Monitoring migratory birds of India’s largest shallow saline Ramsar site (Sambhar Lake) using geospatial data for wetland restoration

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Abstract   Globally, saline lakes occupy about 23% by area, and 44% by volume. Importantly, these lakes might desiccate by 2025 due to agricultural diversion, illegal encroachment, or modify due to pollution, and invasive species. India’s largest saline lake, Sambhar is currently shrinking at a phenomenal rate of 4.23% every decade due to illegal saltpan encroachments. This study aims to identify the trend of migratory birds and monthly wetland status. Birds’ survey was conducted for 2019, 2020 and 2021, and combined it with literature data of 1994, 2003, and 2013, for understanding their visiting trends, feeding habits, migratory and resident birds ratio, along with ecological diversity index analysis. Normalized Difference Water Index (NDWI) was scripted in Google Earth Engine. Results state that lake has been suitable for 97 species. Highest NDWI values was 0.71 in 2021 and lowest 0.008 in 2019. Notably, the decreasing trend of migratory birds coupled with decreasing water level indicates the dubious status for its existence. If these causal factors are not checked, it might completely desiccate. Authors recommend a few steps that might help conservation. Least, the cost of restoration might exceed the revenue generation.

Keywords   Saline lakes · Human interventions · Google Earth Engine · Normalized Difference Water Index · Wetland management · Restoration

Introduction

Globally, saline lakes occupy 23% by area and 44% by volume (Zadereev et al. 2020). These lakes are usually confined to arid and semi-arid regions of the earth (Wurtsbaugh et al. 2017). They show similar vertical stratification to freshwater systems. They primarily differ in their ionic composition due to the salinity factor that ranges from 3 g/L to 300 g/L (Fukushi et al. 2020). Due to anthropogenic pressure and climate change, numerous lakes have rapidly been drying up even before we realize (Hassani et al. 2020). A recent salient example is a 90% decline of the Aral Sea in Uzbekistan and Kazakhstan, within a span of just 50 years (Wang et al. 2020a, b). Notably, as compared to deep saline lakes, shallow ones are far more sensitive, even to slight variations, accelerating their desiccation thereof (Zhang et al. 2020). In fact, their drying condition exposes the lakebed, which is rich in numerous minerals of sodium, magnesium, calcium, lithium, and potassium. Exposure of these minerals can be carried away by the wind of drylands and loose these precious resources. This

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can impact the billion-dollar global mineral market (Connolly et al. 2020). These can also lead to public health hazards, primarily respiratory problems, lung diseases, and related infections due to salt, sand, and dust storms (Tussupova et al. 2020). Additionally, the shrinkage of these lakes or complete desiccation can bring down the entire ecosystem. Consequently, significant amount of funds would be required for their restoration, as opposed to the revenue generation. This has already been seen in the case of Lake Owen’s at Los Angeles city (Zhang 2020). These are vital aquatic ecosystems that provide a wide range of ecosystem services, habitat for lakhs of migratory birds and halo-alkaliphiles. However, they have been ignored compared to their freshwater counterparts (Naik and Sharma 2021). This might be, primarily due to their presence in inaccessible areas (Kolpakova et al. 2019). However, since the launch of first-ever satellite in 1972, application of Remote Sensing (RS) and Geographic Information System (GIS) has enabled conducting landscape-level studies due to the availability of real-time, cost-effective, and dynamic satellite images, which significantly differ from traditional in-situ measurements (Naik and Sharma 2021).

Currently, 6542 satellites are orbiting around the earth, out of which, 3372 are operational, while 3170 satellites are non-operational. The operational ones provide petabytes of datasets (McDowell 2020). Besides, space-borne satellites, other platforms like airplanes, ground-based platforms, Unmanned Aerial Vehicles (UAVs), along with data from statistical, ecological, social, and geological constitute enormous volume of data, also termed as Big Earth Data (BED) (Esch et al. 2020). BED requires high-end desktop computational facilities, developed infrastructure, along with huge storage capacities, which effectively limit earth observation studies (Yao et al. 2020). However, cloud computing platforms, like Google Earth Engine (GEE) has been minimizing the obstacles mentioned above since 2010 (Gorelick et al. 2017). Its data repository is a collection of approximately 40 years of satellite imagery, at multiple Spatio-temporal scales (Mutanga and Kumar 2019). In fact, it has wide range of data of Landsat series; National Oceanographic and Atmospheric Administration Advanced Very High-Resolution Radiometer (NOAA AVHRR), Moderate Resolution Imaging Spectrometer (MODIS); Sentinel 1, 2, and 3, Advanced Land Observing Satellite (ALOS) and many more (Mutanga and Kumar 2019). The minimal requirements are a simple desktop or laptop and internet connectivity (Kennedy et al. 2018). It eliminates the steps like raw satellite data downloading, pre-processing, layer stacking, mosaicking, clipping region of interest before conducting the actual operations, as it has JavaScript-based algorithms for each operation (Vos et al. 2019). This also facilitates importing and uploading of own vector and raster datasets. The results can be exported from GEE in GeoTIFF format to own Google Drive account. This enables minimum dependence on special remote sensing software, such as Earth Resources Data Analysis System (ERDAS) Imagine and Environment for Visualizing Images (ENVI). Nevertheless, these softwares are still needed for special functions that are not offered on GEE (like object-based image assessment) (Wang et al. 2020a, b). Notably, GEE has been widely explored for vegetation mapping and monitoring, such as global estimation of Fraction of Absorbed Photo-synthetically Active Radiation (FAPAR) (Mutanga and Kumar 2019). Leaf Area Index (LAI) (Campos-Taberner et al. 2019), Canopy Water Content (CWC) (Pipia et al. 2021), and Fraction Vegetation Cover (FVC) (Anchang et al. 2020), for agricultural applications like crop area mapping (Vermeulen et al. 2021), crop yield estimation (Liu et al. 2020), and pests and diseases vulnerability (Cao et al. 2021). It has also been used for aquatic ecosystems such as long term chlorophyll monitoring of lake Utah (Cardall et al. 2021), Amu Darya river channel dynamics (Mobariz & Kaplan 2021), classification of Canadian wetlands with 84.37 to 88.96% accuracy, mapping national scale aquaculture ponds (Duan et al. 2020), identification of wetland classes (Gulácsi & Kovács), preparation of wetland inventories with 84% accuracy (Amani et al. 2019) and in India GEE has also been used for land use change of lake Kolleru (Kolli et al. 2020). However, this technology has been quite less explored for saline wetlands.

Remote sensing images have been used to extract water bodies including several methods like single band density slicing (Ding et al. 2016), supervised (Gautam et al. 2015) and unsupervised classification (Dibs 2018) and spectral water indexes (Fisher et al. 2016). However, among all these methods, index-based method is widely accepted, due to its efficient and user-friendly process (Gautam et al. 2015). At first, Normalized Difference Water Index (NDWI)
was proposed by McFeeters (1996) using the green and Near Infrared (NIR) bands of satellite images, as water bodies do have strong absorbability and low radiation in the range from visible to infrared wavelengths. Xu (2006) modified NDWI and named it MNDWI by substituting original NIR band with shortwave-infrared (SWIR) band to decrease commission errors in vegetation, built-up, and soil. Further, Feyisa et al. (2014) developed an Automated Water Extraction Index (AWEI), which removes misclassification of shadow as water, by using multiple spectral bands. Tasseled Cap Wetness (TCW) index has also been used for water studies (Chen et al. 2019). Even though there are numerous indices available, NDWI has been the most accepted and widely used, due to its simplicity, wide applicability to any water system, and usability with any satellite datasets (Watson et al. 2018) such as for water body detection (Özelkan 2020), surface water mapping at 91% accuracy (Li et al. 2018), such as for water body detection (Özelkan 2020), surface water mapping at 91% accuracy (Li et al. 2013), for surface water dynamics (Sathianarayanan 2018), differentiating between water body and settlement areas (Singh et al. 2015) and in India for Rabi River basin (Taloor et al. 2021).

This study is conducted in the largest shallow saline Ramsar site of India. It is currently undergoing desiccation due to salt pan encroachment, illegal water extraction, brine theft and increasing urban pressure. As a result of which, the whole ecology is at stake. Many of the birds visiting to Sambhar Lake are dependent on saline-alkaline lakes for fulfilling part of their life cycle. Their declining population for this lake indicates existence of some disturbance in their habitat requirement. Availability of water in the lake is the prime factor for the structural and functional aspects of this ecosystem. The authors started this research with the motive to analyze prime aspect of this lake (saline soil, water, birds, halophytes and halophiles). However, due to COVID-19 pandemic, methodology was modified. So, in order to analyze the current position, this study aims to investigate the status of migratory birds and water availability. For this purpose, we performed our research in multiple phases. First, we conducted bird survey for three consecutive years, i.e., 2019, 2020 and 2021. We combined data gathered from this survey with literature survey data to understand and analyze the long-term visiting trends, migratory and resident ratio, feeding habits, and ecological diversity index calculation. Secondly, we examined the monthly status of wetland for our survey period, using NDWI in GEE platform. This paper is divided into five sections; the first, provides a brief overview of the global status of saline lakes, developmental phases of remote sensing from desk computing to cloud computing and further applicability of NDWI. The second section elaborates on the study area, and methodology followed for bird and wet-land status. The third highlights the results, while the fourth, discusses the results. Lastly, section five concludes the study.

Materials and methods

Study area

Sambhar Salt Lake (26° 52′ to 27° 02′ N; 74° 54′–75° 14′ E) is a playa wetland, located towards the east of the Thar Desert (Fig. 1), surrounded by the Aravali hill ranges of India (Kaushik and Raza 2019). It is located 80.7 km away from Jaipur, which is the state capital of Rajasthan. The lake can be reached via National Highway 48 and Rajasthan State Highway 57 (Singh et al. 2018). In 1961, the Government of India (GoI) took over this region on a 99-year lease under the Ministry of Commerce and Industry Salt production. India exports approximately 230 million tons of salt to the global market after China and USA, to 198 countries like Japan, Bangladesh, Qatar, Indonesia, South and North Korea, Malaysia, U.A.E, and Vietnam (Naik and Sharma 2021). Being an inland wetland, it is 230 km² (22.5 km in length and 3–1 km in width) (Sharma et al. 2020a). A 5.16 km long dam was built for reservoir (77 km²) and wetland area (113 km²) (Sharma et al. 2020b). Its saline character is contributed by the presence of salts of sodium, calcium, potassium, and magnesium cations and chloride, carbonate, bicarbonate, and sulphate anions (Sharma et al. 2021). It seems white in areas that are rich with salt content; grey with less salt, and brown with no salt content. Being in semi-arid climatic zone, it receives about 500 mm rainfall during monsoon (i.e. July–September), and has water during winter (i.e. October–March) when the temperature is between 11 and 24.4 °C. It almost dries out in summer (i.e. April–June) when the temperature rises to 40.7 °C. It is a shallow lake with vertical depth ranging from 3 to 0.6 m during monsoon to summer seasons (Sar et al. 2021). Its water system is supported by ephemeral streams like Mendha, Kharian, Rupnagar, and Khandel, forming a catchment of 5520 km² (Kumari 2021). This amazing site is one of the most important visiting grounds for migratory water birds on the East Asian, Central Asian, and East African flyways. It was declared as Ramsar site on
23 March 1990 (Bairwa et al. 2021). There are about 1 lakh water birds, primarily flamingos coming over in the winter to this lake, and most of them are distributed in the saltpan areas, as there is some water left in the natural wetland area (Bhatia et al. 2021). Unfortunately, the water level of this lake has been decreasing rapidly due to illegal saltpan encroachments (Naik and Sharma 2021). Notably, it also provides shelter to rich floral diversity, such as species of 37 herbs, 14 shrubs, 14 trees, 15 grass, 6 chlorophyceae, 25 Cyanophyceae and 7 Bacillariophyceae (Sharma et al. 2019). Hence, regular monitoring of water birds and their distribution along with mapping their habitats in entire flyways are necessary for their conservation.

Bird census data

Migratory birds visit to the lake during winter season. So, 3 surveys were carried out for 3 days each, during the winter season of the years 2019, 2020 and 2021. To maintain the uniformity the surveys were organized every third week of January to second week of February. The wetland survey included both the natural wetland as well as saltpan. Bird counting was done barefoot for some inaccessible sites, while other sites were visited using vehicles. 10 observation points were used, from which the bird censuses were conducted. To avoid two-fold counting, when a flock of birds flew away into any section, it was not recorded. Censuses were carried out, using binoculars and camera during morning periods, when birds are
most active. This was carried for almost three hours (6:00 to 10:00 AM; GMT +5:30). Species identification and their foraging habitat were recorded using Asian Waterbird Census (AWC) given form. As Sambhar Lake has elevation of almost 360 m above mean sea level, and is surrounded by the Aravalli hill range in the outer boundary, there are no visual topographic hindrance for the surveys. Surveys were conducted by the same volunteers to avoid variation. Importantly, the availability of time-series data from literature are scarce. However, we selected for the years 1994–1997 (Kumar 2008), 2003 (Shukla and Bhatnagar 2005), 2013 (Sharma et al. 2013). These censuses were mostly conducted during winter season which matched our period of study.

Satellite data

Sentinel-2 mission was launched in 2015 by European Space Agency (ESA). It provides open access to high spatial resolution optical and microwave data. Compared to the oldest satellite series Landsat, it provides images with more spectral bands, higher spatial and temporal resolutions, and wider swath. Thereby, it has a wide range of applicability in the fields of land monitoring (Phiri et al. 2020), vegetation (Garioud et al. 2021), agricultural (Segarra et al. 2020), water (Soomets et al. 2020) and soil research (Ramos et al. 2020). The Sentinel-2 data contains 13 spectral bands representing Top of Atmospheric (TOA) reflectance scaled by 10,000 (Li et al. 2020). Additionally, three Quality Assurance (QA) bands are available, among which, one (QA60) is a bitmask band with cloud mask information (Meraner et al. 2020). Each Sentinel-2 product set (zip archive), and contains multiple granules, which are individual assets in GEE (Xulu et al. 2021). Sentinel-2 carries the format as COPERNICUS/S2/20211005T002653_20211231T102149_T56MNN as a GEE asset (Xiao et al. 2021). The first numeric part represents the data acquisition date and time, the second part signifies the product generation date and time, and the final six-character string represents unique granule identifier, showing its UTM grid reference. For this study, the Level-2 data found in the collection of COPERNICUS/S2_SR were accessed for 3 years from 2019 to 2021 from GEE.

Google Earth Engine

Sentinel-2 images from 2019 to 2021 were assessed, using various functions, as described in Table 1. To reduce the effect of cloud cover, we used two removal techniques: (1) GEE algorithm based on sorting algorithm in which, images having less than 20% cloud cover are sorted. (2) GEE algorithm based on pixels method in which, it assigns a cloud score to individual pixels, and selects the lowest available range of cloud scores. Further, it computes the per-band percentile values from the selected pixels (Nazarova et al. 2020). Here, we specifically used the second method, along with QA60 algorithm for updating

| S. no. | Functions | Purposes |
|-------|-----------|----------|
| 1     | ee.ImageCollection | To select satellite for which data will be used |
| 2     | ee.Date   | To define date for which data will be selected |
| 3     | .filterMetadata | To filter metadata for which image will be selected |
| 4     | .filterBounds | To define region of interest |
| 5     | .clip     | To clip region of interest |
| 6     | .sort     | To define cloud cover |
| 7     | .mask     | To mask cloudy image |
| 8     | Map.centerObject | To display median of selected image |
| 9     | .Map.addLayer | To display image |
| 10    | .image.select | To select the desired bands |
| 11    | .img.normalizedDifference | To calculate NDWI |
| 12    | .select   | To select desired NDWI image |
| 13    | .rename   | To rename the output image |
| 14    | .Export.image.toDrive | To export final output to drive |
cloud cover mask. Then, NDWI was calculated using the respective function and visualized it in GEE.

Normalized Difference Water Index

The water index is based on the spectral features of water, so that it can differentiate between water and non-water classes, and extract water pixels according to a suitable threshold. McFeeters (1996) stated that values of NDWI greater than zero represent water surfaces, while values less than, or equal, to zero represent non-water surfaces. Vegetation and soil characteristics usually have zero to negative values and are suppressed. NDWI is calculated using Eq. (1) where Band 2 is the TOA green light reflectance, while Band 4 is the TOA near-infrared (NIR) reflectance.

\[
NDWI = \frac{(Green - NIR)}{(Green + NIR)}
\]  

(1)

Exporting

The water surface extraction algorithm was used in the GEE platform every month. It identified the parts of the lake, both with and without water. Then, NDWI for each month was exported to Google drive, using a Java code, and downloaded in.tif format. In Arc GIS, these indices outputs were reclassified into 5 classes to find the actual water spread area of the lake, and finally a map was composed. The comprehensive methodology is shown in Fig. 2.

Results

Birds’ status

Trend analysis

From the combined results of literature and our survey, it is calculated that in total (Fig. 3a, b), 97 species belonging to 23 families have visited the lake since 1994. These families include Anhingidae, Accipitridae, Alaudidae, Alcedinidae, Anatidae, Ardeidae, Burhinidae, Charadriidae, Ciconiidae, Cuculidae, Glareolidae, Gruidae, Ibidorhynthidae, Laridae, Motacillidae, Pelecanidae, Phalacrocoracidae, Phoenicopteridae, Podicipedidae, Rallidae, Recurvirostridae, Scolopacidae, Threskiornithidae. Notably, among these, 9 species belong to near threatened, 3 vulnerable, 2 endangered and 77 least concern as per IUCN Red List.

70 species of 17 families visited in between 1994 and 1997 (Fig. 3c). They include Accipitridae (1), Anatidae (15), Anhingidae (1), Ardeidae (8), Charadriidae (7), Ciconiidae (2), Glareolidae (1), Gruidae (3), Laridae (5), Pelecanidae (1), Phalacrocoracidae (2), Phoenicopteridae (2), Podicipedidae (2), Rallidae (2), Recurvirostridae (2), Scolopacidae (14), Threskiornithidae (2). Species of 6 families which belong to Alaudidae, Alcedinidae, Burhinidae, Cuculidae, Ibidorhynthidae, and Motacillidae were absent. 51 species of 16 families visited in 2003 (Fig. 3d). They are Anatidae (6), Anhingidae (1), Ardeidae (7), Charadriidae (4), Ciconiidae (2), Glareolidae (1), Gruidae (3), Laridae (5), Pelecanidae (1), Phalacrocoracidae (2), Phoenicopteridae (2), Podicipedidae (1), Rallidae (3), Recurvirostridae (2), Scolopacidae (7), Threskiornithidae (4). Species which belong to 7 families Alaudidae, Accipitridae, Alcedinidae, Burhinidae, Cuculidae, Ibidorhynthidae, and Motacillidae were absent. 43 species of 10 families visited in 2013 (Fig. 3e). They are Anatidae (8), Ardeidae (4), Burhinidae (4), Charadriidae (2), Gruidae (4), Laridae (2), Phoenicopteridae (1), Podicipedidae (2), Recurvirostridae (15) and Scolopacidae (1). Species which belong to 13 families Anhingidae, Accipitridae, Alaudidae, Alcedinidae, Ciconiidae, Cuculidae, Glareolidae, Ibidorhynthidae, Motacillidae, Pelecanidae, Phalacrocoracidae, Rallidae, and Threskiornithidae were absent.
28 species of 9 families visited in 2019 (Fig. 3f). They include Anatidae (5), Ardeidae (1), Burhinidae (5), Charadriidae (2), Motacillidae (2), Phoenicopteridae (1), Podicipedidae (2), Recurvirostridae (9) and Scolopacidae (1). Species which belong to 14 families Anhingidae, Accipitridae, Alaudidae, Alcedinidae, Ciconiidae, Cuculidae, Glareolidae, Gruidae, Ibiodromithidae, Laridae, Pelecanidae, Phalacrocoracidae, Rallidae and Threskiornithidae are absent. 32 species of 12 families visited in 2020 (Fig. 3g). They
are Accipitridae (1), Alaudidae (1), Alcedinidae (2), Anatidae (2), Ardeidae (5), Charadriidae (1), Cuculidae (1), Laridae (2), Motacillidae (2), Phoenicopteridae (2), Recurvirostridae (12), and Scolopacidae (1). Species which belong to 11 families like Anhingidae, Burhinidae, Ciconiidae, Glareolidae, Gruidae, Ibidorhynthisdae, Pelicanidae, Phalacrocoracidae, Podicipedidae, Rallidae, and Threskiornithidae are absent. 41 species of 13 families visited in 2021 (Fig. 3h). They are Alcedinidae (9), Anatidae (6), Ardeidae (3), Charadriidae (1), Ciconiidae (3), Laridae (2), Phalacrocoracidae (1), Phoenicopteridae (1), Podicipedidae (3), Rallidae (2), Recurvirostridae (6), Scolopacidae (3) and Threskiornithidae (1). Species that belong to 10 families, like Anhingidae, Accipitridae, Alaudidae, Burhinidae, Cuculidae, Glareolidae, Gruidae, Ibidorhynthisdae, Motacillidae, and Pelicanidae were absent. The details of ‘bird analysis’ is given in Table S1.

**Feeding habit analysis**

From Fig. 4a, it is clear that the Sambhar Lake always attracts a great number of carnivorous birds, as compared to herbivores and omnivores. In between 1994 and 1997, 70 species of birds visited the lake, out of which 46 species were carnivores, 8 species were herbivores, and 16 species were omnivorous. In 2003, out of total 51 bird species, 36 were carnivores, 4 were herbivores and 11 were omnivores. In 2013, out of total 43 species, 30 were carnivores, 4 were herbivores and 9 were omnivores. In 2019, out of total 28 species, 21 were carnivores, 4 were herbivores and 3 were omnivores. In 2020, out of total 32 species, 26 species were carnivores, 2 species were herbivores, and 4 species were omnivores. In 2021, out of total 41 species, 28 species were carnivores, 4 were herbivores and 9 were omnivores. Carnivorous birds visit this lake which feed upon fishes, eggs, small mammals, insects, reptiles, frogs, worms, crustaceans, mollusks, snails, amphibians, insect larvae, snakes, lizards, spiders, mice, grasshoppers, crickets, flies, moths, nestling birds, earth worms, cray fishes, bees, tadpoles, leeches, clams, mussels, turtles, caterpillars, beetles, termites, ants, midges, grubs, mantids, stick insects, cicadas, maggots, cyprinids, pikes, roaches, eels, perchers, burbots, sticklebacks, muddy loaches, shrimps and offal. Herbivores birds...
feed upon seeds, roots tubers, parts of plants, grasses, aquatic plants, seeds, grains, various grasses, oats, wheat, barley, leaves, cereal stubbles, growing crops, nuts, rice, sweet corn, and roots. Omnivorous birds eat either of the available food.

**Migratory pattern analysis**

From Fig. 4b, it is seen that there are more migratory birds than resident birds in this lake. Among the total of 70 species of birds that visited during 1994–1997, 57 were migratory, while only 13 were resident. In 2003, among 51 species, 39 were migratory, while 12 were resident species. In 2013, out of total 43 species, 39 were migratory, and only 4 were resident species. In 2019, out of total 28 species, 23 were migratory, while 5 were resident species. In 2020, out of total 32 species, 24 were migratory, and 8 were resident species. In 2021, out of total 41 species, 32 were migratory, and 9 were resident species. Majority of migratory birds that visit the lake are primarily from European countries like Iceland, England, Ireland, Hungary, Italy, Spain, Turkey. Birds also visit from other countries like Africa, and Iran during winter season for resting, roosting, and breeding as shown in Fig. 4c.

**Ecological diversity index**

Two ecological species diversity indices have been calculated (Table 1). They include Shannon–Weiner and Simpson diversity for the year of our study period (2019–2021). The values of Shannon–Weiner index are 2, 1.09, 3.07 for 2019, 2020 and 2021 respectively. The values of Simpson index are 0.21, 0.42, and 0.07 for 2019, 2020 and 2021 respectively.

**Wetland status**

For Sambhar Lake, 2019, 2020 and 2021 were very vital years. In 2019, it faced its first ever avian botulism, in 2020, country wide longest shut down due to COVID-19 and in 2021 repeated phase-wise locks downs. All these cumulatively affected the economic activities, which could be the prime factor for its degradation. So, it is important to note the year wise NDWI values. Since, shallow lakes are most vulnerable to water level fluctuation with slight changes in wind speed increase or rise in temperature. The fluctuation fastens if the lakes are inland lakes as most of them are also endorheic basins. Since, Sambhar Lake is fulfilling the above criteria, also additionally it is located near to a semi-arid desert of India, it is more prone to surface water fluctuation. So, important to provide month wise NDWI values also.

**2019**

In the year 2019 (Fig. 5), the highest NDWI value for the whole year was 0.6 in October, and lowest was 0.08 in July. During winter, the highest value was 0.6 in October and 0.35 in November. During summer, the highest was 0.29 in April and 0.11 in June. During monsoon, the highest value was 0.41 in September and 0.08 in July.

**2020**

In the year 2020 (Fig. 6), the highest NDWI value for the whole year was 0.67 in February, and lowest was 0.1 in June. During winter, the highest value was 0.67 in February, and 0.39 in March. During summer, the highest was 0.49 in April, and 0.1 in June. During monsoon, the highest value was 0.5 in September and 0.15 in July.

**2021**

In the year 2021 (Fig. 7), the highest NDWI value for the year until July was 0.71 in February and lowest was 0.1 in June. During winter, the highest value was 0.71 in February, and 0.26 in March. During summer, the highest was 0.28 in April and 0.08 in June. Cannot be compared as the data is available for only July month with value 0.21.

From the results of NDWI it observed that the water regime is fluctuating every month putting adverse impact to the lake ecosystem.

**Discussion**

We investigated the status of wetland and migratory birds for 2019, 2020 and 2021, accompanied by data retrieved from literature and bird survey data. We analyzed the trends, feeding habits and migratory behavior of the migratory birds to the study area. The monthly status of wetland was also integrated. We
conducted bird census consistently for three years during winter to collect our primary data. We used literature as a secondary source of data for identifying bird details in previous years, along with Arc GIS software for preparing field visit plans, and identifying sampling locations. We used Sentinel 2 B satellite data of 2021 for preparing the study area map, and field visiting map of 2021 January. Largely, we found the results to be very depressing. Since the last few decades, there has been a decreasing trend of migratory birds visiting the lake. Birds of many families have stopped visiting. Numerous IUCN listed birds that used to come, have also stopped coming to the lake. Due to continuous shrinkage of wetland, there is little water to support aquatic life forms, which serve as a foundation of the complex food web. This is distinctly reflected in the decreasing trend of birds. The field photographs are shown in Fig. 8, in which Fig. 8a–c represent seasonal change of lake color, 8d and 8e showcase flocks of flamingo, and common ruff respectively and 8f show our bird census team with AWC.

It is also disheartening to state that the trend of visiting birds consistently decreased till 2019. In fact, during the monsoon period of 2019, the lake received heavy rainfall which helped to revive the water level.
Shockingly, this lake encountered first-ever avian botulism in its history (Jhajhria 2020). It was observed on 13th November 2019 by some tourists. In this incidence, more than forty thousand migratory birds, primarily northern shoveler died (Jhajhria 2020). To avoid any human infection, the salt extraction activity was legally stopped for nearly two months (November, December, and January) (Jhajhria 2020), which helped to retain the water level, during these months, as shown in figures of wetland maps, observed using GEE. Meanwhile, COVID-19 was also scaring the country, and India had its longest countrywide shutdown due to COVID-19 from March to May 2020. This completely restricted any sort of economic activity within the lake. This further helped the water retention in the lake even during the drying months (April–May) as shown in result section. This prolonged the availability of water in the lake is reflected in the increasing pattern for the years 2020 and 2021 bird censuses.

Analyzing the temporal trend of birds, it is observed that during 1994, the lake welcomed 70
species, which belonged to 17 families. These further reduced to 28 species of 9 families in 2019. The most dominating families used to be Anatidae and Scolopacidae. They accounted for 41.4%, which reduced to 21.4% in 2019. Though consistently Scolopacidae maintained to be the dominating family till 2020; in 2021, it was the second dominating family. During 1994–1997, out of total 15 birds of Anatidae, 13 were migratory birds. Among these 13, 8 were omnivorous and 5 were herbivorous. Among the two resident birds, 1 was omnivorous, while the other was herbivorous. The point of concern is for Common pochard, being a migratory bird, currently under vulnerable category of IUCN red list appeared in 1994–1997, but were further not identified until 2020 survey. Though it reappeared only in 2020, again was absent in 2021 survey. Other birds of this family which also have irregular visiting patterns to this lake includes Ruddy Shelduck, Cotton Pygmy Goose, Gadwall, Eurasian Wigeon, Mallard, Garganey, Red-Crested Pochard, Common Pochard, and Tufted Duck.

Focusing on Scolopacidae, out of 14 birds that visited, all were migratory birds, and among them, 13 were carnivorous and 1 omnivorous. In this family, two species of Black-tailed godwit and Curlew sandpiper are under near threatened category. Interestingly the first species has been consistently recorded, but the latter was never seen further. Common snipe was recorded in 1994 and 2003 only. Further, only 1 Pin-tailed snipe was recorded in 2020. Eurasian Whimbrel and Sanderling were never recorded in subsequent years. Species like Broad-billed sandpiper, green sandpiper, Wood Sandpiper, Red Phalarope, and Ruddy Turnstone, which were absent in 1994–1997 phase were identified during our survey.

Fig. 7 NDWI maps of 2021
periods in different years. Additionally, considering other families, Egyptian vulture of Accipitridae family, which is also an endangered listed bird never recorded after 1994–1997 survey. However, in 2020, Western Marsh-Harrier, another species of this family was observed.

Anhingidae (Darter, near threatened), Glareolidae (Collared pratincole), Gruaidae (Sarus crane, Demoiselle crane, and Common crane) and Pelecanidae (Great white pelican) almost disappeared after 2003, and were never recorded further. Families Ciconiidae (Painted stork, near threatened and Black stork), Phalacrocoracidae (Little Cormorant and Great cormorant), Rallidae (purple moorhen was never found again, Eurasian coot and Common moorhen were found again, and White-breasted Waterhen was for the first time observed in 2021), and Threskiornithidae (Glossy ibis, Eurasian spoonbill, Red-naped Ibis, and Oriental white ibis) re-appeared after revival of the lake water during 2020–2021. Families like Alaudidae, Alcedinidae (White-breasted Kingfisher), Cuculidae (Greater Coucal), and Motacillidae (White Wagtail, Grey Wagtail, and White-browed Wagtail) appeared during our survey period only. Some families that have been persistently visiting the lake includes Anatidae, Ardeidae, Charadriidae, Laridae, Phoenicopteridae, Podicipedidae, Recurvirostridae, and Scolopacidae; however, not all the species consistently visited.

To emphasize feeding habits, it is clear that the lake had always been dominated by carnivores, followed by omnivores and least by herbivores. The trophic structure of this lake starts with the phytoplankton, which survives in the lake during monsoon to winter (Vijay et al. 2016). The lake receives rainfall of about 500 mm from July to October during monsoon season. The vital abiotic factors regulating its ecosystem are oxygen, salinity, alkalinity, temperature and brine density. During monsoon it has high oxygen level and other factors are low. (Upasani and Desai 1990). The oxygen level starts decreasing, and other parameters start increasing towards winter season, up to March. These shifts in abiotic factors from monsoon to winter also leads to shifting in biotic factors like phytoplankton, zooplankton, insect, crustacea, protozoa, rotifer and other vertebrates and invertebrates (Shukla and Bhatnagar 2005). During monsoon, the color of the brine appears green to dark green (Fig. 8a) due to the presence of abundant oligohaline organisms like cyanobacteria, algae, and diatoms (Upasani and Desai 1990). These are prime foods for rich heteroptera diversity residing in the

Fig. 8 (a–c) represents the seasonal change of lake color, (8d) and (8e) showcase flocks of flamingo, and common ruff respectively, and (8f) show our bird census team with AWC.
lake. Sometimes it is also suitable for freshwater species on dilution of brine (Baid 1959).

Subsequently, it changes to orange (Fig. 8b) to dark pink color (Fig. 8c) by the end of winter, taken over by euryhaline organisms (Vijay et al. 2018). These oligohaline and euryhaline are also called true aquatic life forms for the lake. These favorable seasons, accompanied by suitable abiotic condition at pH level 7 to 10 promote their sporulation, germination and germling developments for phytoplankton (Reddy 1984). Salinity ranges from 50 to 120 mg/l, while brine density from 1.07 to 1.17 g/cm$^3$ from monsoon to winter season (Bhat et al. 2015). The lake supports rich biodiversity of vertebrates, invertebrates, phytoplankton, and prokaryotes when the salinity is below 50 gm/l (Baid 1959). These are found towards the shoreline of the lake. During summer (April-June), when it increases to 100 gm/l to 120 gm/l, there is shift in organisms by hygrophilic life forms like haloalkaliphilic sulphate, reducing bacteria, Dunaliella spp., cyanobacteria, archaea. Halophilic bacteria of the lake are also categorized as chemoautotrophs, chemoheterotrophs, photoautotrophs, photoheterotrophs and chemolithotrophs (Baid 1959; Upasani and Desai 1990; Sharma et al. 2020a). These rich primary producers form the backbone of rich primary producer diversities with 14 protozoa, 15 rotifers, 45 crustacea (Dermaptera: 29 and Coleoptera: 45) and 74 insect species (Kumar 2005).

With a further increase in salinity to above 200 g/l, biodiversity is completely limited to species of Dunaliella sp. and Archaea sp., only found in the core region of the lake, thereby giving dark red color to the brine, accompanied by dead algal cells (Gupta et al. 2015). This lake has always had one or the other life form during every season. However, during monsoon to winter season, it supports abundant freshwater body organisms to slightly haloalkaliphilic ones, which attract laks of migratory birds from different countries (Sharma et al. 2020b). Birds are considered to be the most commonly accepted ecological indicator. Their decreasing trend in this lake indicates a disturbance in the respective organisms of lower trophic levels. Disturbance in the organism configuration is a visible result of changing abiotic factors like pH, salinity, alkalinity, oxygen and carbon dioxide, along with disturbed landscape variables’ wetland shape, size, patch, corridors and hydrological connectivity between shoreline and core part of the lake (Naik and Sharma 2021). All these factors primarily indicate the highly fluctuating water level, as shown in the monthly water index maps of 2019, 2020 and 2021 coinciding with our bird survey time frame.

If the maps of 2019 are observed, the lake is devoid of water during winter season, for January, February, and March, when it is expected to have water. During the dry months of April, May and June, there is no water in lake. According to Naik and Sharma (2021), the lake has been shrinking at a constant rate of 4.23% since 1963 every decade. Already 30% of the lake has been converted to saline soil, and saline soil to barren land. Illegal salt pan encroachments, along with excessive groundwater, extracted using electrical pumps, are among the prime causes of desiccating status of the lake. Additionally, increasing settlement areas, domestic and commercial waste dumping, and other pollution are also putting urban pressure on the lake (Sharma et al. 2020b). As there used to be no water, it has often been used as vehicular testing sites, which cause noise pollution in the peripheral area (Kumar 2005). Based on the wetland status till January 2019, it has been predicted that the lake might be completely desiccated by 2059, even losing its saline character (Naik and Sharma 2021). This would ultimately reflect on the global level ecological connectivity led by the migratory birds.

Surprisingly, there was sufficient rainfall in the state of Rajasthan during monsoon period of 2019, which helped to retain its water level, as seen in August to December maps. According to some local unpublished sources the lake welcomed laks of migratory birds, indicating thereby a positive sign of the revival of the lake. Unfortunately, within this period, the lake also encountered a massive avian botulism catastrophic event, a first in its entire history of its existence. Due to this event, all the economic activities were banned till the reason for botulism was identified. This prohibited illegal activities, and helped more water retention for January, February, March 2020, as compared to the same period of 2019. Meanwhile, due to the COVID-19 pandemic worldwide, there was complete shutdown from March till May 2020. This helped in maintaining the water level even during the summer months of April, May, June, and July. However, from August 2020 onwards, after unlocking, the condition has again started deteriorating, as economic activities resumed. From the maps of monsoon period of 2020 continuously till monsoon...
of 2021, the lake has been again desiccating. According to the Sambhar Salt Ltd, 77 km² towards the east is allowed for salt extraction, while rest of the 113 km² is allowed for ecological purposes, migratory birds and groundwater recharge. But practically, every part of the lake has been encroached, stealing brine worth 330 billion dollars in the global salt market. This might again reduce the water level, and subsequently the visiting migratory birds.

High rainfall, short-term control over economic activities and COVID-19 lockdown, combined helped in reviving the water level without any capital investment. These indicate that the lake does have high resilience capacity, and can be restored with little, but a proper conservation and management plan. According to The Gazette of India, 26 September 2017, PART II—Sect. 3—Sub-section (i), in context to Sambhar Lake, a Sambhar Development Authority (SDA) should be formulated. This authority should designate an expert each for wetlands ecology, hydrology, fisheries, landscape planning and socioeconomics, besides one from the civil society; they should meet at least thrice in a year. SDA should list out all the activities that are allowed, regulated, or prohibited within the Sambhar Lake. Additionally, the government should allocate budget and human resources to this authority to ensure smooth functioning. It should also encourage activities like ecological rehabilitation and rewilding of nature, research, environmental education and participation activities, habitat management and conservation of wetland-dependent species, community-based ecotourism with minimum construction activities, harvesting of wetlands products within regenerative capacity. Government should take the necessary steps based on the “wise-use” principle of Ramsar Convention ‘wise use’. SDA should strictly monitor the activities listed in 2017 rules that prohibit within notified wetlands, such as the setting up of any industry and expansion of existing industries, manufacture or handling or storage or disposal of construction and demolition waste, solid waste dumping, discharge of untreated wastes and effluents from industries, cities, towns, villages, and other human settlements. It must ensure prohibition of any type of illegal salt pan encroachment and wetland conversion to non-wetland use. For this, SDA might also take necessary assistance from professional institute(s)/organization(s). Further, with the help of remote sensing experts, hotspots for different migratory birds and unique halophytes and halophiles should be identified. Then, their eco-sensitive buffer zones should be mapped, using remote sensing and GIS technology. Their habitat suitability assessment should also be modeled with respect to different climatic scenarios. These steps, coupled with complete check of illegal salt pan encroachment, and excess ground water extraction would be to maintain complete ecological integrity of the lake. Further, all of these would automatically support good quality of brine formation for both pan and kyars salt produced in this lake. In turn, this would help the Indian government to overcome the loss of salt production.

It is widely believed that inland saline lakes are either salt-producing sites or a wasteland. Though there are globally 200 inland temporary and permanent Ramsar sites (RSIS, Accessed August 10 2021), still they are not considered to be conserved. These conceptions have already led to the conversion of world’s numerous large saline lakes like Aral Sea, Caspian Sea, Lake Urmia, Lake Salton, Lake Utah, Dead Sea, and Lake Balkhash. billion dollars businesses have collapsed, lakhs of livelihoods have been lost, in addition to loss of habitats of migratory birds, halo-tolerant vertebrates and invertebrates, along with several recreational and educational sites.

Especially, our findings highlight the factors responsible for the desiccation of this Ramsar site, which might also be the cause of other lacustrine wetlands. It also provides a novel approach towards regular monitoring of the lakes integrating GEE. Taken together, our findings along with previous studies point towards the urgent need to conserve the rich biodiversity of inland saline wetlands, playa wetlands, shallow wet-lands, sabkhas, salterns, saltpans, athalassohaline lakes and soda lakes of the world. These ecosystems are the blue lifeline for semi-arid to arid regions, going to the alternative of freshwater bodies in the near future almost in every climatic zones. GEE replacing the high-end desktop computational requirement with cloud computation. This technology is helpful for wetland practitioners, researchers, bureaucrats of shallow lakes in which water regime fluctuate very frequently. However, it is nearly impossible to keep an eye on the study areas at monthly basis for collecting field data which requires a lot of time and effort to generate useful information. Additionally, monthly analysis using remote sensing technology requires high-end work stations to download,
process, and analyze satellite images which is also nearly impossible for all wetland related persons. Like in this case, the authors did not have high-end workstation at their home during COVID-19 lock down. The continuous and intense monitoring was possible only because of the cloud computation availability of GEE. The manuscript is limited to only NDWI application of GEE. However, this platform as many other JavaScript based algorithms for soil, salinity, algae, vegetation, turbidity etc. which are the basis of preparation of management and restoration plans. GEE is user friendly for a person with little coding knowledge. It means, the tedious task of mapping and monitoring can be conducted easily and timely, fastening the task of landscape level analysis to some extent. Hence, this new approach of integration of cloud computation with the ecological datasets can fasten the conservational networks during the United Nations Decade on Ecosystem Restoration (2021–2030).

It is important to mention that the study was conducted during the first phase of COVID-19 pandemic situation. Due to repeated country wide lockdowns and shut downs, sufficient field data could not be collected, sampling and laboratory analysis could not be done. These limitations are important to be discussed. Firstly, this study does not cover the results about vegetation aspects of the lake. However, it was not analyzed. It is because, most of the inland saline-alkaline lakes are situated amid desert ecosystems. These ecosystems have sparse vegetation and very difficult to study using optical remote sensing datasets. As, Sambhar Lake is also one of the gateways to world’s 17th largest desert known as Great Indian desert or the Thar desert. The dominant vegetation are halophytes and xerophytes which are difficult map using Sentinel (10 m spatial resolution) datasets. It requires intense field survey which was also planned to do but could not achieve the target due to repeated COVID-19 pandemic lockdowns. Secondly, this study also does not include information about soil. Soil salinity index was calculated in GEE every month for 2019, 2020 and 2021. But it was observed that, it did not have significant changes every month like surface water change, these results were not included in the current manuscript. Thirdly, accuracy assessment of NDWI was not included in the manuscript. Though, accuracy assessment of NDWI values with the field data sets was planned to be conducted but due to COVID-19 lock downs regular field visits could not be done and subsequently, correlation analysis was not performed. However, during bird census GPS locations were taken and presented in Fig. 1 and the seasonal status of the lake is given in Fig. 8a–c. According to Singh et al (2015), in most of cases, the water signatures are misclassified with the settlements or construction areas. During the research for past, present and future Land Use Land Cover of this lake, authors had conducted intense field visits with accuracy assessment which is presented in the published manuscript (Naik and Sharma 2021). It is mentioned that there are not construction features in the lake. Most importantly as it is a saline lake, the signatures of salt and saline soil are white and grey in color, so there is very least chance of misclassification of water bodies. So even if accuracy assessment was not conducted, no wrong information would be delivered though this manuscript. Importantly, the above reasons do not affect the overall accuracy of the results and reduce the importance of the study. Future research may choose to extend this work by conducting species distribution modeling for keystone species, like lesser flamingo, machine learning techniques like Multivariate Adaptive Regression Splines (MARS) for multiple species simultaneously, use of microwave datasets for bathymetric analysis, integrated trophic status index, spectral library generation of haloalkaliphiles using hyperspectral datasets, use of Artificial Intelligence and Internet of Things for water, soil and brine quality monitoring.

Conclusions

The current study has been conducted in the largest shallow saline wetland of India, Sambhar Lake. It is experiencing severe threat due to illegal salt-pan encroachment, use of illegal electric cables for excessive underground water extraction and stealing of brine worth 330 billion dollars in the global salt market. Such activities are consistently degrading the ecosystem, creating thereby an imbalance at each trophic level, right from the primary producer to the tertiary consumer level. This study aimed to analyze the status of migratory birds, and the water
level of the wetland, using integrative approach of ground survey and remote sensing. However, due to avian botulism in 2019, COVID-19 shut down in 2020 and repeated lockdowns in 2021, the proposed methodology was changed. GEE helped to monitor the lake every month even when the authors were at home. The comprehensive results showcase the blurred future of this amazing Ramsar site. If urgent conservation steps are not taken, as discussed, it might be completely lost, before its lease period (2059) as a salt industry. This research would encourage other wetland specialist, researchers, conserve this ecosystem for using GEE. There are 148 such inland saline Ramsar sites and other unidentified sites sharing this common fate of desiccation; they should be prioritized during the UN Decade on Ecosystem Restoration.

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Declarations

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