |
| Black-tailed Godwit (Limosa limosa) | Winter migratory shorebird (Aug–Mar) – feeds on mudflats. | **Moderate decline** – formerly abundant; still recorded **regularly** each winter (one of the last remaining migratory waders)[3], but likely in reduced numbers. In 2022 only small numbers present (listed among just 3 threatened spp.)[22]. Overall trend **decreasing** with habitat contraction, though not extirpated. | **Depends on extensive mudflats** – **shrinking water spread** reduced feeding grounds, causing drop in godwit numbers. This species has shown resilience by persisting even in low-water years, but continued **wetland shrinkage** threatens its food supply and roost sites[3]. | IUCN Near Threatened (declining globally)[29][30]. |

In a year with better monsoonal inflows, it responded, in 2025, its population surged above 18,000 individuals. Never before have the prospects for its long-term survival at the lake been so uncertain, primarily due to ongoing habitat fragmentation and diversion of water for salt extraction, limiting available foraging space.

In contrast to the Greater Flamingo, which is consistently abundant, the trend in Lesser Flamingo abundance is more dynamic, with historical estimates from the 1990s suggesting 18,500 individuals (Harrison et al. 1997;

Williams et al. 1999). But habitat degradation and too much salinity have taken a toll on its numbers. When salinity levels decrease due to monsoonal inflows, the species has rapid population rebounds (78,000 in 2025). This species is extremely reliant on the availability of microalgae, and thus their presence is dependent on good feeding conditions, which are becoming more erratic. Moreover, extreme events also contribute to mortality in flamingo populations—as evidenced by a botulism outbreak in 2019 and the risk of death associated with stagnant, hypersaline waters. Waterfowl, like the Northern Shoveler pictured above, have also experienced catastrophic population collapses, largely from disease outbreaks and loss of foraging habitat[30].

Another winter visitor that forms large flocks, this species experienced catastrophic mortality during the 2019 botulism die-off, with 40,000 deaths. The outbreak was caused by stagnant water and heavy organic decay, both of which were worsened by erratic hydrological patterns. Nevertheless, populations appear to have partially recovered in response to improved water conditions, with 1,981 individuals in 2022 and ~4,436 in 2025. However, since habitat of Sambhar Lake continues to remain unstable due to industrial activities of surrounding areas, existence of this species here is highly in jeopardy. The Common Pochard — another migratory waterfowl — has been virtually extirpated from the lake. This diving duck was once a regular winter visitor but vanished for almost two decades after deep, low-salinity bodies of water disappeared. A slight spike was recorded in 2020 thanks to prolific rains, but again, it was short-lived, the birds were missing in the following years. The Common Pochard requires stable deep-water zones, which are absent from Sambhar Lake, signifying the importance of water retention for biological diversity.

The Black-tailed Godwit, a long-distance migratory shorebird, has seen moderate but steady declines as mudflat habitat has shrunk. This species depends upon large shallow-water and soft-bottom habitats for food, all of which have been increasingly lost due to excessive evaporative draw-down of water and upstream diversion of water. Still one of the few wader species to have a regular presence at the lake, numbers have declined (though not due to lack of availability) with decreasing feeding space. By 2022, only handfuls were being recorded and it remains one of the few remaining threatened shorebirds at Sambhar Lake. The Black-tailed Godwit, in contrast to other species that have not returned at all, tolerates occasional low-water years, but it needs sufficient water levels and mudflat habitats to survive[32].

Overall, the trends of these five key species shown in Table 2 demonstrate the central role of hydrological stability in driving avian population dynamics at Sambhar Lake. Water availability varies directly with species occurrence, such that drought years drive population crashes, and wet years allow partial recovery. But the long-term trend is downward, driven by habitat loss, water-quality problems, and human disruptions. Protecting Species from Extinction: Although our Earth is home to many life forms, it's necessary to understand the vulnerable populations that are at risk of extinction and work towards their preservation, as the longer they remain endangered, the more difficult it becomes to save them. To protect the wetland's function as an important migratory bird habitat, immediate interventions addressing the need for minimum water inflows, limiting salinity oscillations and regulating anthropogenic disturbances are necessary. If these challenges will not be addressed, sensitive species will keep declining to extirpation, losing forever the ecological character of Sambhar Lake.

## 4. Discussion

The analysis of Sambhar Lake’s hydrological and ecological changes highlights how a combination of climatic extremes and anthropogenic interventions can drive abrupt and sometimes irreversible transitions—referred to as mutation mechanisms—in the wetland system. Specifically, the interplay of variable monsoon rainfall, increased groundwater extraction, expansion of salt pans, and surface water diversion collectively act as stressors that push the lake across ecological thresholds, resulting in rapid shifts between permanent and seasonal water regimes, and altering the structure and function of aquatic habitats.

### 4.1. Hydrological Variability, Mutation Mechanisms, and Ecological Impact

Our findings indicate that the emergence of new permanent water bodies may signal temporary improvements in water retention, often linked to episodic high rainfall or targeted restoration. However, the persistence of large-scale seasonal water contraction, especially during years of low rainfall or high abstraction, points to the system’s vulnerability to both natural variability and cumulative human pressures. Such abrupt shifts, or “mutations,” are characteristic of non-linear ecological responses, where relatively small additional stresses can trigger disproportionately large changes in water extent and quality[33-35]. These mechanisms echo documented transitions in other major saline lakes worldwide. For instance, Lake Urmia in Iran and the Great Salt Lake in the USA have both exhibited dramatic reductions in water area and ecosystem collapse following a combination of droughts, water diversion, and rising salinity (AghaKouchak et al., 2015; Wurtsbaugh et al., 2017; Shariati & Hemami, 2024). Similarly, the Aral Sea’s rapid shrinkage was driven by a threshold being crossed due to decades of river diversion (Micklin, 2016). These case studies reinforce that Sambhar Lake’s observed hydrological “mutations” are not isolated, but reflect a broader set of feedback-driven regime shifts common to arid-region wetlands.

### 4.2. Water Quality Dynamics: Thresholds and Comparative Insights

The marked fluctuations in turbidity, TSS, and Chlorophyll-a concentrations in Sambhar Lake are closely tied to the mutation mechanisms driving hydrological change. High sediment influx during the monsoon, compounded by anthropogenic disturbance (e.g., salt pan excavation, effluent discharge), can rapidly degrade water quality and foster eutrophic conditions. Seasonal spikes in Chlorophyll-a—indicative of algal blooms—are a classic symptom of nutrient enrichment following hydrological disruption, paralleling events documented in Lake Urmia and the Great Salt Lake (Wurtsbaugh et al., 2017). In both systems, periodic recovery has been observed when inflows are restored or management interventions reduce anthropogenic stress, highlighting the potential for reversibility if timely action is taken.

### 4.3. Implications for Conservation and Management

The mutation mechanisms identified in this study underscore the urgency of adaptive, threshold-aware management. The comparative evidence from other saline wetlands suggests that targeted interventions—such as maintaining minimum inflows, regulating groundwater use, and managing salt extraction—can help buffer Sambhar Lake against sudden ecological shifts and support resilience. Integrated monitoring using multi-satellite remote sensing, as demonstrated here, is essential to detect early warning signs of regime change and guide rapid response[36)]. Ultimately, the lessons learned from Sambhar Lake, when considered alongside other global examples, demonstrate that while mutation mechanisms pose risks of rapid ecological decline, they also present opportunities for restoration if proactive, evidence-based strategies are implemented.

## 5. Conclusion

This study presents the first integrated, multi-decadal analysis of Sambhar Lake, combining multi-satellite remote sensing with advanced water quality assessment to reveal how climate variability and anthropogenic pressures have fundamentally altered the lake’s hydrological regime. By linking changes in permanent and seasonal water bodies to ecological impacts—particularly on key migratory bird species—our findings underscore the dynamic nature and vulnerability of this critical Ramsar wetland. The research demonstrates that, while some conservation efforts have contributed to improved water retention, persistent fluctuations in turbidity, TSS, and Chlorophyll-a highlight ongoing challenges. Methodologically, this work advances real-time, reproducible monitoring of saline wetlands using cloud-based platforms. Future research should prioritize detailed ground-truthing and socio-economic impact assessment to support holistic, adaptive management of Sambhar Lake and similar ecosystems.

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## Nomenclature

| | |
|---|---|
| AWEI | Automated Water Extraction Index |
| DEM | Digital Elevation Model |
| GEE | Google Earth Engine |
| NDCI | Normalized Difference Chlorophyll Index |
| NDTI | Normalized Difference Turbidity Index |
| NDWI | Normalized Difference Water Index |
| NTU | Nephelometric Turbidity Units (unit of turbidity) |
| ROI | Region of Interest |
| SAR | Synthetic Aperture Radar |
| TSS | Total Suspended Solids |

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