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*Type of the Paper (Article, Review, Communication, etc.)*

# Migratory birds monitoring of India's largest shallow saline Ramsar site with big geospatial data using Google Earth Engine for restoration

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**Abstract:** Globally, saline lakes occupying 23% by area 44% by volume among all the lakes might desiccate by 2025 due to agricultural diversion, illegal encroachment, pollution, and invasive species. India's largest saline lake, Sambhar is currently shrinking at the rate of 4.23% due to illegal saltpan encroachment. This research article aims to identify the trend of migratory birds and monthly wetland status. Birds survey was conducted for 2019, 2020 and 2021 and combined with literature data of 1994, 2003, and 2013 for visiting trend, feeding habit, migratory and resident ratio, and ecological diversity index analysis. Normalized Difference Water Index was scripted in Google Earth Engine. Results state that it has been suitable for 97 species. Highest NDWI values for the was whole study period was 0.71 in 2021 and lowest 0.008 in 2019 which is highly fluctuating. The decreasing trend of migratory birds coupled with decreasing water level indicates the dubious status for its existence. If the causal factors are not checked, it might completely desiccate by 2059 as per its future prediction. Certain steps are suggested that might help conservation. Least, the cost of restoration might exceed the revenue generation.

**Keywords:** Inland saline wetland; lake; ecosystem, biodiversity, human interventions, Google Earth Engine, Normalized Difference Water Index, Restoration

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## 1. Introduction

Globally, saline lakes occupy 23% by area 44% by volume among all the lakes [1]. They are usually confined to arid and semi-arid regions of the earth [2]. They show similar vertical stratification to freshwater systems but differ primarily in their ionic composition due to salinity ranging from 3 g/L to 300 g/L [3]. Due to anthropogenic pressures and climatic uncertainty, numerous lakes are rapidly drying even before we could know [4]. The recent example is 90% decline of the Aral Sea in Uzbekistan and Kazakhstan over just 50 years [5]. Compared to deep saline lakes, shallow ones are furthermore sensitive to slight variation accelerating their desiccation [6]. Their drying condition exposes the lakebed rich in numerous minerals of sodium, magnesium, calcium, lithium, and potassium, which might impact billion-dollar global market [7]. These can also lead to public health hazards primarily respiratory problems, lung diseases, and related infections raised due to salt, sand, and dust storms [8]. Additionally, shrinkage of these lakes or complete desiccation can collapse whole ecosystems also. Consequently, there more budget will be required for their restoration compared to the revenue generation as in case of Lake Owen's for Los Angeles city [9]. Even if these are vital aquatic ecosystems providing wide range of ecosystem services, habitat for lakhs of migratory birds and haloalkaliphiles, they are ignored compared to their freshwater counterparts [10], primarily due to their geographic locations in inaccessible areas [11]. However, since the launch of first-ever satellite in 1972, application of Remote Sensing and Geographic Information System has enabled to conduct landscape-level studies due to availability of real-time, cost-

effective, and dynamic satellite images significantly different from traditional in situ measurements [10].

Currently, 6,542 satellites are orbiting around Earth as of 1, 2021, out of which 3,372 are operational and 3,170 satellites are non-operational providing petabytes of datasets [12]. Besides, space-borne satellites, other platforms like airplanes, ground-based platforms, Unmanned Aerial Vehicles, along with data from statistical, ecological, social, and geological constitute enormous volume of data also termed as Big Earth Data (BED) [13]. BED requires high-end desktop computational facilities, developed infrastructure, huge storage capacities which limits the earth observation studies [14]. However, the availability of cloud computing platforms like Google Earth Engine (GEE) removes the above said obstacles since 2010 [15]. Its data repository is a collection of approximately 40 years of satellite imagery, at multiple Spatio-temporal scales [16]. 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 [16]. The only requirements are a simple desktop or laptop and internet connectivity for any time assessment and monitoring [17]. 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 [18]. This also facilitates importing and uploading of own vector and raster datasets and results can be exported from GEE in GeoTIFF format to own Google Drive account [19]. 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, they are still needed for special functions that are not offered on GEE (like object-based image assessment) [16]. GEE has been widely explored for vegetation mapping and monitoring such as global estimation of Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) [20], Leaf Area Index (LAI) [21], Canopy water content (CWC) [22], and Fraction Vegetation Cover (FVC) [23], for agricultural applications like crop area mapping [24], crop yield estimation [25] and pests and diseases vulnerability [16].

However, this has been quite less explored for saline wetland application. Remote sensing images have been used to extract water bodies including several methods like single band density slicing [26], supervised [27] and unsupervised classification [28] and spectral water indexes [29]. However, among all these methods, index-based method is widely accepted due to its efficient and user-friendly process [27]. At first, Normalized Difference Water Index (NDWI) was proposed by [30] using the green and Near Infrared (NIR) bands of satellite images as waterbodies have strong absorbability and strong absorbability and low radiation in the range from visible to infrared wavelengths. [31] 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, [32] developed the Automated Water Extraction Index (AWEI) which remove misclassification of shadow as water, by using multiple spectral bands. Tasseled Cap Wetness (TCW) index has also been used for water studies [33]. 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 [34].

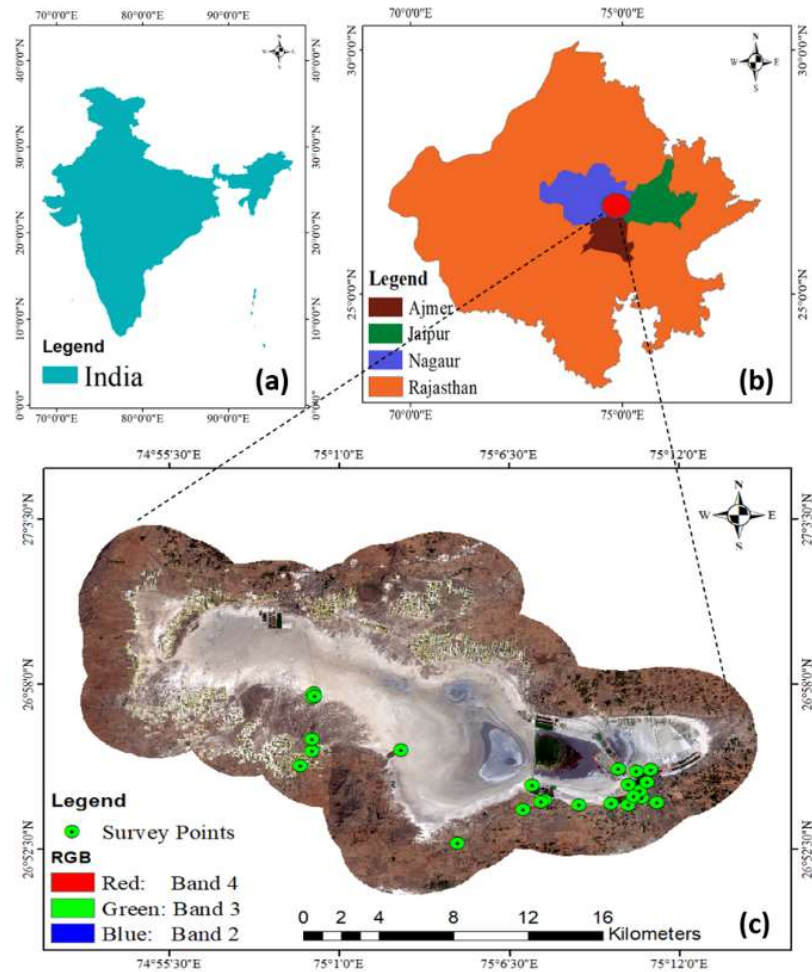
The current study is conducted in the largest shallow saline Ramsar site of India. It is currently undergoing desiccation due to saltpan encroachment, illegal water extraction, brine theft and increasing urban pressure. As a result of which, whole ecology is at stake. So, to analyse the current position, this research article aimed to investigate the status of migratory birds and water availability. For this purpose, we performed research in phase. Firstly, we conducted bird survey for consistent three years, 2019, 2020 and 2021 and combined it with the literature survey data for long-term visiting trend analysis, migratory and resident ratio, feeding habit analysis and ecological diversity index calculation. Secondly, we examined the monthly status of wetland for our survey period using NDWI in Google Earth Engine platform. This paper is divided into five sections. The first section

provides a brief overview of global status of saline lakes, developmental phases of remote sensing from desk computing to cloud computing and further applicability of NDWI. Second section elaborates on the study area, and methodology followed for bird and wetland status. Third section showcases the results obtained. Fourth section discusses the whole results and further section five concludes the research.

## 2. Materials and Methods

### 2.1 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 Thar desert (Figure 1) surrounded by Aravali hill ranges of India [35]. It is located 80.7 km away from Jaipur, the state capital of Rajasthan via National Highway 48 and Rajasthan State Highway 57 [36]. 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, as India exports approximately 230 million tons of salt to global market after China and USA, to 198 countries like Japan, Bangladesh, Qatar, Indonesia, South and North Korea, Malaysia, U.A.E, and Vietnam [10]. Being an inland wetland, it is 230 km<sup>2</sup> (22.5 km in length and 3-1 km in width) [37]. A 5.16 km long dam is built for reservoir (77 km<sup>2</sup>) and wetland area (113 km<sup>2</sup>) [38]. Its saline character is contributed by the presence of salts of sodium, calcium, potassium, and magnesium cations and chloride, carbonate, bicarbonate, and sulphate anions [39]. It seems white in areas with rich 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 (July-September), has water during winter season (October- March) when the temperature is between 11 °C to 24.4 °C [40]. It almost dries out during summer season (April-June) when temperature rises to 40.7 °C. It is also a shallow lake with vertical depth ranging from 3 m to 0.6 m during monsoon to summer seasons [41]. Its water system is supported by ephemeral streams like Mendha, Kharian, Rupnagar, Khandel forming the catchment of 5,520 km<sup>2</sup> [42]. This amazing site is one of the most important visiting grounds for migratory waterbirds on the East Asian, Central Asian, and East African flyways declared as Ramsar site on 23 March 1990 and it is also an Important Bird Area [43]. There are about 1 lakhs waterbird primarily flamingo overwintering in this lake and most of them are distributed in the saltpan areas as there is a little water left in the natural wetland area [44]. The water level of this lake is decreasing due to illegal saltpan encroachment [10]. Moreover, 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 [45]. Hence, regular monitoring of waterbirds and their distribution along with mapping their habitats in entire flyways are necessary for their conservation.



**Figure 1.** Study area. (a) is India; (b) is Rajasthan with three states and (c) is True Colour Composite of Sambhar Lake of 8 January 2021 with birds' survey points.

## 2.2 Bird census data

We carried out 3 surveys for 3 days each during the wintering season of 2019, 2020 and 2021, every third week from January to second week of February when the migratory birds visit the lake. The wetland survey included both the natural wetland area as well as saltpan areas. Bird counting was done on 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. Surveys were carried out during morning period 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 almost 360 m above mean sea level and is surrounded by Aravalli hill range in the outer boundary of the lake, there are no visual topographic hindrance for the survey. Surveys were conducted by the same volunteers to avoid variation. The availability of time-series data from literature is scarce with non-uniform patterns. However, we selected for the years 1994-97 [46], 2003 [47], 2013 [48]. These censuses were mostly conducted during winter season which matched our study period.

### 2.3 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 wide range of applicability in the fields of land monitoring [49], vegetation [50], agricultural [51], water [52], and soil research [53]. The Sentinel-2 data contain 13 spectral bands representing Top of Atmospheric (TOA) reflectance scaled by 10000 [54]. Additionally, three Quality Assurance (QA) bands are available among which one (QA60) is a bitmask band with cloud mask information [55]. Each Sentinel-2 product set (zip archive) contains multiple granules which are individual assets in GEE [56]. Sentinel-2 has the format as COPENNICUS/S2/20211005T002653\_20211231T102149\_T56MNN as a GEE asset [57]. 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 COPENNICUS/S2\_SR were accessed for three years from 2019 to 2021 from GEE.

### 2.4 Google Earth Engine

Sentinel-2 images from 2019 to 2021 have been assessed using functions (Table. 1). To reduce the effect of cloud cover, there are two removal techniques available: (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 pixel and selects the lowest available range of cloud scores and then computes per-band percentile values from the selected pixels [58]. Here, we have used the second method along with QA60 algorithm for updating cloud cover mask. Then, NDWI was calculated using the respective function and visualized it in GEE.

### 2.5 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 then extract water pixels according to the suitable threshold. [30] 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. The NDWI is calculated using Eq. (1) where Band 2 is the TOA green light reflectance and Band 4 is the TOA near-infrared (NIR) reflectance.

$$NDWI = ((Green - NIR)) / ((Green + NIR)) \quad (\text{Equation 1})$$

For Sentinel 2 data, band 3 is the green band and band 8 is the NIR band.

### 2.6 Exporting

The water surface extraction algorithm was used in the GEE platform every month. It identified the parts of lake with and without water. Then, this NDWI for each month was exported to google drive using 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 map composed. The comprehensive methodology is shown in Figure 2 below.



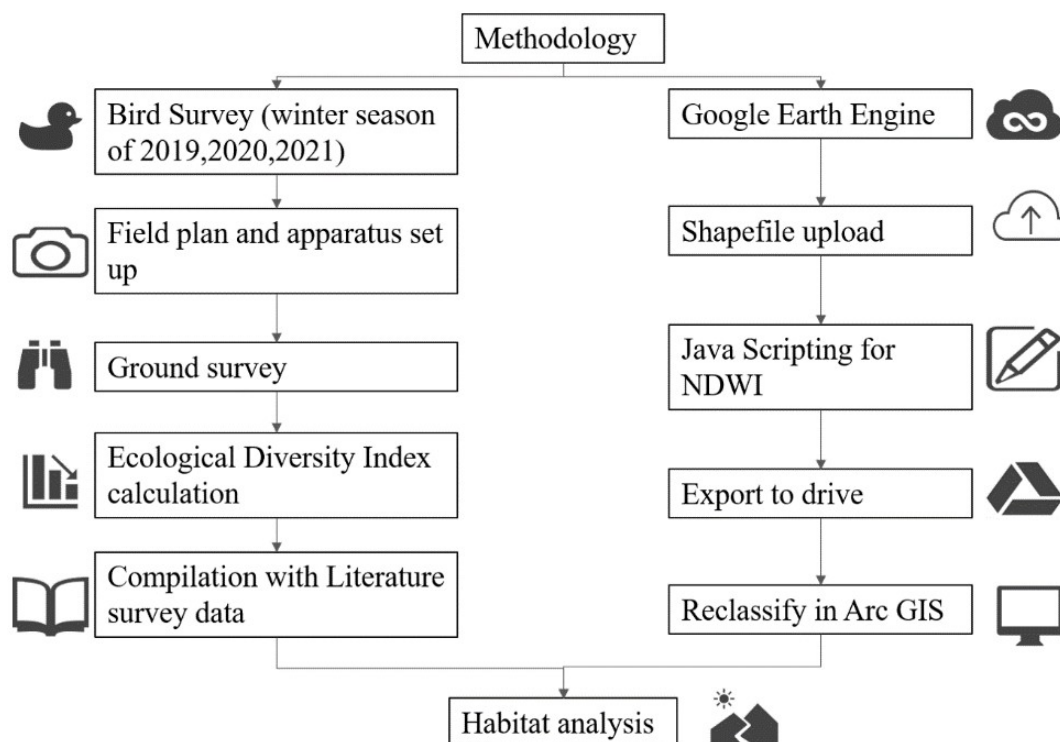


Figure 2. Methodology

Table 1. List of Google Earth Engine functions used.

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
12	img.normalizedDifference	To calculate NDWI
13	.select	To select desired NDWI image

14	.rename	To rename the output image
15	Export.image.toDrive	To export final output to drive

3. Results

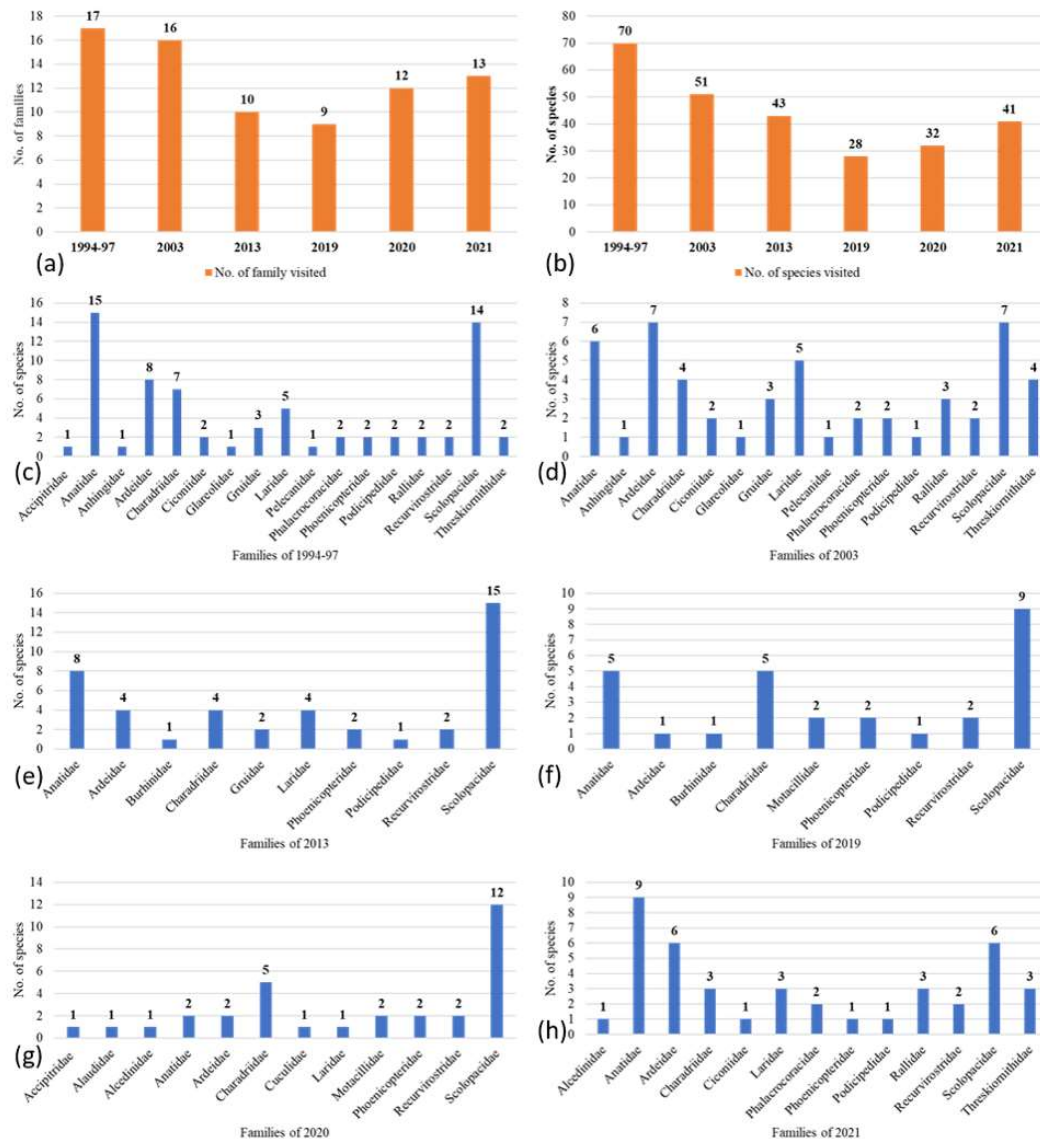
3.1 Bird status

3.1.1 Trend analysis

From the combined results of literature and author’s survey, it is calculated that in total as shown in Figure 3 (a &b), 97 species belonging to 23 families have visited the lake since 1994. These families are Anhingidae, Accipitridae, Alaudidae, Alcedinidae, Anatidae, Ardeidae, Burhinidae, Charadriidae, Ciconiidae, Cuculidae, Glareolidae, Gruidae, Ibisorhynchidae, Laridae, Motacillidae, Pelecanidae, Phalacrocoracidae, Phoenicopteridae, Podicipedidae, Rallidae, Recurvirostridae, Scolopacidae, Threskiornithidae. 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 family visited in between 1994-1997 (Figure 3 c). They are 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, Ibisorhynchidae, and Motacillidae were absent. 51 species of 16 families visited in 2003 (Figure 3 d). 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, Ibisorhynchidae, and Motacillidae were absent. 43 species of 10 families visited in 2013 (Figure 3 e). 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, Ibisorhynchidae, Motacillidae, Pelecanidae, Phalacrocoracidae, Rallidae, and Threskiornithidae are absent.

28 species of 9 families visited in 2019 (Figure 3 f). They are 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, Ibisorhynchidae, Laridae, Pelecanidae, Phalacrocoracidae, Rallidae and Threskiornithidae are absent. 32 species of 12 families visited in 2020 (Figure 3 g). 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, Ibisorhynchidae, Pelecanidae, Phalacrocoracidae, Podicipedidae, Rallidae, and Threskiornithidae are absent. 41 species of 13 families visited in 2021 (Figure 3 h). 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 which belong to 10 families like Anhingidae, Accipitridae, Alaudidae, Burhinidae, Cuculidae, Glareolidae, Gruidae, Ibisorhynchidae, Motacillidae, and Pelecanidae are absent. Details of bird analysis is given in Table S1.



**Figure 3.** showing temporal graphs of bird presence/absence results. (a) and (b) show family and species wise and (c-h) show class-wise distribution.

### 3.1.2 Feeding habit analysis

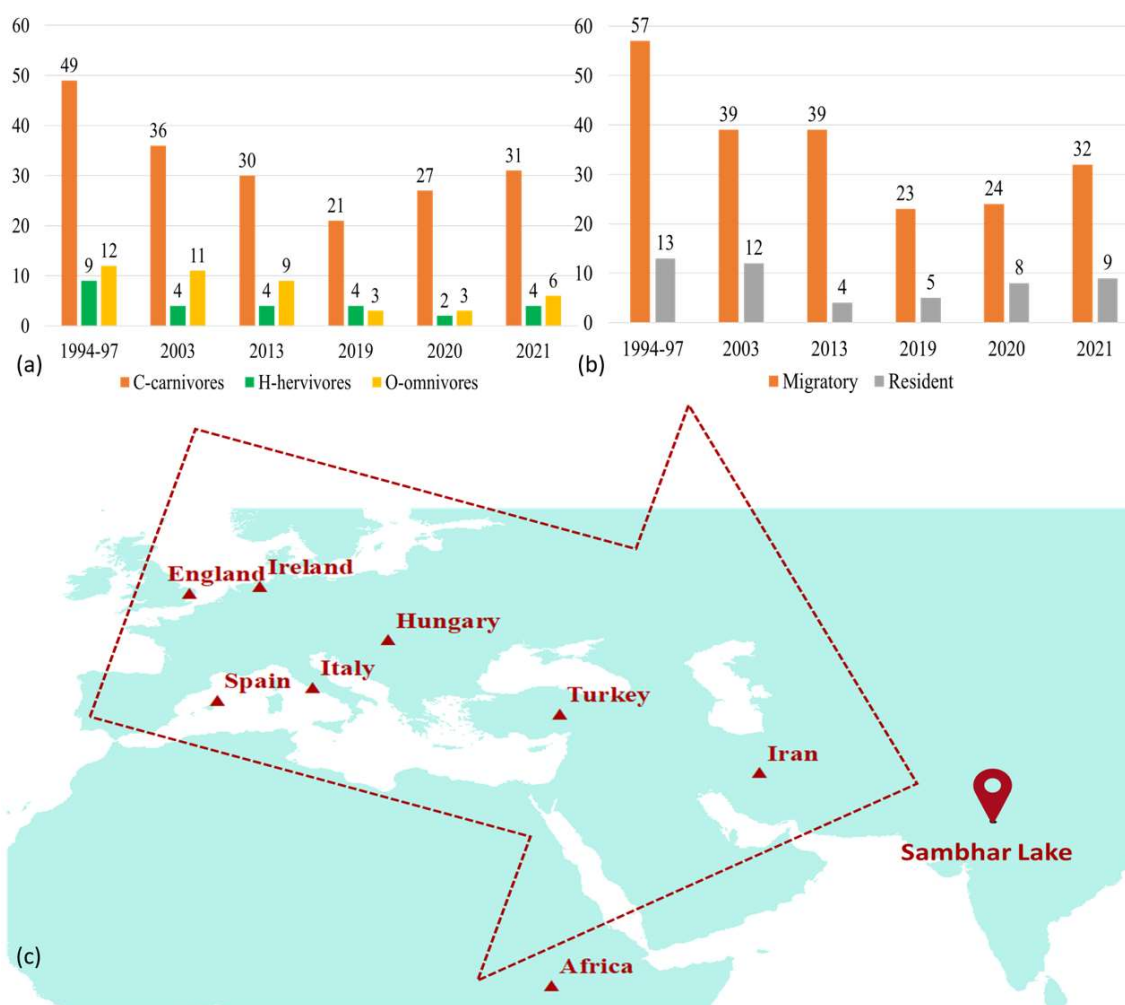
From Figure 4 a, it is clear that Sambhar Lake always attracts a greater number of carnivores birds as compared to herbivores and omnivores. In between 1994-97, total of 70 birds visited the lake, out of which 46 species were carnivores, 8 species were herbivores, and 16 species were omnivores. In 2003, 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. Carnivores birds visit this lake to 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, locusts, grubs, mantids, stick insects, cicadas, maggots, cyprinids, pikes, roaches, eels, perches, burbot, sticklebacks, muddy loaches, shrimps, offal and 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. Omnivores birds eat either of the available food.

### 3.1.3 Migratory pattern analysis

From the Figure 4 b, it is observed that there are more migratory birds than the resident birds of this lake. Among the total 70 birds visited during 1994-97, 57 species were migratory and 13 were resident. In 2003, among 51 species, 39 are migratory and 12 are resident species. In 2013, out of total 43 species, 39 are migratory and 4 are resident species. In 2019, out of total 28 species, 23 are migratory and 5 are resident species. In 2020, out of total 32 species, 24 are migratory and 8 are resident species. In 2021, out of total 41 species, 32 are migratory and 9 are resident species. All the migratory birds visited to the lakes primarily from but not limited to European countries like Iceland, England, Ireland, Hungary, Italy, Spain, Turkey, Africa, and Iran during winter season for resting, roosting, and breeding as shown in Figure 4 c.



**Figure 4.** (a) shows feeding habit, (b) shows migratory/resident type and (c) major visiting countries.

3.1.4 Ecological diversity index

Two ecological species diversity indices have been calculated (Table 2). They are 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.

Table 2. Ecological Diversity Index.

Year	Shannon-Weiner index	Simpson index
2019	2	0.21
2020	1.09	0.42
2021	3.07	0.07

3.2 2019

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

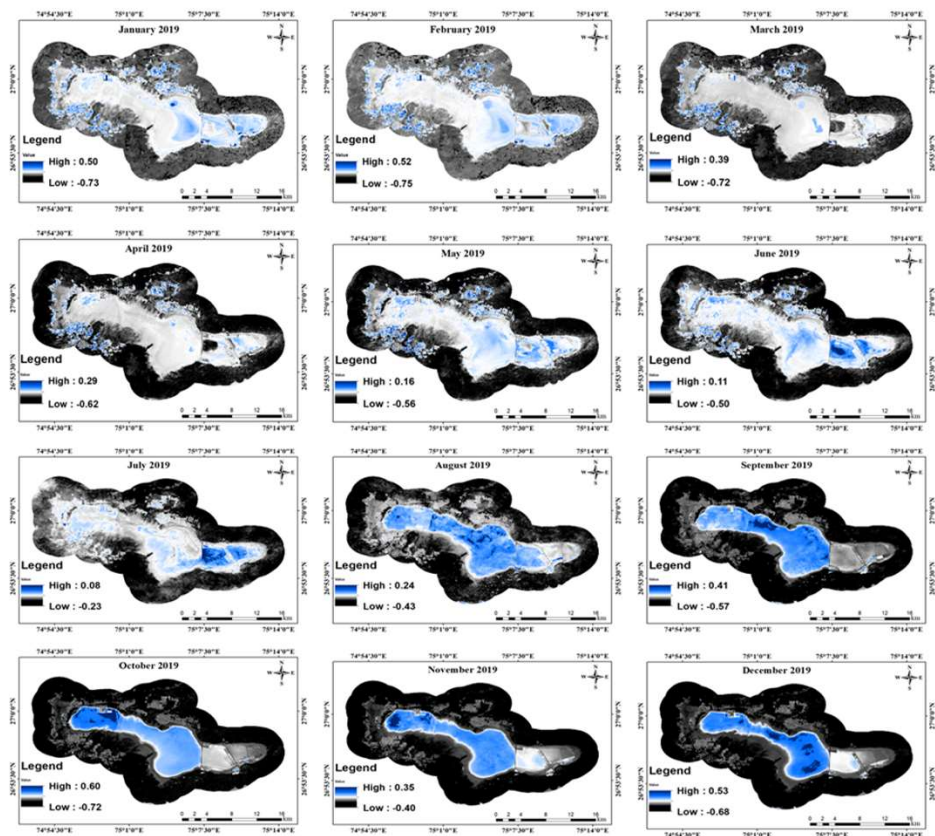


Figure 5. NDWI maps of 2019.

3.3 2020

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

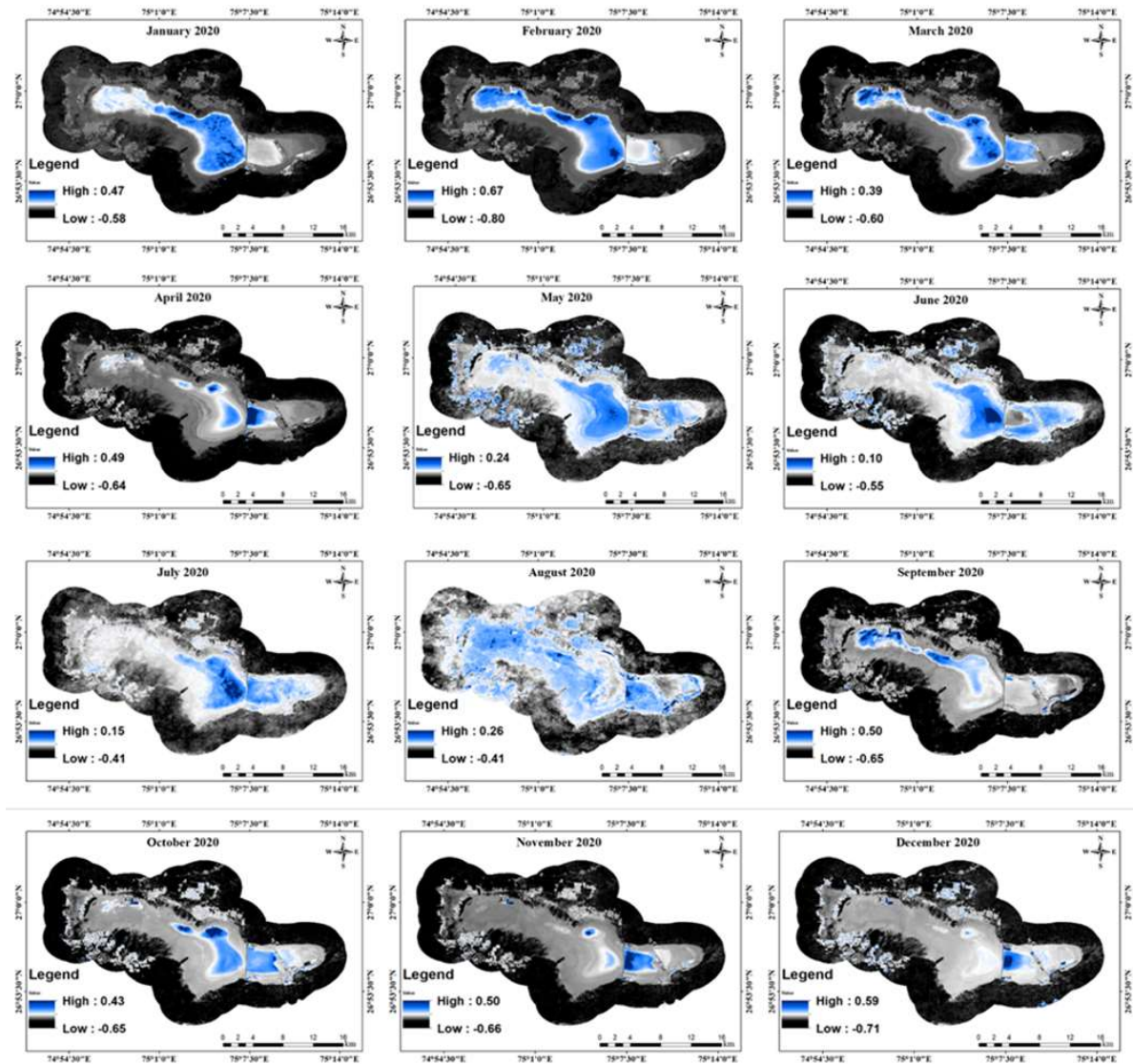


Figure 6. NDWI maps of 2020.

3.4 2021

In the year 2021 (Figure 7), the highest NDWI value for the year until July was 0.71 in February and lowest was 0.1 in June. During winter season (January-March), the highest value was 0.71 in February and 0.26 in March. During summer season (April to June),



highest was 0.28 in April and 0.08 in June. Cannot be compared as the data is available for only July moth with value 0.21.

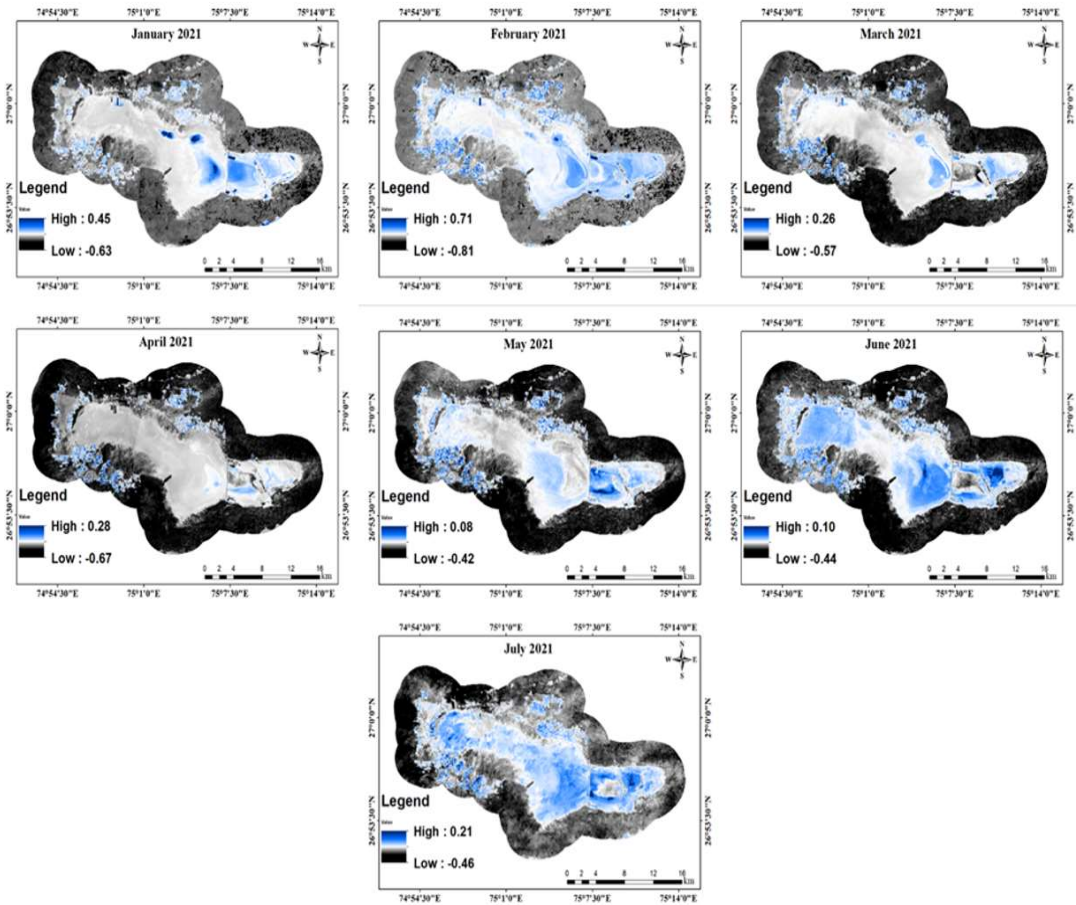


Figure 7. NDWI maps of 2021.

Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited.

Title 1	Title 2	Title 3
entry 1	data	data
entry 2	data	data <sup>1</sup>

4. Discussion

In the present article, we investigated the wetland and migratory bird status for 2019, 2020 and 2021 accompanied by the literature bird survey data. We analyzed the trend analysis, feeding habits and migratory whether there is any shift in visiting pattern of migratory birds to the study area. We addressed the research question like which birds used to come during last decades and now which birds are coming, which feeding habit birds used to come and is there any shift, what was the ratio of migratory versus resident birds and also to identify whether this lake supports any IUCN listed bird. The monthly status of wetland was also integrated. We conducted bird census consistently for three years during winter season to collect primary data. We used literature as secondary source of data for identifying bird details in previous years and Arc GIS software for preparing field visit plans and identifying sampling locations. We used Sentinel 2 B satellite data of

2021 for preparing study area map and field visiting map of 2021 January. We found results to be very depressing. Since last decades there has been a decreasing trend of migratory birds visiting the lake. Birds of many families have stopped visiting. Numerous IUCN listed birds 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 are foundation of complex food web. This is distinctly reflected in the decreasing trend of birds. The field photographs are shown in Figure 8 below in which Figure 8 a-c represent seasonal change of lake colour, 8 d and 8 e showcase flocks of flamingo and common ruff respectively and 8 f show our bird census team with Asian Waterbird Census.

It is disheartening to state that the trend of visiting birds has consistently been decreasing pattern till 2019. During the monsoon period of 2019, the lake received heavy rainfall after 30 years [59] which helped to revive the water level. Shockingly, this lake encountered first-ever avian botulism in its history [44]. It was observed on 13 November 2019 by some tourists. In this incidence more than forty thousand migratory birds, primarily Northern Shoveler died [44]. To avoid any human infection, the salt extraction activity was legally stopped for nearly two months (November, December, and January) [44] 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 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 belong to 17 families which further reduced to meagerly 28 species of 9 families in 2019. The most dominating families used to be Anatidae and Scolopacidae. They combinedly 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 second dominating family. During 1994-97, 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 and 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 1994-97 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 are 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 these 13 were carnivorous and 1 omnivorous. In this family, two species Black-tailed godwit and Curlew sandpiper are under Near Threatened category. Interestingly the first bird has been consistently recorded but the later bird has further never seen indicating a dubious state for this wetland existence. 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 1994-97 phase were identified during our survey periods in different years. Additionally, considering other families Egyptian vulture of Accipitridae family, which is also an endangered listed bird never recorded after 1994-97 survey, however, in 2020, Western Marsh-Harrier, another species of this family was observed.

Anhingidae (Darter, near threatened), Glareolidae (Collared pratincole), Gruidae (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) like reappeared 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 for the time during our survey period only. Some families have been persistently visiting the lake are Anatidae, Ardeidae, Charadriidae, Laridae, Phoenicopteridae, Podicipedidae, Recurvirostridae, and Scolopacidae, however not all the species consistently visited.

To emphasize feeding habits, it is clear that lake has 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 season [60]. The lake receives rainfall of about 500 mm from July to October during monsoon season. During monsoon, the vital abiotic factors regulating its ecosystem like oxygen level is high, whereas salinity, alkalinity, temperature, and brine density are low [61]. Oxygen level starts decreasing and other parameters start increasing towards winter season up to March. These shift 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 colour of the brine appears green to dark green (Figure 8a) due to presence of abundant oligohaline organisms like cyanobacteria, algae, and diatoms [61]. These are prime food for rich insects' diversity of heteroptera. Sometimes it is also suitable for freshwater species on dilution of brine [62].

Subsequently, it changes to orange (Figure 8 b) to dark pink colour (Figure 8 c) by the end of winter season taken over by euryhaline organisms [60]. These oligohaline and euryhaline are also called true aquatic life forms for the lake. These favourable seasons accompanied by suitable abiotic condition at pH level 7 to 10 promote their sporulation, germination and germling developments for phytoplankton [63]. Salinity ranges from 50 mg/l to 120 mg/l and brine density from 1.07 to 1.17 g/cm<sup>3</sup> from monsoon to winter season [64]. The lake supports rich biodiversity of vertebrates, invertebrates, phytoplankton, and prokaryotes when the salinity is below 50 gm/l [62]. These are found towards the shoreline of the lake. During summer season (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 chemo-lithotrophs [62; 61; 37]. 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 [65].

With the further increase in salinity to above 200 gm/l, biodiversity is completely limited to species of *Dunaliella sp.* and Archaea sp. only found in the core region of the lake giving dark red colour to the brine accompanied by dead algal cells [66]. 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 lakhs of migratory birds from different countries [38]. Birds are considered to be the most commonly accepted ecological indicator. Their decreasing trend in this lake indicates the disturbance in the respective organisms of lower trophic levels. Disturbance in the organism configuration is the visible result of changing abiotic factors like pH, salinity, alkalinity, oxygen and carbon dioxide and disturbed landscape variables wetland shape, size, patch, corridors and hydrological connectivity between shoreline and core part of the lake [10]. 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. Already 30% of

the lake has been converted to saline soil and saline soil to barren land. Illegal salt pan encroachment, excessive groundwater extract using electrical pumps are the prime cause 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 [38]. 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 [10]. This will ultimately reflect on the global level ecological disconnectivity led by the migratory birds.

Surprisingly, after 30 years there was sufficient rainfall in the Rajasthan state 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 had welcomed lakhs of migratory birds, indicating a positive sign of revival of lake. Unfortunately, within this period the lake also encountered first ever in its history, a massive avian botulism catastrophic event. Due to this event, all the economic activities were banned till the reason for botulism was identified. This prohibited the illegal activities and helped more water retention for January, February, March 2020 as compared to same period of 2019. Meanwhile, due to worldwide COVID-19 pandemic, there was complete shutdown from March till May 2020. This helped to maintain 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 the economic activities were allowed. From the maps of monsoon period of 2020 continuously till monsoon of 2021, the lake is again desiccating. According to the Sambhar Salt Ltd, 77 km<sup>2</sup> towards the east is allowed for salt extraction and rest of the 113 km<sup>2</sup> 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 after 30 years, short term control over economic activities and COVID-19 lockdown, combinedly helped to revive the water level without any capital investment. These indicate that the lake has high resilience capacity and can be restored with little but a proper conservation and management plan. We suggest a practically implementable restoration plan for this lake. According to The Gazette of India, 26 September 2017, PART II—Section 3—Sub-section (i), in context to Sambhar Lake, 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 civil society and shall meet at least thrice in a year. SDA should list out all the activities allowed, regulated, or prohibited within Sambhar Lake. It should allocate budget and human resources to this authority to ensure smooth functioning and 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, integrating wetlands as nature-based solutions for climate change mitigation and adaptation are likely to be aligned with the “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). With the help of remote sensing experts, hotspots for different migratory birds and unique halophytes and halophiles be identified. Then, their eco-sensitive buffer zones be mapped using remote sensing and GIS technology. Further, their habitat suitability assessment be modelled with respect to different climatic scenarios. These steps coupled with complete check of illegal salt pan encroachment and excess

ground water extraction to maintain complete ecological integrity of the lake. These will automatically support good quality of brine formation for both pan and kyars salt produced in this lake. This will help Govt. of India 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 [67] still they are not considered to be conserved. These conceptions have already led to 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 business has collapsed, lakhs of livelihoods have been lost, in addition to loss of habitats of migratory birds, halo-tolerant vertebrates and invertebrates, recreational and educational sites.

Especially, our findings highlight the causal factors responsible for the desiccation of this Ramsar site that might also be the causes of other lacustrine wetlands. It also provides a novel approach towards regular monitoring of the lakes integrating Google Earth Engine. Taken together, our findings of previous studies point towards the urgent need to conserve the rich biodiversity of inland saline wetlands, playa wetlands, shallow wetlands, sabkhas, salterns, salt pans, athalassohaline lakes and soda lakes of the world. These ecosystems are the blue lifeline for semi-arid to arid regions and 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 the cloud computation which can be accessed in the field itself for real-time monitoring as well. 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).

The only limitation of this study is that we have not gone for the soil and water quality tests. Assessment of physico-chemical and biological parameters during our survey period of 2019-2021 would have given complete picture of trophic status of the lake. However, due to repeated country-wide lock down and shut down for COVID-19 pandemic situation, authors could not achieve this target. However, this might not impact much as the results are combined with the available literature. Future research may extend this work by conducting species distribution modelling 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.

**Figure 8.** Field photographs

## 5. 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 imbalance at each trophic level from primary producer to 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 Google Earth Engine. The comprehensive results showcase the blurred future of this amazing Ramsar site, designated under criteria A due to its unique character. If urgent conservational steps are not taken as discussed, it might be completely lost before its lease period (2059) as a salt industry. This research will help to conserve this ecosystem. Due to COVID-19, food type analysis could not be conducted. However, it did not impact much. Not only this lake but there are also 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.

**Supplementary Materials:** Table S1 is attached below.

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