



# Assessment of Wetland Ecosystem's Health Using Remote Sensing – Case Study: Burullus Wetland – Ramsar Site

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## Abstract

Complex ecosystems as wetlands are very sensitive to changes and disturbances. Human activities causing habitat fragmentation that alter landscapes affect the wetland ecosystems and negatively influence biodiversity. The health of the ecosystem is measured as a homeostasis between the system components and stability or resilience of the system against disturbance; therefore, any anthropogenic disturbances can cause dramatic changes in the balance of wetland ecosystem. Burullus, the second largest of the Egyptian northern coastal wetlands along the Mediterranean coast, has been recognized recently as critically endangered ecosystem according to an assessment using IUCN Red List of ecosystems. The study sought to assess Burullus wetland's health based on multispectral indicators related to the structure, function, and resilience of the ecosystem. Three indices were calculated to quantify the health of the wetland: the structure index, vigor index, and resilience index. The overall status of the wetland indicates a dynamic state and rapid transformation, which occurred over the study period. The outcomes indicated that Burullus's health has progressively deteriorated in the recent investigated years of 2016 and 2019 compared to the reference years of 1984 and 1986. The assessed indicators revealed a trend towards more deterioration of its ecological system due to the LULC transformations, anthropogenic interventions, and overexploitation of its natural resources. In addition, the growth in the impervious surfaces by 9% in the recent years due to expansion in urbanization was detected. All of these factors may affect the ecological balance and the health of the wetland to some extent. The fragility of this wetland and the continuous fragmentation of it occurs due to human activities that threaten its important and unique habitats. The integrated framework for the assessment of Burullus wetland's health based on remotely sensed data and using geospatial techniques can be utilized for the assessment of other similar coastal wetlands at national and regional scales.

**Keywords** Ecological resilience indicator · Landscape deviation degree · Disturbance · Land use change · Impervious surface

## Introduction

Natural ecosystems particularly freshwater ecosystems and wetlands are enduring intensive and widespread disruptions and threats induced by human activities globally (Daryadel and Talaei 2014). Sustainable utilization and maintenance of the wetland's goods and services under the current trends of population growth is very difficult and requires adequate

management. Increasing extent of human exploitation of natural resources and modification of the environment has adversely affected the health of wetlands (Finlayson and Horwitz 2015). In addition to suffering from many anthropogenic disturbances such as land use/land cover changes, pollution, dumping of solid and liquid wastes, introduction of alien invasive species, and unsustainable ecotourism, many wetlands are being affected by the consequences of the global climate change such as sea level rise (Daryadel and Talaei 2014).

Ecosystem's health is a concept that has often been applied to the evaluation of ecosystems status. According to Costanza (1992), an ecosystem is healthy, if it is stable and sustainable, i.e., if the ecosystem is functioning and sustaining its structure and self-sufficiency over time, and is resilient to environmental strains and disturbances. In another way, the

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health of an ecosystem is related to its ability to continue to provide a particular set of ecological services within its surrounding landscape. This considers whether the ecosystem and its external inputs, such as energy or fertilizer, are sustainable on the long term, as well as, whether the ecosystem can withstand or recover from perturbations, and maintain capacity for resistance and resilience, and any similar issues. The capacity to respond to perturbations and the capacity to provide ecological services to a larger whole are common properties related to ecosystem health (Rapport et al. 2001). Mageau et al. (1995) have expanded on the concept and proposed the use of indicators on the vigor, productivity, organization, and resilience of ecosystems as effective measures of ecosystem health.

Approaches for the evaluation of ecological resilience of ecosystems employed assessments methodologies that utilized different sets of data including field observation, socio-economic, and remotely sensed data. For example, Washington-Allen et al. (2008) measured resilience of dryland community using time series of satellite images to assess the changes in the landscape in response to drought disturbance utilizing the transformed normalized difference vegetation index (TNDVI) as indicator. Yan et al. (2014) measured forest ecosystem resilience by formulating a hierarchical indicator system of the weighted sum of all indicators influencing the ecosystem resilience including topographic and edaphic factors. Integrated assessment approaches have been used to evaluate wetlands resilience as an indicator of ecosystem health (e.g., Sun et al. 2016; Chen et al. 2019; Chaparro-Herrera et al. 2021; Das et al. 2022). The indices used for the assessment of wetlands health such as the Wetland Health Index (Chen et al. 2019) and Estuarine Wetland Ecosystem Health (Chi et al. 2018) were mainly developed by weighting different ecological indicators using the Analytical Hierarchy Process (AHP) (e.g., Xiao et al. 2019; Bentley et al. 2022; Imdad et al. 2022). Chen et al. (2019) evaluated 19 wetlands health in China based on WHI that was formulated by weighting indicators of water, soil, landscape, and social variables using AHP approach. The health of urban wetland was evaluated by Chaparro-Herrera et al. (2021) through clustering water quality indices, zooplankton diversity, and plant diversity indicators using agglomerative hierarchical algorithm. The presser-state-response (PSR) model was also applied on set of ecological indicators to assess wetlands' health and identify the major influencing indicators in the evaluation of wetlands health and resilience (e.g., Sun et al. 2016; Das et al. 2022).

However, the approach of assessing ecosystem resilience is still an active area of research and needs more attention for integrating their outcomes in the management of natural resources decision-making process. Assessing the wetland resilience is highly required to ensure the long-term conservation of the wetland, sustaining the provisioning of

the ecological goods and services and sustainability of bio-economy and associated development efforts. Assessment of ecosystem resilience is very important for guidance on rational land management approaches and for informing decision makers.

Remote sensing technology is appropriate for wetland mapping and monitoring, particularly when funds are limited and information on wetland areas, surrounding land uses, and wetland losses are not available (Hossen and Negm 2016). The availability of high spatial resolution remotely sensed data and multirate satellite images facilitates change detection studies. Also, remote sensing can be used as a tool to provide a quantitative assessment of ecosystem resilience (e.g., Yan et al. 2014; White et al. 2020), which help in providing scientific basis for resource management and conservation efforts and therefore is of great significance for the maintenance of critical ecological services. Therefore, the current study aimed at formulating an integrated framework for the assessment of wetland ecosystem health based on remotely sensed data and using geospatial techniques that can be utilized for the assessment of other similar coastal wetlands. More specifically, the main objectives of the study are to (1) conduct an analysis of the role of human intervention through changes in land use/cover and landscape pattern on habitat fragmentation using remote sensing and geospatial techniques; (2) assess measures of ecosystem structure, function and resilience as indicators of ecosystem stability using remotely sensed data; (3) formulate a comprehensive approach based on an integrated set of indicators of the wetland structure, vigor and function for the assessment of the wetland health and resilience using remotely sensed data and landscape metrics; and (4) analyze the impact of LULC changes on the ecosystem health and resilience of Burullus wetland over the last few decades.

Measuring ecological resilience is essential to the study of sustainable development because ecosystem resilience plays a crucial role in maintaining provisioning of ecological services and continuity of bioeconomy (Yan et al. 2014). It can be used as an indicator of system wellbeing and ability to respond to the rehabilitation efforts towards environmental sustainability. The outcomes of the study can provide guidance for ongoing and future management efforts and decision-making process related to the development activities and ecosystem restoration and rehabilitations plans in Burullus wetland.

## Study Area

The wetland subject of the current study is deemed as one of the five main coastal wetlands of Egypt. The wetland region which encompasses Lake Burullus and its surroundings (Fig. 1) has been declared as a protected area in 1998 (Galal et al. 2012;

Ghoraba et al. 2019). It has been recognized in 1988 as one of the internationally important wetlands recognized by the Ramsar Convention (Hossen and Negm 2016). It has been recognized recently as a critically endangered ecosystem based on an assessment using the IUCN Red List of ecosystems (Ghoraba et al. 2019). Burullus wetland contains a variety of habitats, varying from freshwater swamps and reedbeds in the south, to salt marshes and mudflats in the north. Sand dunes dominate the sand bar separating the lake from the Mediterranean Sea (Shaltout et al. 2005).

According to Khalil (2013), the main threats facing the wetland are (1) loss of the most valuable habitats to agriculture and urbanization; (2) the rapid growth in human population, which increases the rate of consumption, puts great pressure on the natural resources and heightens the potential of disturbance incidence; (3) increase pollution and waste disposal from agricultural drainage, municipal wastewater disposal directly onto the lake, and solid waste dumping, which contribute significantly to the eutrophication

and pollution of the lake; (4) excessive and illegal fishing practices and hunting of migratory birds which negatively affect the wildlife and the fish production; and (5) lack of management planning and low awareness of environmental and conservation issues contribute to the irrational natural resources utilization patterns.

## Materials and Methods

### Satellite Imagery Data

The assessment of the ecosystem's health condition required investigating series of satellite images to allow the detection of the changes over the last few decades. Nine Landsat satellite images acquired at different dates were downloaded from the USGS Earth Explorer database (<https://earthexplorer.usgs.gov/>). The images were carefully selected based on the minimum cloud cover percentage and the dates were

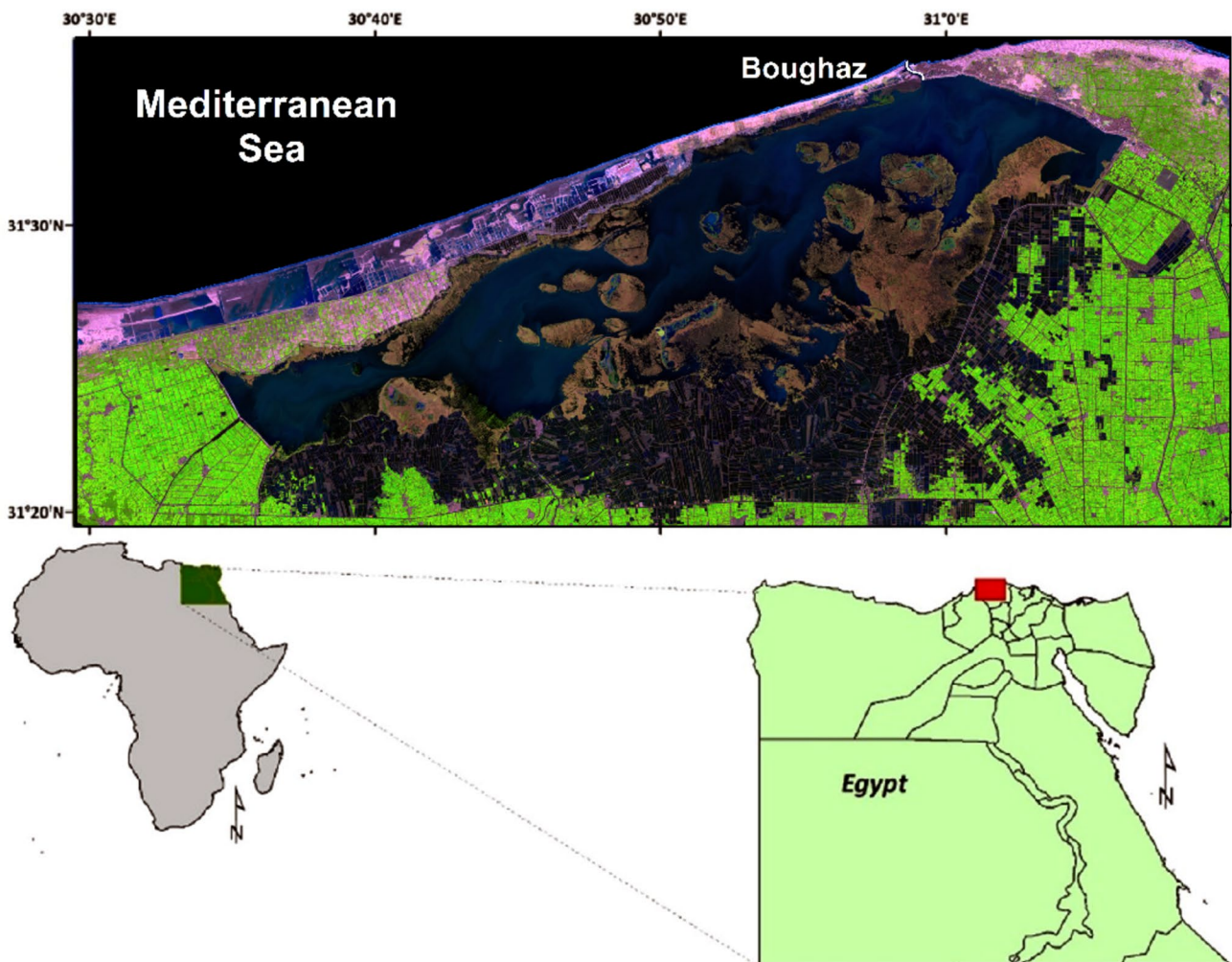


Fig. 1 Location of the Burullus wetland study area in Egypt

carefully selected to represent each season of summer and winter to account for the seasonal changes. Nine images were chosen in the period between 1984 and 2019. The characteristics of the selected satellite images are presented in Table 1 Supplementary Material. The flowchart of the steps used for the satellite images classification is outlined in Fig. 2.

Radiometric correction of the remotely sensed data were conducted in order to compensate for differences in sun illumination, the atmospheric conditions and variations in sensor characteristics (Chen et al. 2005). The images were radiometrically corrected to transform digital number (DN) values into Top-Of-Atmosphere (TOA) reflectance values. The radiometric correction of Landsat 5 images (1984, 1986, 1992, 1995, 2001, 2006, and 2010) was conducted according to Chander et al. (2009). For Landsat 8 satellite images acquired in 2016 and 2019, the correction was achieved according to USGS (2016).

## LULC Classification

Land use/land cover (LULC) classification of the obtained satellite images was conducted to assess the changes in the habitats over the study period. Satellite image classification is the process of assigning pixels to specific thematic classes (Perumal and Bhaskaran 2010). In this current study, supervised classification was applied within the framework of ERDAS Imagine image processing software (ERDAS 2015). Each image was classified into seven LULC classes namely open water, reed vegetation, agriculture, aquaculture, salt marshes, built-up, and sand bar.

## Ecosystem Health Indicators

Healthy ecosystems should have both the capability to maintain the provisioning of ecological services and the capacity to support sustainable development for human beings (Xiao et al.

2019). The ecosystem health assessment framework known as VOR (Vigor/Organization/Resilience) introduced by Yan et al. (2016) was followed to investigate the change in the ecosystem health over the study period. Three indicators related to the ecosystem's organization (structure), vigor (function), and resilience were assessed. All indicators were measured and analyzed using remotely sensed data and geospatial analysis techniques. The approaches pursued by Ekumah et al. (2020) and Costanza and Mageau (1999) were followed. The hierarchy of the process used for the assessment of the wetland health and resilience is presented in Fig. 3. The ecosystem health index (EHI) was estimated according to Xiao et al. (2019) as follows:

$$EHI = \sqrt[3]{(ERI) \times (ESI) \times (ECVI)}$$

where ERI is the ecosystem resilience index, ESI is the ecosystem structure index, and ECVI is the ecosystem vigor and function index.

## Ecosystem Structure

The ecosystem structure implies the biotic and the abiotic composition of the ecosystem, which denotes the physical structure and the biological association and how these components are organized (National Research Council 2005), for example, wetland plant density or configuration, and watershed connectivity (Palmer and Febria 2012). The structural stability of an ecosystem is the function of the spatial heterogeneity, habitat connectivity, and shape. In this study, the assessment of the change in ecosystem structure stability was based on estimation of landscape metrics and fragmentation analysis conducted on the LULC maps produced in the preceding steps.

Ecosystem structure index (ESI) was assessed as an indicator of ecosystem structure stability following the approach of Peng et al. (2017) and Xiao et al. (2019), which is based on assessing landscape metrics indicators of landscape heterogeneity, connectivity and shape as follows:

**Table 1** Percentage of LULC categories, and accuracy assessment measures (the overall accuracy and kappa statistic) for the classified maps of the study area between 1984 and 2019

LULC	Year									
		1984	1986	1992	1995	2001	2006	2010	2016	2019
<b>Open water</b> (%)		21.23	25.95	12.19	16.34	15.65	17.44	16.95	16.90	20.35
<b>Reed vegetation</b>		14.59	24.37	22.02	19.76	18.10	16.70	16.69	15.70	11.47
<b>Sand bar</b>		6.25	10.39	10.49	4.81	5.07	8.11	8.60	5.58	10.33
<b>Salt marsh</b>		28.56	16.04	6.13	16.35	8.91	6.57	3.18	1.01	1.68
<b>Agriculture</b>		22.77	17.92	31.54	31.07	31.25	30.58	30.47	33.97	31.60
<b>Built-up</b>		1.86	1.25	5.65	4.69	5.37	9.02	5.00	9.88	5.83
<b>Aquaculture</b>		4.73	4.07	11.98	6.99	15.65	11.57	19.10	16.97	18.74
<b>Accuracy assessment</b>	<b>Overall accuracy (%)</b>	94.5	96.5	92.0	97.5	95.0	93.5	96.0	94.5	94.0
	<b>Kappa</b>	0.933	0.958	0.904	0.969	0.939	0.922	0.951	0.933	0.926

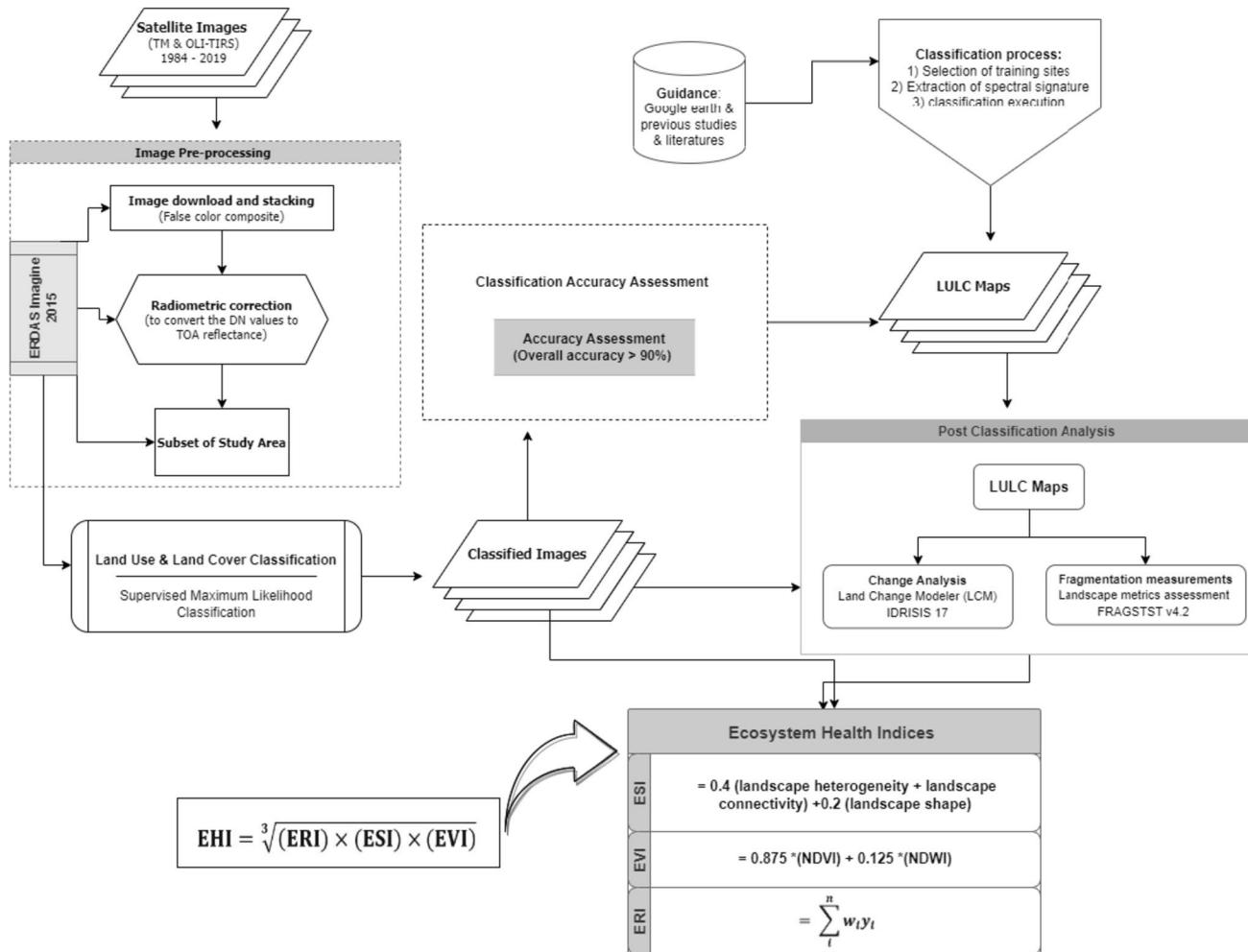


Fig. 2 A framework of the methodology used for the assessment of ecosystem resilience and wetland health

$$ESI = 0.4(\text{landscape heterogeneity} + \text{landscape connectivity}) + 0.2(\text{landscape shape})$$

Indicator of spatial heterogeneity was estimated based on the Shannon diversity index and Shannon evenness index. Indicator of landscape connectivity was estimated based on

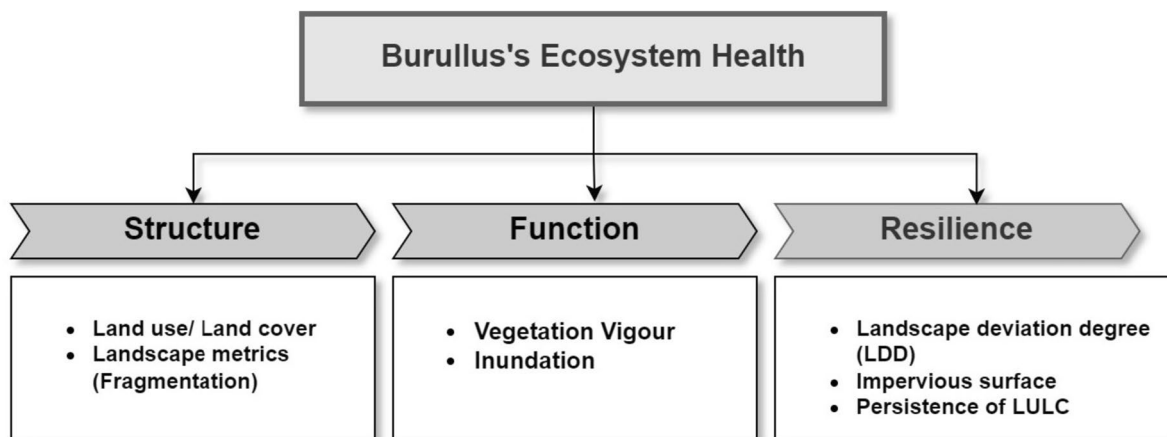


Fig. 3 Hierarchy of the approach used for Burullus wetland ecosystem health assessment

the Interspersion and Juxtaposition Index, the DIVISION index, and the Contagion Index (CONTAG). According to Xiao et al. (2019), landscape heterogeneity and connectivity indicators have equivalent and dominant positions in the analysis of landscape patterns, so were assigned the same weight of 0.4. Indicator of the landscape shape was estimated using the Perimeter-Area Fractal Dimension index and was assigned a relatively lower weight 0.2.

A detailed definition of the indicators used and its calculations are available in FRAGSTAT user guide (McGarigal 2015).

The landscape metrics were assessed using FRAGSTATS v4, a package for spatial pattern analysis program for categorical and continuous maps, developed by McGarigal et al. (2012).

### Ecosystem Function

Ecosystem function is defined as any activity that occurs in an ecosystem as an outcome of the interactions among the species (plants, animals, or other organisms) and the interactions of these species with their surroundings (National Research Council 2005). Examples of ecosystem function are population survival rate, nutrient uptake, and transformation rates, and reproductive or survival rates (Palmer and Febria 2012). Vegetation productivity is one of the main functions of ecosystems; and often used as an indicator on ecosystem vigor (Peng et al. 2017).

The two parameters used in the assessment of ecosystem functions are vegetation vigor and inundation. Vegetation vigor (variability) was estimated by assessing the Normalized Difference Vegetation Index (NDVI) for each Landsat subset in summer and winter. NDVI is used as indicator of the vegetation biomass and vigor, phenology and productivity (Pettorelli et al. 2005). NDVI is calculated as a ratio between the red and near infrared (NIR) bands values using the following equation:

$$NDVI = (NIR - Red)/(NIR + Red)$$

Where NIR is near infrared band spectral reflectance value and red corresponds to the reflectance in the red portion of the electromagnetic radiation spectrum.

On the other hand, inundation was calculated using the Normalized Difference Water Index (NDWI) for evaluating the water body condition. NDWI was proposed by McFeeters (1996) as an indicator that can be applied for the evaluation of water quality based on spectral data. NDWI is calculated as a ratio between the green and near infrared (NIR) bands values using the following equation:

$$NDWI = (Green - NIR)/(Green + NIR)$$

Green corresponds to the spectral reflection in the visible green portion of the electromagnetic radiation and (NIR) in near infrared portion of the EM spectrum.

The ecosystem function and vigor indicator was estimated according to Ekumah et al. (2020) as follows:

$$ECVI = 0.875 * (NDVI) + 0.125 * (NDWI)$$

### Ecological Resilience

Ecological resilience was assessed using three indicators: landscape deviation degree (LDD), impervious surface, and landscape persistence to quantify the extent of all-natural habitats losses in the study area. The landscape deviation degree (LDD) was estimated to measure the degree of extension of human activities which altered the natural landscape, according to Chunxiao et al. (2008) and Ekumah et al. (2020) using the following formula:

$$LDD = \frac{\text{The sum of all artificial surfaces}}{\text{Total area}}$$

Assessing the area of the impervious surface is a valuable indicator on the wetland ecosystems' status as it correlates to the wetlands' health (Guthrie and Deniseger 2001). The impervious surface was measured by summing up all areas changed from the natural habitat to the man-made habitat such as the built-up area, residential areas and roads. Furthermore, the persistence of the wetland was evaluated by subtracting the artificial surfaces areas from the total area of the wetland. The ecological resilience indicator (ERI) was estimated following the approach of Ekumah et al. (2020) based on three indicators as follows:

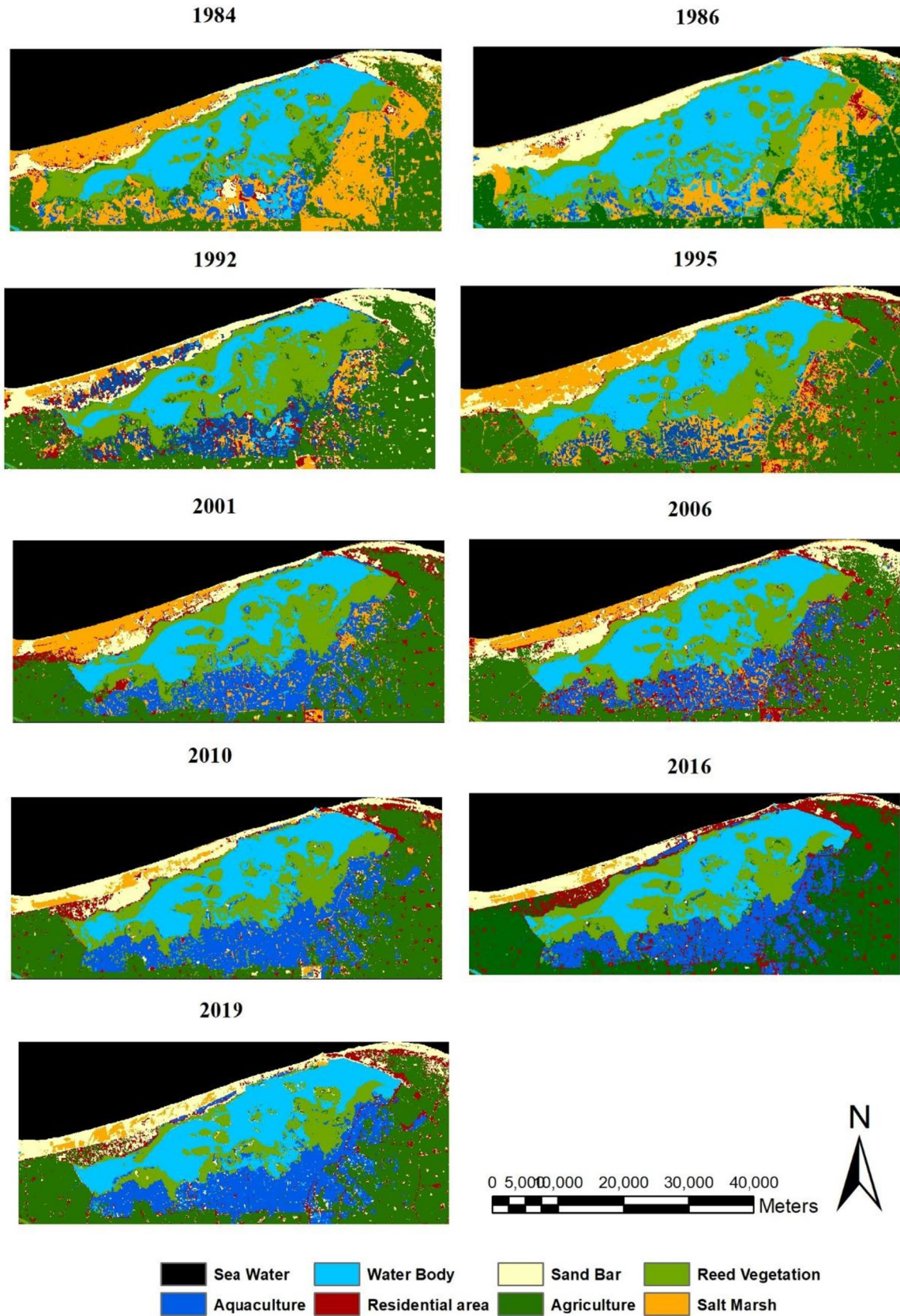
$$ERI = \sum_i^n w_i y_i$$

where  $i_{th}$  assessment indicator  $i$ ,  $w_i$  is the weight of the  $i_{th}$  assessment indicator,  $y_i$  is the value of the  $i_{th}$  assessment indicator, and  $n$  is the number of the indicators.

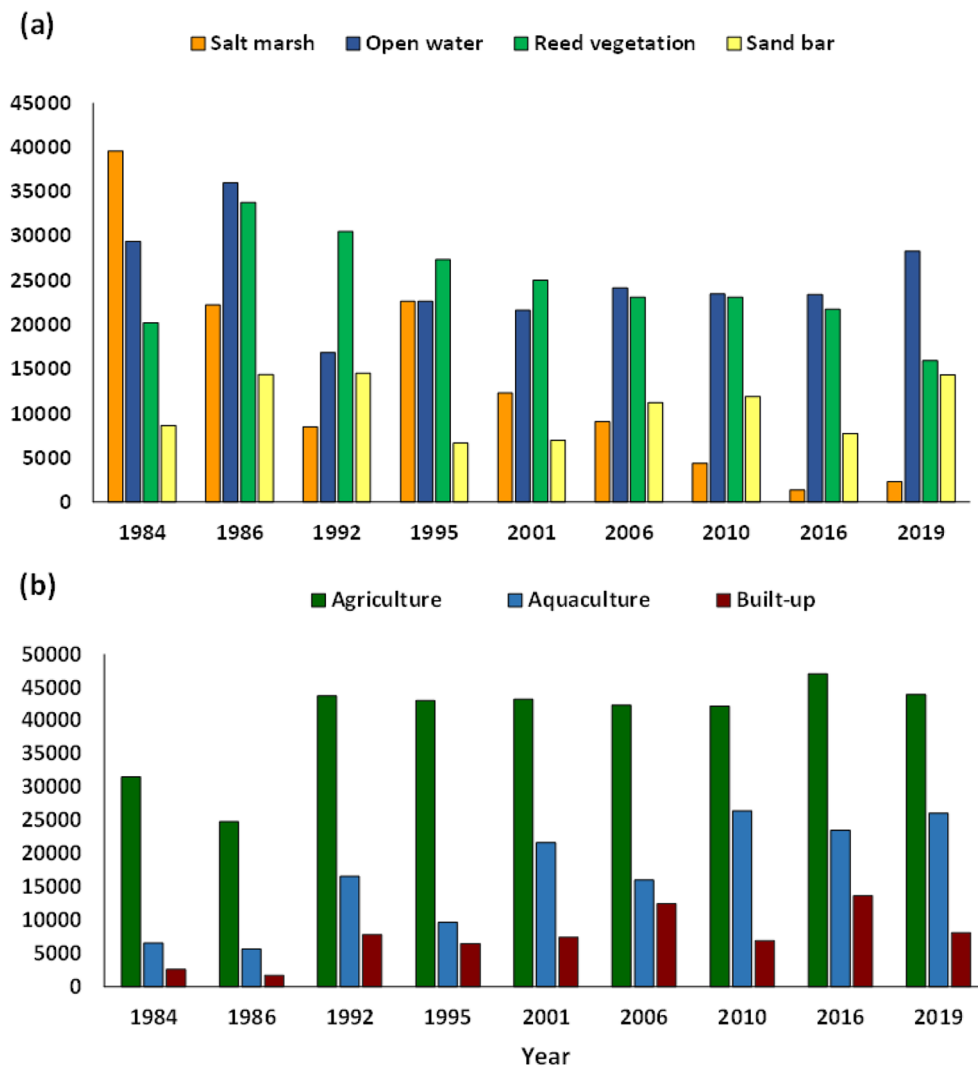
## Results

### LULC Changes

The accuracy assessment of the supervised classification based on the calculations of overall accuracy and kappa statistics revealed a highly accurate classification outcome for the classified LULC maps. The LULC maps attained overall accuracy that exceeded 90% and kappa of more than 0.9 (Table 1), with the 1995 LULC map attaining the highest overall accuracy and kappa statistic (97.5% and 0.969 respectively), while the LULC 1992 map attained the minimum overall accuracy and kappa statistic (92% and 0.904 respectively).



**Fig. 4** LULC distribution in Burullus wetland produced by supervised classification for subsets of Landsat images acquired in the period between 1984 and 2019



**Fig. 5** Area (in hectare) of LULC classes in the study area between 1984 to 2019 **a** land cover and **b** land use types

Analysis of the LULC maps indicated changes in the distribution of the four main natural land cover classes (open water, reed vegetation, salt marshes, and the sand dunes on the northern side of the lake). The change in the natural land cover due to human intervention, which was represented by agriculture, aquaculture, and urban expansion was evident over the last few decades (Fig. 4).

The change analysis revealed that the natural land cover classes were subjected to dynamic changes due to anthropogenic influences and seasonal fluctuations. Most of the classes have fluctuated between loss and gain over the investigated period. The lake water body decreased by 1145.3 ha in 2019 compared to its area in 1984 (Fig. 4). The greatest drop in its area with a loss of 12,527.2 ha (9%) was in 1992. The rate of loss was high, particularly between 1986 and 1995 estimated at nearly 1484 ha/year compared to an average of 208 ha/year over the investigated period.

On the other hand, the reed vegetation decreased over time eventually losing 47% of its area over the investigated period. It occupied 202,163 ha in 1984, which was reduced to 11.47% (15,938.2 ha) in 2019 (Fig. 5 and Table 1). The salt marshes attained an area of 39,571.3 ha in 1984 (28.56%) and it then experienced a trend of reduction with time, where it occupied 2328.84 ha (1.68%) in 2019. Salt

**Table 2** Landscape-level metrics in 1984 and 2019; largest patch index (LPI), total edge (TE), edge density (ED), number of patches (NP), and patch density (PD)

Year	Landscape metrics				
	LPI	TE	ED	NP	PD
1984	23.98	5245710	28.59	7347	4.00
2019	14.36	5049000	27.44	10285	5.59



**Table 3** Class-level metrics for the land cover types in 1984 and 2019; percentage of landscape (PLAND), largest patch index (LPI), edge density (ED), number of patches (NP), patch density (PD), core area % of landscape (CPLAND)

Land cover	Year	Class metrics					
		PLAND	LPI	ED	NP	PD	CPLAND
Open water	1984	16.03	14.14	5.73	528	0.29	13.97
	2019	15.37	14.36	7.58	2070	1.13	13.32
Reed vegetation	1984	11.02	3.15	9.80	2110	1.15	7.99
	2019	8.66	3.42	4.90	426	0.23	6.82
Sand bar	1984	4.72	1.46	3.30	320	0.17	3.45
	2019	7.81	5.84	12.27	3528	1.92	4.50
Salt marsh	1984	21.57	9.27	14.64	1067	0.58	16.24
	2019	1.27	0.38	1.58	233	0.13	0.73

marshes exhibited an increasing trend with a rate of 44.1 ha/year between 1986 and 1995; however, it decreased with the rate of loss of ~604 ha/year, reaching a maximum loss rate (~1231 ha/year) between 1995 and 2016. Meanwhile, the sand bar increased in area from 1984 to 1992 then decreased in 1995, then increased from 2001 to 2019.

On the other hand, the areas dedicated to agriculture, aquaculture, and built-up land uses have increased with time throughout the investigated period. The three land use categories were detected in the LULC map of 1984 with small areas and continued to increase overtime. For example, agriculture occupied 31,546.2 ha in 1984 and slightly increased with time reaching 43,918.5 ha in 2019. Aquaculture increased by 19,490 ha over time, from 6560.28 ha in 1984 to 26,050.6 ha in 2019. Built-up areas experienced some fluctuations over the investigated period, but overall, it increased to 8102.79 ha in 2019 (Table 1).

### Change in Ecosystem Structure: Landscape Metrics/ Fragmentation Analysis

Fragmentation measurements were assessed at both the landscape and class level for each natural land cover category. The analysis of the changes in the landscape pattern over a 35-year period (1984–2019) revealed rapid changes have occurred, with a trend towards more heterogeneity and fragmentation

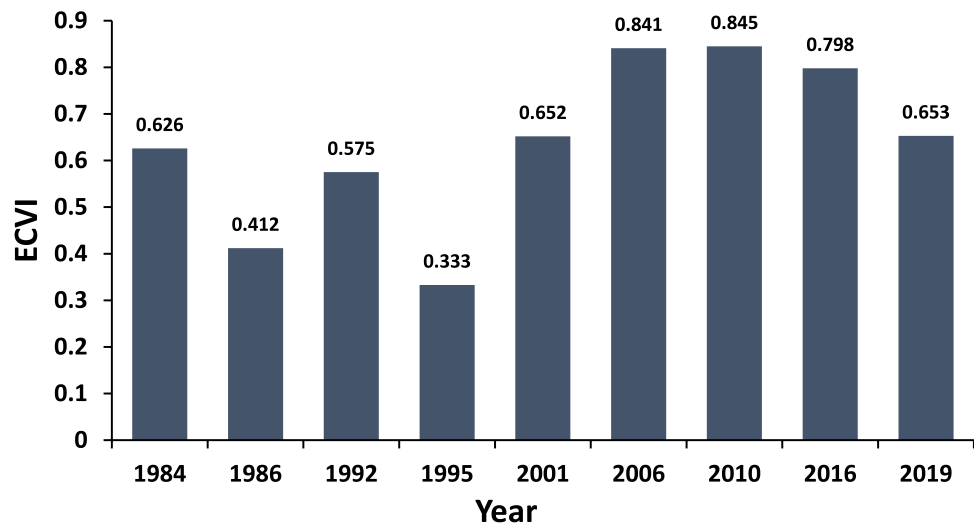
and increase in the overall patch number, total edge, and the reduction in the large patch index (Table 2). The number of patches (NP) and patch density (PD) increased by 2938 and 1.60 respectively. In addition, the largest patch index (LPI) decreased by nearly 40.11% in 2019. The increase in number of patches and the decrease in the largest patch index indicate more fragmentation and breaking up of the landscape into more smaller patches. The pattern of change in the structure of the landscape is probably related to the unique condition of the habitats in the landscape and the different transformations occurred in each one.

The analysis of the change in the pattern of the distribution, shape, and configuration of the natural land cover, which was assessed through at class-level indices revealed a variation in the distribution pattern of the land cover classes (Table 3); and a trend towards fragmentation of the wetland over the study period. While the percentage of the open water in the total landscape slightly changed by 1% between 1984 and 2019, a trend of increase in number of patches from 528 in 1984 to 2070 in 2019 with some fluctuations in between was detected. The edge density increased from 5.73 in 1984 to 7.58 in 2019, indicating fragmentation in the lake proper. On the other hand, the reed vegetation patches decreased in number from 2110 in 1984 to only 426 in 2019, consequently, the edge density decreased by nearly 50% in 2019.

**Table 4** Ecosystem structure index (ESI) assessed for the period between 1984 and 2019

Year	Shape (PAFRAC)	Connectivity			Heterogeneity		ESI
		(CONTAG)	(IJI)	(DIVISION)	(SHDI)	(SHEI)	
1984	1.30	49.45	76.22	0.93	1.70	0.87	1.06
1986	1.29	50.31	70.67	0.90	1.85	0.89	1.08
1992	1.30	47.94	82.08	0.90	1.90	0.91	1.11
1995	1.32	49.24	76.23	0.89	1.88	0.90	1.10
2001	1.30	48.87	78.65	0.89	1.90	0.91	1.10
2006	1.32	47.50	80.60	0.90	1.93	0.93	1.12
2010	1.28	49.87	81.32	0.88	1.88	0.90	1.10
2016	1.30	51.05	66.35	0.89	1.84	0.88	1.07
2019	1.31	50.17	79.24	0.88	1.86	0.89	1.09

**Fig. 6** Ecosystem vigor index (ECVI) assessed for the period between 1984 and 2019



### Ecosystem Structure Index

The ecosystem structure index, the indicator of the ecosystem structure stability (Table 4) was slightly changing throughout the investigated period -ESI value of 1.05 in 1984 and 1.09 in 2019 — despite the changes occurring in the study area. However, an increase by 0.1 in 1992, 2001, and 2006 compared to the 1984 reference year, which indicates more changes in the distribution of the LULCs in these years that exerted changes in the structure of the ecosystem.

### Ecosystem Vigor Index (ECVI)

The analysis of the change in the ecosystem function and vigor was assessed in terms of the fluctuation in the vegetation vigor and inundation of the habitats over the summer and winter, to account for the seasonal variations in the vegetation and water level. The ECVI showed an overall variation throughout the investigated period, fluctuating between 0.3 and 0.9, with the minimum (0.33) attained in 1995, and the maximum (0.84) in 2006 and 2010 (Fig. 6). The variation in the ECVI indicates dynamic changes in the ecosystem vigor over time.

### Ecosystem Resilience Indicators

Ecosystem resilience indicators were calculated for four LULC maps (1984, 1995, 2006, 2019) to represent the status over the last four decades (Table 5). The results revealed that the landscape deviation degree (LDD) greatly increased over time from 30% in 1984 to 56% in 2019 with an increase of 26%. The increase in LDD represents a deviation towards decrease in the natural land cover in the wetland and increase in the impervious surfaces, man-made structures (built-up and residential areas, aquaculture, and agriculture), and other land uses.

This can be attributed to the population growth and the urban encroachment on the natural lands. On the other hand, the persistence in the natural land cover decreased by 27% from 1984 to 2019, due to the continuous changes occurring in the study area. The impervious surface experienced many changes as it exhibited an increase from 1984 to 2006 then experienced a drop in 2019 indicating the dynamic transformations occurring within the wetland ecosystem.

The ecological resilience index (ERI) fluctuated between 0.3 and 0.6, with the maximum (0.63) attained in 1986. The ERI value decreased greatly in recent years as it reached 0.38 in 2016 then slightly increased to 0.41 in 2019, which indicates the capability of the wetland to overcome the disturbance (Fig. 7).

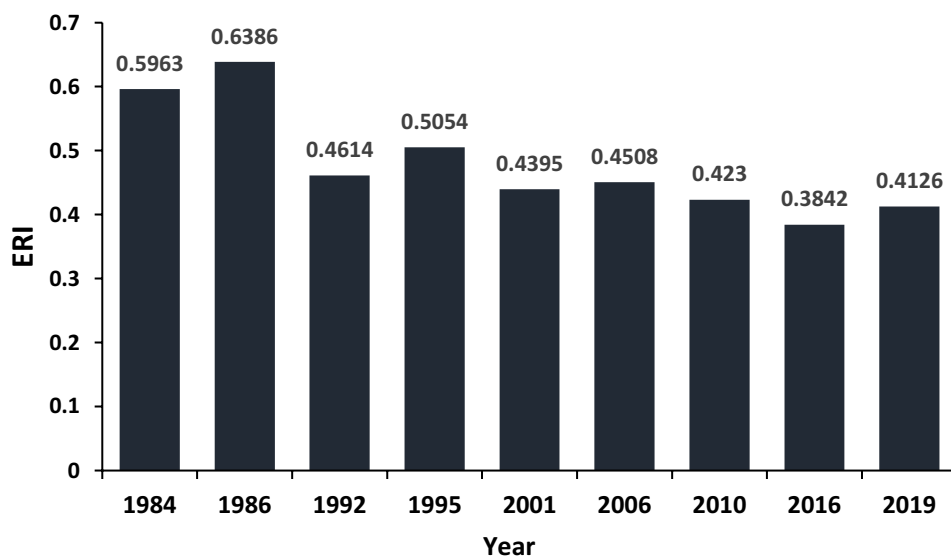
### Ecosystem Health Index (EHI)

The EHI showed variation over the investigated period reaching 0.73 in 1984, decreased in 1995 then increased again in 2001 and 2006 to reach 0.68 and 0.75 respectively. From 2006 to 2019, the index decreased again to reach 0.66 in 2019. Comparing the initial year of 1984 and the recent years and 2019 EHI decreased by 0.07 revealing a trend of slight decline in the ecosystem health (Fig. 8).

**Table 5** Ecosystem resilience indicators values (%) between 1984 and 2019

Indices	1984	1995	2006	2019
<b>Landscape deviation degree (LDD)</b>	29.37	42.75	51.18	56.18
<b>Impervious surface</b>	1.86	4.69	9.02	5.83
<b>Persistence</b>	70.63	57.25	48.82	43.82

**Fig. 7** Ecological resilience index (ERI) assessed for the period between 1984 and 2019

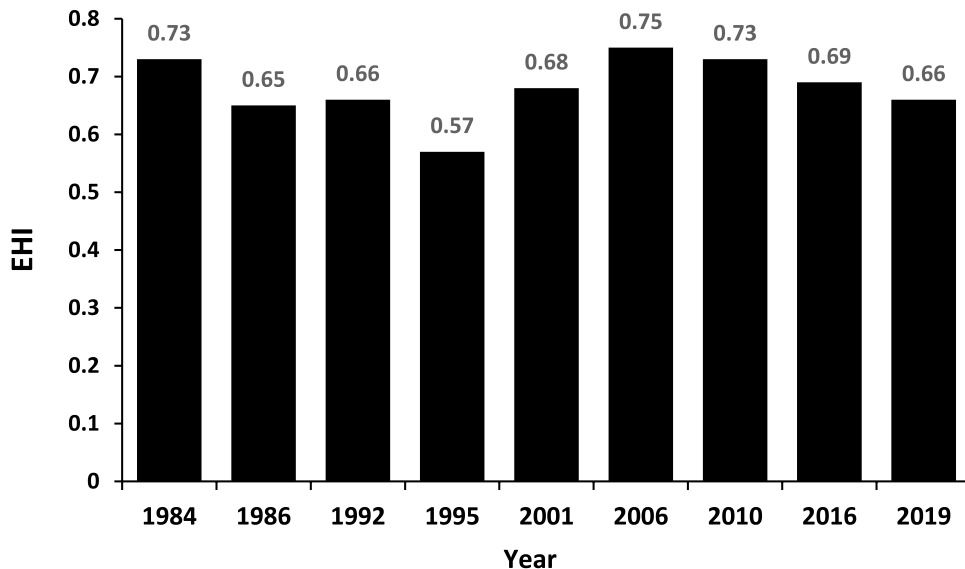


### Discussion

The study highlights a hierarchical approach based on multiple indicators, derived from commonly available remotely sensed-data, to represent key wetland processes and functions for cost-effective monitoring of the changes in wetland ecosystems health at different spatial and temporal scales. Using the hierarchical approach that accounts for the ecosystem structure, function, and resilience the current study attempted to evaluate the state of the ecosystem’s health in one of the most important wetlands in Egypt, Burullus wetland.

The importance Burullus wetland is multifaceted as it includes the second largest coastal lake in Egypt, considered as an internationally important wetland listed as a Ramsar site. It is recognized as an internationally important bird area (IBA) for its significance as a resting area for migratory birds and important nesting area for resident bird species. Additionally, it has been listed recently as a critically endangered ecosystem according to an assessment based on IUCN Red List of ecosystems (Ghoraba et al. 2019). The wetland’s continuous change and fragmentation due to human activities may threaten its important and unique habitat.

**Fig. 8** Ecosystem health index (EHI) assessed for the period between 1984 and 2019



## LULC Changes

The net change in the open water indicates the relationship between the change in the water body and the dynamics changes in the other land cover types of the wetland. The open water is largely affected by the establishment of aquaculture in and around the lake. More than 35% of the losses of the lake body can be attributed to the expansion in aquaculture activities as well as drying of the southern and south-western parts of the lake for reclamation activities as revealed by the study outcomes and was recorded by other studies (e.g., Hossen and Negm 2016; Eid et al. 2020). Expansion in aquaculture increased over time for its higher economic return and the decrease in the quantity and quality of fish catch from the lake (Zingstra 2013).

The uncontrolled urbanization and the fast growth of reed vegetation are the second main causes for the reduction in the open water. The area of reed beds was higher than that of the open water in 1992, 1995, and 2001. Discharge of agriculture and municipal wastes without adequate treatment enhances the growth of the emergent grasses and reed plants leading to increases in the reed vegetation area (Negm and Hossen 2017). The role of anthropogenic activities in increasing the cover of emergent grasses on the expenses of open water area was recognized in other wetlands (e.g., Ramsar wetland Deepor Beel, India (Mozumder et al. 2014); Nal Sarovar, semi-arid part west of India (Singh et al. 2022)). Moreover, discharging wastewater is thought to contribute to the increase in the number and area of islands within the lake, in addition to enhancing the growth of the emergent aquatic plants (Mohsen et al. 2018). The wastewater drained in the lake results in increased clay siltation particularly at the mouth of the drains which leads to drying of silted parts of lake and the increase in the number and area of islands inside the lake. The increase in the shallowness of the lakebed promotes the growth of emergent and floating aquatic plants. This leads to fragmentation and dis-connectivity in the water body. However, the increase in lake proper in 2019 can be attributed to number of factors including the increase in the number of the drains discharging water into the lake; digging up and cleaning out of the clogged drains; and dredging of the lake's inlets, which enhanced the water flow into the lake (Eid et al. 2020; Hany et al. 2021).

## Landscape Fragmentation

The landscape pattern in Burullus wetland tends to be more fragmented where urbanization and human activities are more concentrated. The fragmentation of habitats negatively affects biodiversity, the provisioning of ecological services and the key functions of any ecosystem (Ekumah

et al. 2020). The outcomes revealed that the fragmentation varied with habitat type. Each land cover experienced dynamics changes that differed spatially and temporally. The changes in the number of patches and other landscape metrics revealed a trend towards more fragmentation in both sand bar and salt marsh.

The salt marsh lost more than 90% of its core areas. The core area is deemed as a valuable indicator for the existence and richness of area-sensitive species (Austen et al. 2001; Kupfer 2012). Fragmentation of salt marshes may pose risk to the two important endemic birds' species; the Lesser Short-Toed Lark (*Calandrella rufescens nicolli*), and Egyptian wagtail (*Motacilla flava pygmaea*) for which Burullus salt marshes are the key habitat (Ghoraba et al. 2021).

The sand bar habitat was greatly affected as well. The number of patches increased by 90% and therefore it experienced an increase in the total edge. The fragmentation in the coastal sand dunes and the sand bar can mainly be attributed to the development projects including construction of the international coastal highway and the electric power plant. Moreover, grazing activities, land reclamation projects, and establishment of fish farms have also contributed more disturbance to these habitats (El-Asmar and Al-Olayan 2013; Ghoraba et al. 2021). Agriculture is one of the main factors of wetlands fragmentation and degradation especially if accompanied by other anthropogenic activities such as urban construction, and waste disposal (e.g., Mozumder et al. 2014; Singh and Sinha 2021).

## Ecosystem Resilience

Indicators of ecological resilience were based on assessment of landscape deviation degree, proportion of built-up areas, impervious surfaces, and persistence areas (areas that did not experience any changes over the study period). Dynamic changes in the built-up and settlements areas were revealed in the very vibrant rural landscape. The rural landscape surrounding the main habitats of the wetland has changed throughout the study period due to the agricultural practices (Embabi 2020). The impervious surface, defined as the area of land that hinders the in-filtration of water from the surface into the underlying soil layers (Chithra et al. 2015), is used as a measure of the state of the residential areas. It is associated with human growth and expansion that transform natural land cover into built-up structures such as residential and institutional structures, as well as paved areas like roads and parking lots, which compact the soil and impede its ability to absorb water (Guthrie and Deniseger 2001). The impervious surface soared from 1% in 1984 to ~9% in 2006 and then to ~6% in 2019. Many studies indicated that stream quality starts to degrade when a watershed area is more than 10% impervious (Brabec et al. 2002; Rose et al. 2017); therefore, any increase in the built-up areas will alter

the wetland impervious/pervious surface balance and would eventually lead to more deterioration in the habitat quality and the ecosystem health.

## Ecosystem Health

According to Costanza and Mageau (1999), the healthy ecosystem can maintain its structure (organization) and function (vigor) over time when facing any external stressors. The framework applied in the current study measured indicators related to the main aspects of wetland's health. The ecosystem health index was 0.73 in 1984, the value close to 1 indicates a healthy ecosystem with a good structure and functioning (Xiao et al. 2019). The value fluctuated up and down to 2010, then it started a decreasing trend that reflected a degradation tendency.

The ecosystem resilience index (ERI) values revealed the high dynamic and fast changes undergoing in the wetland. The ERI of the wetland declined from ~0.6 in 1984 to 0.4 in 2019. This can be attributed to the relatively high external pressure and increased human disturbance represented by the continuous development in the area. However, the changes in ESI did not reflect significant changes in the ecosystem structure stability. Hence, we can conclude that the study area is relatively stable in its structure despite all the intensive interventions. The ECVI fluctuated as well greatly over the investigated period, the changes in index value may be attributed to the seasonal changes.

The outcomes indicated that the wetland ecosystem health has progressively deteriorated in the recent investigated years of 2016 and 2019 compared to the reference years of 1984 and 1986, which can be attributed to the accelerated human interventions by converting the natural land cover to man-made habitat and overexploitation of the natural resources. Many development projects affected the sand bar, including the removal of the sand dunes for the construction of summer resorts along the coast, and the construction of the international coastal highway along the northern causing disturbance to the avifauna (Ghoraba et al. 2019). Construction of El-Burullus New Power Station in 2015, and the Black Sand Separation Plant, which is still under construction, may also contribute to the disturbance. In the case of the black sand separation plant, the removal of the sand plains to be used in mineral extraction might cause great disturbance to the dunes dwelling plant and animal species.

The conversion of the natural land cover would lead to more fragmentation in the landscape, which will reduce the ESI value. Also, it would increase the landscape deviation degree, the proportion of built-up areas, and the impervious surfaces, while reducing the persistence areas of the natural habitat, which in turn will be reflected as a low ERI value. The reduction in the natural vegetation cover would lead to lower ECVI. Thus, the overall reduction in the natural habitat will be reflected as a reduction in three indicators used in the evaluation of the wetland health expressed as a reduction in the EHI value.

A low EHI indicates a deterioration in the status of the wetland and consequently, the overall capacity of the wetland to recover from disturbance events may be affected.

It is worth mentioning that there is an initiative from the Egyptian Government to improve the status of all the wetlands in Egypt. Regarding Lake Burullus, a rehabilitation project was initiated in 2018, which has contributed to the improvement in the lake water quality (Hany et al. 2021). The desire for development and fulfillment of human needs can lead to overexploitation and irrational use of natural resources. Therefore, management plans are always needed to achieve the balance between the sustainable natural resources' utilization and the rational development activities in wetlands.

The adoption of a multi-metric approach based on vegetation and hydrogeomorphic condition-based indicators derived from remotely sensed data for assessing ecosystem health and monitoring changes in wetlands, as used in the current study and other studies (e.g., Moore et al. 2014; Mozumder et al. 2014; Taddeo and Dronova 2018; Singh and Sinha 2021; Singh et al. 2022), can reduce costs associated with large-scale monitoring of wetlands and provide speedy health assessment and monitoring of many wetlands at national and regional scale. However, there are some challenges that accompany the use of the indices derived from the multispectral remotely sensed data or those based on classified cover types of wetlands. These challenges might be due to the limitations of the spatial, spectral, and radiometric sensitivities of the sensors that acquired the remotely sensed data (Dronova et al. 2015); or due to the complexity of the wetlands ecosystems with dynamic cover types, rapid phenological changes and regular inundation leading to quick surface variations that need more specific techniques for their detection on the long-term (Taddeo and Dronova 2018; Singh and Sinha 2021; Singh et al. 2022). The use of time series remotely sensed data can help in accounting for the seasonal and short-term surfaces changes, and improve the uncertainty in detecting the long-term changes in wetlands. The overlap in spectral signature between different cover types and the "intra-mixing of cover types" leading to mixing soils and shallow turbid waters, inseparability of reed vegetation and terrestrial vegetation (Mozumder et al. 2014) can increase the uncertainty in detecting changes in wetlands' cover types (Dronova et al. 2015; Singh et al. 2022). This might be circumvented by using higher spatial and spectral resolution remotely sensed data integrated with field observation to allow inclusion of more details that can help refine identification of wetland cover types and water quality parameters (Moore et al. 2014; Mozumder et al. 2014; Singh et al. 2022).

Further study and assessments for the investigated Ramsar site that integrate other drivers including hydrogeomorphological parameters, topographic, socioeconomic drivers, and supporting field data are required for more accurate evaluation of the changes in the wetland health.

## Conclusion

The integrated framework for the assessment of wetlands ecosystem health based on remotely sensed data and using geospatial techniques presented in the current study can be utilized for assessment of other similar coastal wetlands. Overall, the status of the wetland based on the assessed indicators revealed a trend towards more deterioration of its ecological system due to the LULC transformations, anthropogenic interventions, and over-exploitation of its natural resources. The wetland landscape pattern is changing towards gradual fragmentation and degradation. The main anthropogenic disturbances include the conversion of the natural land cover to land uses of aquaculture and agriculture which are considered the main causes of land transformation, in addition to some large development projects that have taken place in the last decade, besides those projects that are still under construction. Anthropogenic disturbances can cause structural changes that can irreversibly affect the flora and fauna within any coastal wetlands system. Given the current trend of urbanization, the impervious surfaces are expected to grow in the future with the population growth, which will affect the previous/impervious surface balance and would eventually lead to more deterioration in the habitat quality and the overall ecosystem health.

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**Data Availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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## References

- Austen, M.J., C.M. Francis, D.M. Burke, and M.S. Bradstreet. 2001. Landscape context and fragmentation effects on forest birds in southern Ontario. *The Condor* 103 (4): 701–714.
- Bentley, S.B., S.A. Tomscha, and J.R. Deslippe. 2022. Indicators of wetland health improve following small-scale ecological restoration on private land. *Science of the Total Environment* 837: 155760. <https://doi.org/10.1016/j.scitotenv.2022.155760>.
- Brabec, E., S. Schulte, and P.L. Richards. 2002. Impervious surfaces and water quality: A review of current literature and its implications for watershed planning. *Journal of Planning Literature* 16 (4): 499–514. <https://doi.org/10.1177/088541202400903563>.
- Chander, G., B.L. Markham, and D.L. Helder. 2009. Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sensing of Environment* 113 (5): 893–903. <https://doi.org/10.1016/j.rse.2009.01.007>.
- Chaparro-Herrera, D., R. Fuentes-Garcia, M. Hernandez-Quiroz, E. Valiente-Riveros, E. Hjort-Colunga, and C. Ponce de Leon-Hill. 2021. Comprehensive health evaluation of an urban wetland using quality indices and decision trees. *Environmental Monitoring and Assessment* 193 (4): 183. <https://doi.org/10.1007/s10661-021-08939-w>.
- Chen, X., L. Vierling, and D. Deering. 2005. A simple and effective radiometric correction method to improve landscape change detection across sensors and across time. *Remote Sensing of Environment* 98 (1): 63–79. <https://doi.org/10.1016/j.rse.2005.05.021>.
- Chen, W., C. Cao, D. Liu, R. Tian, C. Wu, Y. Wang, and D. Bao. 2019. An evaluating system for wetland ecological health: case study on nineteen major wetlands in Beijing-Tianjin-Hebei region, China. *Science of the Total Environment* 666: 1080–1088. <https://doi.org/10.1016/j.scitotenv.2019.02.325>.
- Chi, Y., W. Zheng, H. Shi, J. Sun, and Z. Fu. 2018. Spatial heterogeneity of estuarine wetland ecosystem health influenced by complex natural and anthropogenic factors. *Science of the Total Environment* 634: 1445–1462. <https://doi.org/10.1016/j.scitotenv.2018.04.085>.
- Chithra, S., M.H. Nair, A. Amarnath, and N. Anjana. 2015. Impacts of impervious surfaces on the environment. *International Journal of Engineering Science Invention* 4 (5): 27–31.
- Chunxiao, Z., L. Zhiming, and Z. Nan. 2008. Using remote sensing and GIS to investigate land use dynamic change in western plain of Jilin province. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science* 37: 1685–1690.
- Costanza, R. 1992. Toward an operational definition of ecosystem health. *Ecosystem Health: New Goals for Environmental Management* 239: 269.
- Costanza, R., and M. Mageau. 1999. What is a healthy ecosystem? *Aquatic Ecology* 33 (1): 105–115. <https://doi.org/10.1023/A:1009930313242>.
- Daryadel, E., F. Talaei. 2014. Analytical study on threats to wetland ecosystems and their solutions in the Framework of the Ramsar Convention. *World Academy of Science and Engineering Technology* 2091–2101.
- Das, S., G.S. Bhunia, B. Bera, and P.K. Shit. 2022. Evaluation of wetland ecosystem health using geospatial technology: Evidence from the lower Gangetic flood plain in India. *Environmental Science and Pollution Research International* 29 (2): 1858–1874. <https://doi.org/10.1007/s11356-021-15674-9>.
- Dronova, I., P. Gong, L. Wang, and L. Zhong. 2015. Mapping dynamic cover types in a large seasonally flooded wetland using extended principal component analysis and object-based classification. *Remote Sensing of Environment* 158: 193–206.
- Eid, A.N.M., C.O. Olatubara, T.A. Ewemoje, H. Farouk, and M.T. El-Hennawy. 2020. Coastal wetland vegetation features and digital Change Detection Mapping based on remotely sensed imagery: El-Burullus Lake. *Egypt. International Soil and Water Conservation Research* 8 (1): 66–79. <https://doi.org/10.1016/j.iswcr.2020.01.004>.
- Ekumah, B., F.A. Armah, E.K.A. Afrifa, D.W. Aheto, J.O. Odoi, and A.-R. Afitiri. 2020. Geospatial assessment of ecosystem health of coastal urban wetlands in Ghana. *Ocean & Coastal Management* 193: 105226. <https://doi.org/10.1016/j.ocecoaman.2020.105226>.
- El-Asmar, H.M., and H.A. Al-Olayan. 2013. Environmental impact assessment and change detection of the coastal desert along the central Nile Delta coast. *Egypt. International Journal of Remote Sensing Applications* 3: 1–12.
- Embabi, N.S. 2020. Landscapes of Egypt. In *Environmental Remote Sensing in Egypt*, ed. S.F. Elbeih, A.M. Negm, and A. Kostianoy, 501–532. Cham: Springer International Publishing.
- ERDAS. 2015. ERDAS Imagine (Version 2015): Hexagon Geospatial, Peachtree Corners, Circle Norcross.

- Finlayson, C.M., and P. Horwitz. 2015. Wetlands as settings for human health—the benefits and the paradox. In *Wetlands and Human Health*, ed. C.M. Finlayson, P. Horwitz, and P. Weinstein, 1–13. Dordrecht: Springer, Netherlands.
- Galal, T., K. Shaltout, L. Hassan. 2012. The Egyptian northern lakes: habitat diversity, vegetation and economic importance: LAP LAMBERT Academic Publishing.
- Ghoraba, S.M.M., M.W.A. Halmy, B.B. Salem, N.B.E. Badr. 2021. Application of IUCN Red List of Ecosystems to assess the ecological status of marine bar ecosystems of Burullus wetland: a Ramsar site. *Regional Studies in Marine Science* 45(101844). <https://doi.org/10.1016/j.rsma.2021.101844>.
- Ghoraba, S.M.M. 2019. Assessment of burullus wetland according to iucn red list of ecosystems. (PhD), Alexandria University, Alexandria, Egypt.
- Guthrie, R., J. Deniseger. 2001. Impervious surfaces in French Creek. *BC Ministry of Water, Land and Air Protection, Victoria*. Retrieved from <https://www.env.gov.bc.ca/van-island/es/pdf/Impervious%20Surfaces%20technical%20document.pdf>.
- Hany, A., F. Akl, M. Hagra, A. Balah. 2021. Assessment of recent rehabilitation projects' impact on water quality improvement in Lake Burullus, Egypt. *Ain Shams Engineering Journal*.
- Hossen, H., and A. Negm. 2016. Change detection in the water bodies of Burullus Lake, Northern Nile Delta, Egypt, using RS/GIS. *Procedia Engineering* 154: 951–958. <https://doi.org/10.1016/j.proeng.2016.07.529>.
- Imdad, K., M. Rihan, M. Sahana, S. Parween, R. Ahmed, R. Costache, R. Tripathi. 2022. Wetland health, water quality, and resident perceptions of declining ecosystem services: a case study of Mount Abu, Rajasthan, India. *Environmental Science and Pollution Research International*. <https://doi.org/10.1007/s11356-022-21902-7>.
- Khalil, M. 2013. Environmental management of Burullus Protectorate (Egypt), with special reference to fisheries. *International Journal of Environmental Science and Technology* 4: 93–104.
- Kupfer, J.A. 2012. Landscape ecology and biogeography: Rethinking landscape metrics in a post-FRAGSTATS landscape. *Progress in Physical Geography: Earth and Environment* 36 (3): 400–420. <https://doi.org/10.1177/0309133312439594>.
- Mageau, M.T., R. Costanza, and R.E. Ulanowicz. 1995. The development and initial testing of a quantitative assessment of ecosystem health. *Ecosystem Health* 1: 201–213.
- McFeeters, S.K. 1996. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing* 17 (7): 1425–1432. <https://doi.org/10.1080/01431169608948714>.
- McGarigal, K., SA Cushman, E Ene. 2012. FRAGSTATS v4: spatial pattern analysis program for categorical and continuous maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. Available at the following web site: <http://www.umass.edu/landeco/research/fragstats/fragstats.html>.
- McGarigal, K. 2015. FRAGSTATS User Guide.
- Mohsen, A., M. Elshemy, and B.A. Zeidan. 2018. Change detection for Lake Burullus, Egypt using remote sensing and GIS approaches. *Environmental Science and Pollution Research* 25 (31): 30763–30771.
- Moore, T.S., M.D. Dowell, S. Bradt, and A.R. Verdu. 2014. An optical water type framework for selecting and blending retrievals from bio-optical algorithms in lakes and coastal waters. *Remote Sensing of Environment* 143: 97–111.
- Mozumder, C., N. Tripathi, and T. Tipdecho. 2014. Ecosystem evaluation (1989–2012) of Ramsar wetland Deepor Beel using satellite-derived indices. *Environmental Monitoring and Assessment* 186 (11): 7909–7927.
- National Research Council. 2005. *Valuing ecosystem services: toward better environmental decision-making*: National Academies Press.
- Negm, A.M., and H. Hossen. 2017. Sustainability of water bodies of Northern Egyptian Lakes: Case studies, Burullus and Manzalla Lakes. In *The Nile Delta*, ed. A.M. Negm, 455–467. Cham: Springer International Publishing.
- Palmer, M.A., and C.M. Febria. 2012. The heartbeat of ecosystems. *Science* 336 (6087): 1393. <https://doi.org/10.1126/science.1223250>.
- Peng, J., Y. Liu, T. Li, and J. Wu. 2017. Regional ecosystem health response to rural land use change: A case study in Lijiang City, China. *Ecological Indicators* 72: 399–410.
- Perumal, K., R. Bhaskaran. 2010. Supervised classification performance of multispectral images. *Journal of Computing* 2(2). Retrieved from <https://sites.google.com/site/journalofcomputing/>.
- Pettorelli, N., J.O. Vik, A. Mysterud, J.-M. Gaillard, C.J. Tucker, and N.C. Stenseth. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution* 20 (9): 503–510. <https://doi.org/10.1016/j.tree.2005.05.011>.
- Rapport, D., G. Böhm, D. Buckingham, J.J. Cairns, R. Costanza, J. Karr, et al. 2001. Ecosystem health: The concept, the ISEH, and the important tasks ahead. *Ecosystem Health* 5: 82–90. <https://doi.org/10.1046/j.1526-0992.1999.09913.x>.
- Rose, A., J.E. Wilson, and L.M. Lavkulich. 2017. Analysis of impervious surface area, and the impacts on soil-based agriculture and the hydrologic cycle: A case study in the agricultural land reserve in Metro Vancouver, British Columbia. *Canada. Agricultural Sciences* 8 (08): 837. <https://doi.org/10.4236/as.2017.88062>.
- Shaltout, K.H., M.T. Khalil, Y.M. Al-Sodany. 2005. Lake Burullus: burullus protected area (Vol. 13): Publication of national biodiversity unit. *Egyptian Environmental Affairs Agency*.
- Singh, M., and R. Sinha. 2021. Hydrogeomorphic indicators of wetland health inferred from multi-temporal remote sensing data for a new Ramsar site (Kaabar Tal). *India. Ecological Indicators* 127: 107739.
- Singh, M., S. Allaka, P.K. Gupta, J.G. Patel, and R. Sinha. 2022. Deriving wetland-cover types (WCTs) from integration of multi-spectral indices based on Earth observation data. *Environmental Monitoring and Assessment* 194 (12): 878.
- Sun, T., W. Lin, G. Chen, P. Guo, and Y. Zeng. 2016. Wetland ecosystem health assessment through integrating remote sensing and inventory data with an assessment model for the Hangzhou Bay, China. *Science of the Total Environment* 566–567: 627–640. <https://doi.org/10.1016/j.scitotenv.2016.05.028>.
- Taddeo, S., and I. Dronova. 2018. Indicators of vegetation development in restored wetlands. *Ecological Indicators* 94: 454–467.
- USGS. 2016. *LANDSAT 8 (L8) DATA USERS HANDBOOK* (Vol. Version 2.0): Department of the Interior, US Geological Survey.
- Washington-Allen, R.A., R.D. Ramsey, N.E. West, B.E. Norton. 2008. Quantification of the ecological resilience of drylands using digital remote sensing. *Ecology and Society* 13(1): 33. [online] URL: <http://www.ecologyandsociety.org/vol13/iss1/art33/>.
- White, H.J., W. Gaul, D. Sadykova, L. León-Sánchez, P. Caplat, M.C. Emmerson, and J.M. Yearsley. 2020. Quantifying large-scale ecosystem stability with remote sensing data. *Remote Sensing in Ecology and Conservation* 6 (3): 354–365.
- Xiao, R., Y. Liu, X. Fei, W. Yu, Z. Zhang, and Q. Meng. 2019. Ecosystem health assessment: A comprehensive and detailed analysis of the case study in coastal metropolitan region, eastern China. *Ecological Indicators* 98: 363–376.
- Yan, Y., C. Zhao, C. Wang, P. Shan, Y. Zhang, and G. Wu. 2016. Ecosystem health assessment of the Liao River Basin upstream region based on ecosystem services. *Acta Ecologica Sinica* 36 (4): 294–300.
- Yan, H., J. Zhan, B. Liu, W. Huang, Z. Li. 2014. Spatially explicit assessment of ecosystem resilience: an approach to adapt to climate changes. *Advances in Meteorology*, 2014.
- Zingstra, H.L. 2013. Lake Burullus: local food security and biodiversity under pressure, final report: W. U. Centre for Development Innovation. Retrieved from <https://library.wur.nl/WebQuery/wurpubs/fulltext/297256>.