International Journal of Sustainable Development Goals

www.ijsdg.org
eISSN: 3080-5023

Assessment of Urban Encroachment Using High-Resolution Satellite Imagery and Advanced Change Detection Techniques: A Case Study of Lake Maryut, Alexandria, Egypt (2002–2025)

Neama Hussen Selim Ali [1,*], Mohamed Ezz El Din El Raey[2,*]

[1] Department of Environmental Studies, Institute of Graduated Studies and Research, University of Alexandria, Alexandria, Egypt

[2] Department of Environmental Studies, Institute of Graduated Studies and Research, University of Alexandria, Alexandria, Egypt

ARTICLE INFO

Article history:
Received 2 November 2025
Received in revised form 5 February 2026
Accepted 11 April 2026
Available online 11 April 2026

Keywords:
Lake Maryut; Change detection; Cross tabulation; Temporal dynamics; Urbanization

ABSTRACT

Accurate and up-to-date information on land cover and land use, along with their temporal dynamics, is essential for producing reliable land cover maps and supporting ecosystem monitoring, urban planning, policy development, and resource management. This study assesses land cover changes in Lake Maryut, south of Alexandria, Egypt, from 2002 to 2025, a period marked by significant socio-political shifts following the 2011 revolution. High-resolution QuickBird imagery (0.5 m; 2002–2014) and medium-resolution Sentinel-2 imagery (10 m; 2020–2025) were integrated with topographic maps, remote sensing techniques, and Geographic Information System (GIS) analysis to detect and quantify spatial transformations. Change detection was performed using a post-classification comparison approach supported by cross-tabulation for pixel-based assessment. The results reveal substantial urban encroachment into agricultural land and wastewater infrastructure, contributing to notable environmental pressures on the lake. The lake's surface area declined from 75.9 km² in 2002 to 69.5 km² in 2014, 67.8 km² in 2020, and 52.9 km² in 2025, amounting to a total loss of approximately 23 km² at an average annual reduction rate of 0.95 km². These findings underscore the pressing need for targeted management strategies to mitigate ongoing environmental degradation and foster sustainable development in the region.

1. Introduction

Wetlands are critically important for biodiversity and human wellbeing, but face a range of challenges. This is especially true in the Mediterranean region, where wetlands support endemic and threatened species and remain integral to human societies, but have been severely degraded in recent decades *[33].* Wetlands and shallow lakes remain among the most threatened ecosystems

[1*] *Corresponding author.*
E-mail address: neamaselim780@gmail.com

[2*] *Corresponding author.*
E-mail address: melraey@mail.com

https://doi.org/10.59543/qythq794

globally, with ongoing declines in both extent and ecological quality *[11].* In North Africa, the impacts of land-use and land-cover changes on ecologically significant wetland systems have been particularly pronounced *[4].*However, the nature and pace of wetland degradation and loss in North Africa are still not fully documented or monitored comprehensively, with most studies limited to site-specific assessments and a lack of coordinated regional monitoring *[31] , [12] , [11].*

The increasing population growth, combined with finite natural resources, has escalated pressure on environmental resources to satisfy the rising demand for food, fuel, and urban expansion. These pressures pose significant challenges to ecological ecosystems, often resulting in unsustainable regional development. Such environmental challenges are frequently linked to insufficient proactive planning and inadequate enforcement of regulatory policies. Maryut Lake has been subjected to various physical and biological changes mainly due to the different human activities that have serious impacts on its quality and a subsequent deterioration in its ecological parameters *[17]*. Consequently, acquiring accurate and timely information regarding land use and land cover (LU/LC) dynamics derived from advanced remote sensing technologies is essential for enhancing the visualization and comprehension of complex interactions between anthropogenic activities and ecological systems. Furthermore, addressing socio-economic factors within specific temporal contexts is imperative for effective environmental management. High-resolution remote sensing-based change detection analyses of urban areas afford critical insights and robust tools for decision-makers. Such information enables the formulation of informed and proactive planning strategies, which are vital for achieving sustainable development objectives for both current and future generations.

2. Study Area

Wetland lakes are defined as enclosed bodies of water, either freshwater or saline, with an average depth of less than six meters. These systems are characterized by periodic or permanent shallow inundation and strong ecological linkages to adjacent wetlands. Within this context, Lake Maryut exemplifies a typical wetland lake in northern Egypt. Over the centuries, the shallow coastal lakes of the Nile Delta have been subjected to various anthropogenic and natural disturbances, including hydrological alterations, pollution, and extensive land reclamation activities *[1], [25], [2].* The lake receives pollution from a number of different sources and is highly eutrophic. The lake area is dominated by vegetation, principally Common Reed *(Phragmites australis)* and water hyacinth (Eichhornia crassipes), which, if left unmanaged *[7]*, reducing oxygen levels for fish, impacts upon the fisheries, and creating habitats for disease-carrying mosquitoes *[21).*

Lake Mariout is one of the most important coastal brackish water lakes in Egypt. It is an inland closed ecosystem, situated south of Alexandria city and west of the Nile Delta *[34].* Lying between Longitudes 29º 51/ 00// - 29º 56/ 15// E, and Latitudes 31º 04/ 15// - 31º10/ 45// N *[15].* The lake and the associated Maryut Valley extend approximately 80 km along the northwestern coastal region and about 30 km southward, comprising several basins delineated by highways and railways as shown in Figure 1 *[26]*. The lake's average depth ranges from 0.5 to 1.2 m, with a water surface elevation of approximately −2.8 m relative to mean sea level, placing it within a unique hydrological context. From a hydrological perspective, Lake Maryut differs from other northern Delta lakes as it lacks a natural connection to the Mediterranean Sea and mainly receives inflow from agricultural and domestic drainage canals, which significantly influence its salinity and ecological balance *[30], [29].*The main drains and canal are Qalaa drain, El-Ummum drain, and Nubaria canal. The water inflow to the lake comes mainly from these sources plus those from the East and West treatment plants began in 1993 to treat Alexandrian wastewater. Both are primarily treatment plants and they discharge their final effluents into the lake and from the petrochemical area *[3].*

The lake is divided into five basins that exhibit partial interconnection through breaches in the dykes of the El-Umum Drain and Nubaria Canal. Since the late nineteenth century, these agricultural drainage canals have served as the primary water sources for the lake. To maintain the water level at approximately −2.8 m below sea level, excess water is discharged into the Mediterranean Sea via the El-Max Pumping Station, which was constructed for this purpose *[27].* Historically, Lake Maryut has been recognized as an important northern Egyptian lake supporting diverse biodiversity and serving as a vital resource for fish production, salt extraction, and scenic value within the broader "Maryut Valley". The ecological integrity of Lake Maryut and its socio-economic importance remain central to discussions of sustainable development and environmental management in the Nile Delta region.

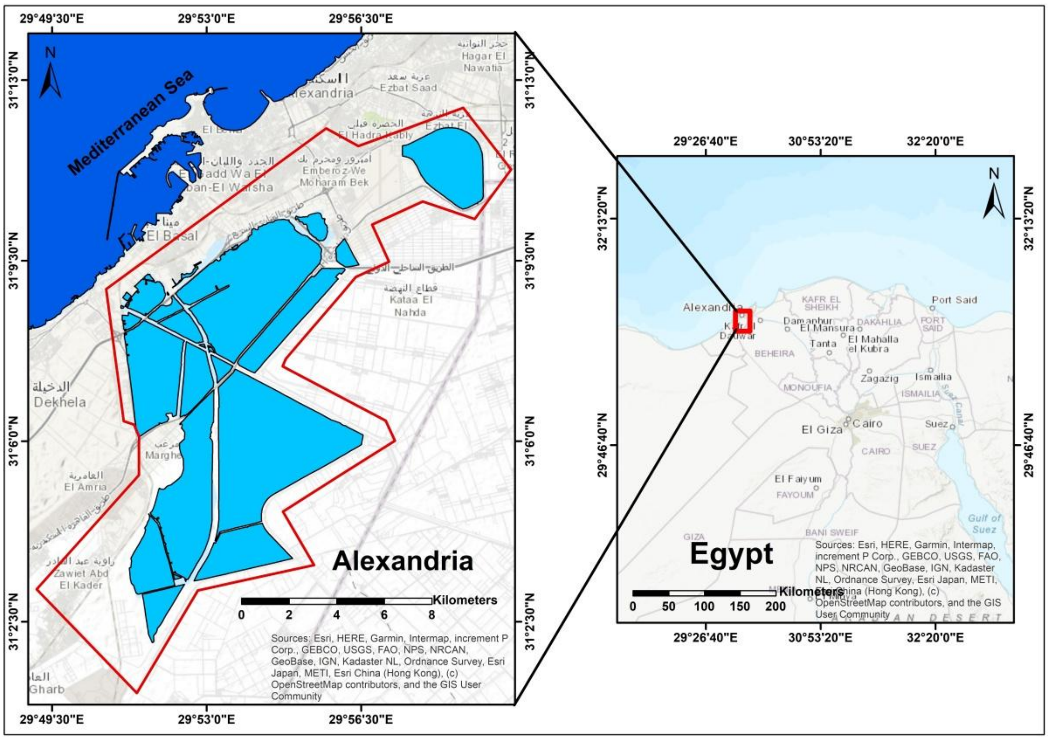

Fig. 1. Location of the Study Area: Lake Maryut

3. Materials and Methods

In this study, a comprehensive assessment of temporal land cover changes was conducted through the integration of multiple datasets. Digital satellite imagery, topographic maps, field surveys, and Geographic Information System (GIS) software were utilized to ensure a robust technical evaluation. QuickBird satellite imagery, with a spatial resolution of 0.5 m, was acquired for the years 2002 and 2014 from Geo-Map Consultants under contract with Digital Globe Incorporated (Longmont, CO, USA). Sentinel-2 imagery, featuring a spatial resolution of 10 m, was obtained for the years 2020 and 2025 from the Copernicus Open Access Hub *(dataspace.copernicus.eu)* as illustrated in Figure 2. All images were geometrically corrected and registered to the Universal Transverse Mercator (UTM) coordinate system, Zone 35N, based on the WGS-84 datum. Two QuickBird data products were used: panchromatic images for high-resolution visual interpretation and multispectral images, which include visible and near-infrared bands, for detailed spectral analysis. Topographic maps at a scale of 1:25,000, published by the Military Survey Authority (Cairo, Egypt), along with ground truth data from field surveys, were integrated to enhance the precision of land cover change detection. This multi-source approach strengthens the reliability of findings and emphasizes the importance of combining diverse datasets to support sustainable land management initiatives.

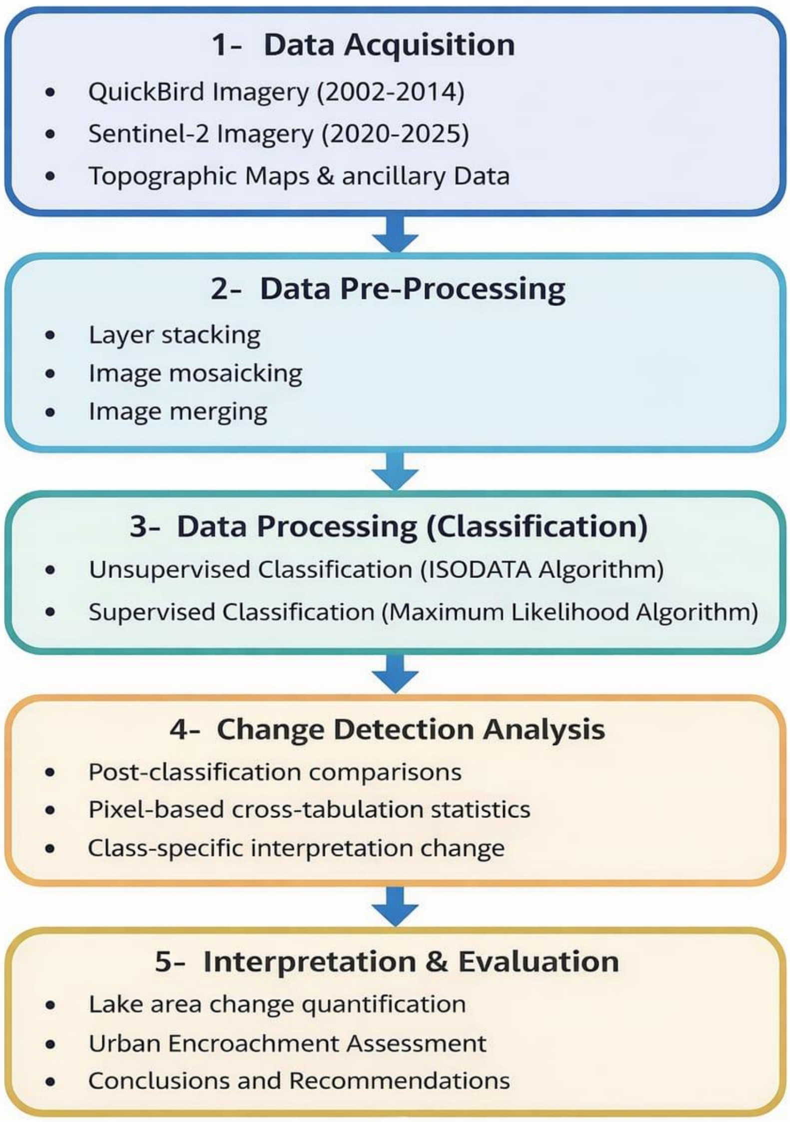

Fig. 2. Conceptual framework for land cover change analysis

3.1 Image Pre-Processing

Pre-processing steps enhances the accuracy of surface reflectance measurements, allowing for clearer and more reliable data for analysis. It is essential for applications such as precision agriculture, environmental monitoring, and land-use analysis *[10].* The process aimed to preserve essential spectral information while improving visual clarity. The pre-processing workflow comprised three main steps: layer stacking, image mosaicking, and resolution merging, implemented using ERDAS Imagine 2014 software.

Layer stacking, or band combination, was employed to merge four spectral bands into a single composite image. Image mosaicking aims to expand spatial coverage by integrating multiple Digital Orthophoto Maps into a unified whole *[35].* In this study, six QuickBird panchromatic and six multispectral scenes representing Lake Maryut were mosaicked simultaneously, producing large composite panchromatic and multispectral images. Digital image-merging is a critical technique for enhancing image resolution and quality. The objective of image merging is to effectively fuse high-resolution panchromatic images with limited spectral information and low-resolution multispectral images, thereby generating a fused image with a high spatial resolution and rich spectral information *[32]*. By combining PAN and MS bands we may create imagery with the greatest qualities of both. In any imagery processing operation, the final fused imagery is a modern imagery that is more helpful for both conceptualization of man and machine *[13].* Multispectral Lake Maryut images, providing visible and near-infrared data at 2 m resolution, were fused with 0.5 m panchromatic imagery to generate synthetic images that retained spectral detail and spatial precision. The resulting 0.5 m fused images were subsequently used for classification analysis.

3.2 Image Processing

Image processing involves converting an image into a digital form and carrying out certain actions to get valuable information from the input image *[5].* In this study, all processing was conducted in ERDAS Imagine 2014, a leading commercial software platform for remote sensing and GIS integration. Image classification involves assigning pixels to specific land cover categories based on spectral characteristics. Two principal classification approaches were implemented: unsupervised and supervised pixel-based classification.

In unsupervised classification, statistical patterns in image data are automatically identified without prior ground-truth information, producing a thematic raster layer of spectrally similar clusters *[18).* The ISODATA algorithm is widely applied for this purpose, groups pixels based on minimum spectral distance, and iteratively refines clusters through merging and splitting until optimal separation is achieved *[18].* In this study, the ISODATA algorithm was used to generate 50 initial spectral clusters, which were subsequently consolidated into six primary land cover classes. Refinement was guided by spectral signatures, topographic maps, ground-truth observations, visual interpretation, and Google Earth imagery. Separability analysis was performed using a transformed divergence algorithm to evaluate statistical distances and minimize overlap between classes.

Supervised classification involves analyst-guided selection of training samples representing known land cover types. In this process, representative training areas (AOI) were defined on the original images to create supervised signature files for each class. Signatures derived from both supervised and unsupervised methods were combined using the Maximum Likelihood algorithm to produce the final land cover map, consisting of six land cover classes as illustrated in Table 1. An accuracy assessment was performed to evaluate classification reliability, using 200 randomly selected validation points per image. The resulting accuracy metrics confirmed the robustness of the classification outputs for temporal land cover analysis in the Lake Maryut region.

Table 1

Land covers classes and their descriptions in the study area

Land Cover Classes	Description
Water type (1)	**includes Hydrodome Farm and some parts of other lake basins**
Water type (2)	**includes the Lake basins (Main basin, Aquaculture basin, North-West basin, South-East basin, and South-West basin)**
Vegetation (1)	**Common Reed *"Phragmites Australis"***
Vegetation (2)	**Water Hyacinth *"Eichhornia Crassipes"*, and Torpedo Grass *"Panicum Stagninum"***
Vegetation (3)	**includes Papyrus *"Cyperus"*, Cuscuta *"Potamogeton Pectinatus"*, Cat Tall *"Ceratophyllum Demersum"*, and *"Najas Marina"***
Built-up area	**Residential, Commercial, Industrial, Airports, Roads, Bare soil, and Railways**

3.3 Change Detection Analysis

Change detection in remote sensing is the process of identifying changes in a scene from a pair of images captured in the same geographical area but at different time periods, which has broad applications in urban development, agricultural surveys, and land cover monitoring *[8]*. It allows the assessment of both the spatial distribution and the qualitative aspects of landscape transformation. One of the most well established and widely used detection techniques among the supervised change detection techniques is post-classification comparison. This technique finds change by comparing the thematic classification maps of two dates.

Post classification comparisons of land cover statistics are used to identify shift patterns, gains and losses (positive and negative, respectively) in each land cover class *[19]*. In this study, post-classification comparison was employed as the primary method to detect land cover changes between 2002 and 2025. This technique involves comparing classified thematic maps from multiple years to identify significant transitions in land cover categories. The analysis was supported by cross-tabulation statistics, which measure the spatial correspondence and areal extent of land cover classes across two time periods. These statistics quantify the number of coinciding pixels, the total area of overlap (in hectares or square kilometers), and the percentage of each class transition *[22].*

The resulting cross-tabulation matrix reveals the dominant directions and magnitudes of land cover change, enabling the quantification of transformation dynamics within the study area. Layers illustrating specific change types were generated to support spatial interpretation and to evaluate the rate, nature, and distribution of land cover modifications in the Lake Maryut region. In addition to post-classification comparison, a complementary visual change detection technique was applied, following the methodology proposed by *[16].* This method enhances temporal comparison by recoding each land cover class to facilitate class-specific interpretation. In this process: Each target class was assigned a value of 2 in the earlier year (2002 or 2020) and 3 in the later year (2014 or 2025), while all other classes were coded as 1. The reclassified image from the earlier year was multiplied by the corresponding reclassified image from the later year. The resulting change detection output included the following value classes:

1 (1 × 1): Areas unrelated to the target class.
2 (2 × 1): Areas where the target class was lost.
3 (3 × 1): Areas where the target class was gained.
6 (2 × 3): Areas where no change occurred (class persistence).

This technique improves visual interpretation of class-specific transformations and facilitates the identification of spatial patterns and temporal trends. Finally, a comprehensive

Geographic Information System (GIS) database was established for the Lake Maryut study area, integrating all processed spatial datasets. This GIS framework supports advanced spatial analyses, environmental modeling, and decision-support applications for sustainable land management and monitoring.

4. Results and Discussion

Land represents one of the most critical natural resources, underpinning both the sustenance of life and the advancement of human development activities *[28].* The availability of accurate land use and land cover (LULC) data is paramount for effective planning, informed decision-making, and the sustainable management of land resources. The monitoring and analysis of urban environments necessitate current LULC maps to facilitate the responsible stewardship of metropolitan areas. The growing accessibility of high-resolution satellite imagery has significantly enhanced the capacity to detect and monitor even minor structural changes in land cover. This study employed classified QuickBird and Sentinel-2 satellite imagery to systematically analyze land cover changes in Lake Maryut and its adjacent areas over the period from 2002 to 2025. Post-classification imagery for the years 2002, 2014, 2020, and 2025 was utilized for change detection, as illustrated in Figure 3 and detailed in Table 2.

The overall classification accuracy achieved for the 2002 QuickBird image was 96.0%, with a Kappa coefficient of 0.9492. The 2014 QuickBird image attained an accuracy of 98.0% (Kappa coefficient: 0.9748), while the 2020 Sentinel-2 image exhibited an accuracy of 98.1% (Kappa coefficient: 0.9859). The 2025 Sentinel-2 image demonstrated an accuracy of 97.0% with a Kappa coefficient of 0.9592. The analysis of post-classified imagery across the outlined years revealed significant land cover changes within the study area, which encompasses approximately 138.8 km². Notably, the Water Type (1) class experienced a substantial decline, decreasing from 15.0 km² in 2002 to 5.2 km² in 2025. Similarly, the Vegetation (1) class decreased from 24.0 km² in 2002 to 20.0 km² in 2025. Conversely, the Water Type (2) class expanded from 43.0 km² to 48.6 km² during the same timeframe, an increase attributed to the deterioration of water quality in the lake. Furthermore, the Built-up Area class grew from 45.0 km² in 2002 to 57.0 km² in 2025, primarily driven by urbanization and the encroachment of developed areas into erstwhile lake zones. To quantify and contextualize these changes, a cross-tabulation algorithm was employed to analyze the spatial distribution of thematic transformations within the study area.

Table 2
Land cover changes in the study area from 2002 to 2025

Land cover classes	2002	2014	2020	2025	Change rate 2002-2025 (km²)
Water type (1)	**15**	**14**	**5.1**	**5.2**	**-9.8**
Water type (2)	**43**	**36**	**53.7**	**48.6**	**5.6**
Vegetation (1)	**24**	**30**	**22.9**	**20**	**-4**
Vegetation (2)	**11**	**10**	**9.1**	**7**	**-4**
Vegetation (3)	**1**	**3**	**1.5**	**1.3**	**0.3**
Built-up area	**45**	**46**	**46.5**	**57**	**12**

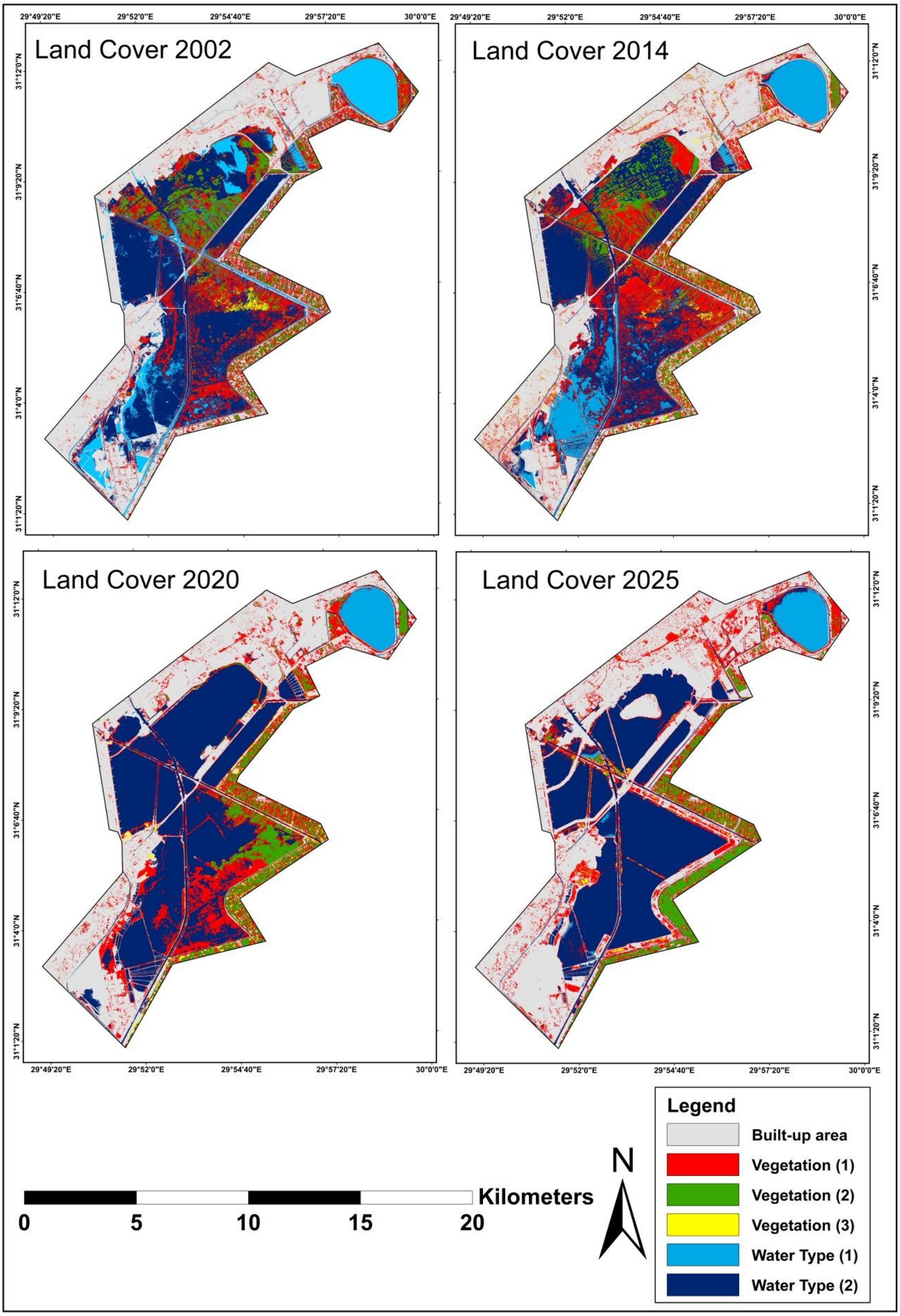

Fig. 3. Post-classification maps of the study area from 2002 to 2025

The results, presented in Tables 3 and 4, underscore land cover transitions in terms of both percentage and area (km²). The cross-tabulation results illustrated significant areas transitioning from Water Type (1) to Water Type (2), a phenomenon closely linked to the ongoing discharge of untreated wastewater into Lake Maryut. Additionally, the expansion of the Built-up Area correlates with increased urban sprawl and the development of infrastructure, including roads and residential zones. Transitions from aquatic environments to vegetative cover also emerged, largely due to the aggressive proliferation of aquatic plants such as Common Reed *(Phragmites australis),* Water Hyacinth *(Eichhornia crassipes),* and Torpedo Grass *(Panicum repens).* During the period from 2002 to 2014, the area covered by Common Reed increased significantly from 24.0 km² to 30.0 km², indicative of vigorous plant growth. However, from 2020 to 2025, this coverage declined from 22.9 km² to 20.0 km², likely as a result of targeted lake-cleaning interventions implemented in certain sectors. Overall, the dynamic changes observed across the six land cover classes are primarily driven by the evolving hydrological and environmental characteristics of Lake Maryut. Fluctuations in water levels, attributed to flooding from high discharge rates originating from the El-Umum Drain and Nubaria Canal, as well as subsequent recession in some areas, have contributed to alternating periods of overflow and exposure of surrounding roads and bare soil. Furthermore, the ongoing transformation of water bodies into vegetation and built-up regions reflects both ecological processes and anthropogenic influences shaping the landscape. In addition to the post-classification comparison and cross-tabulation analyses, a complementary visual change detection technique was employed to strengthen the temporal assessment of land cover dynamics. This technique supports class-specific interpretation of spatiotemporal variations, as demonstrated in Figures 4, 5, 6 and Table 5.

Table 3

Cross-Tabulation Matrix of land cover changes in Lake Maryut (2002–2014), area in percentages and km²

2014 Classes	2002 Classes											
	Water type (1)		Water type (2)		Vegetation (1)		Vegetation (2)		Vegetation (3)		Built-up area	
	%	km²	%	km²	%	km²	%	km²	%	km²	%	km²
Water type (1)	52.8	7.5	12.4	4.5	2.7	0.8	7.6	0.8	1.95	0.04	2.5	1.1
Water type (2)	39.6	5.6	68.6	24.9	25.5	7.6	24.9	2.5	17	0.4	5.2	2.4
Vegetation (1)	0.99	0.1	11.9	4.3	38.4	11.5	30.3	3	31.1	0.8	9.9	4.5
Vegetation (2)	0.30	0.04	4	1.5	16.8	5	25.3	2.5	12.1	0.3	2.6	1.2
Vegetation (3)	0.33	0.05	0.58	0.2	0.81	0.2	0.91	0.09	2.4	0.1	0.11	0.05
Built-up area	6	0.8	2.6	0.9	15.8	4.7	10.9	1.1	35.5	0.9	79.7	36.4
Total	100	14.2	100	36.4	100	29.9	100	9.9	100	2.6	100	45.7

Table 4

Cross-Tabulation Matrix of land cover changes in Lake Maryut (2020–2025), area in percentages and km²

2025 Classes	2020 Classes											
	Water type (1)		Water type (2)		Vegetation (1)		Vegetation (2)		Vegetation (3)		Built-up area	
	%	km²	%	km²	%	km²	%	km²	%	km²	%	km²
Water type (1)	94.3	4.8	0.6	0.4	0.03	0.01	0.01	0.001	0	0	0.03	0.01
Water type (2)	4.7	0.24	74	39.7	25.1	5.7	23.1	2.1	1.4	0.03	1.57	0.8
Vegetation (1)	0.87	0.04	7.7	4.2	32.1	7.4	25.4	2.3	31.3	0.5	12	5.6
Vegetation (2)	0	0.0001	0.5	0.2	10.3	2.3	40	3.6	19.2	0.3	0.9	0.4
Vegetation (3)	0.01	0.0004	0.9	0.5	2.4	0.5	1.9	0.2	0.4	0.006	0.2	0.09
Built-up area	0.09	0.005	16.4	8.7	30.1	7	9.6	0.9	47.7	0.7	85.4	39.6
Total	100	5.1	100	53.7	100	22.9	100	9.1	100	1.54	100	46.5

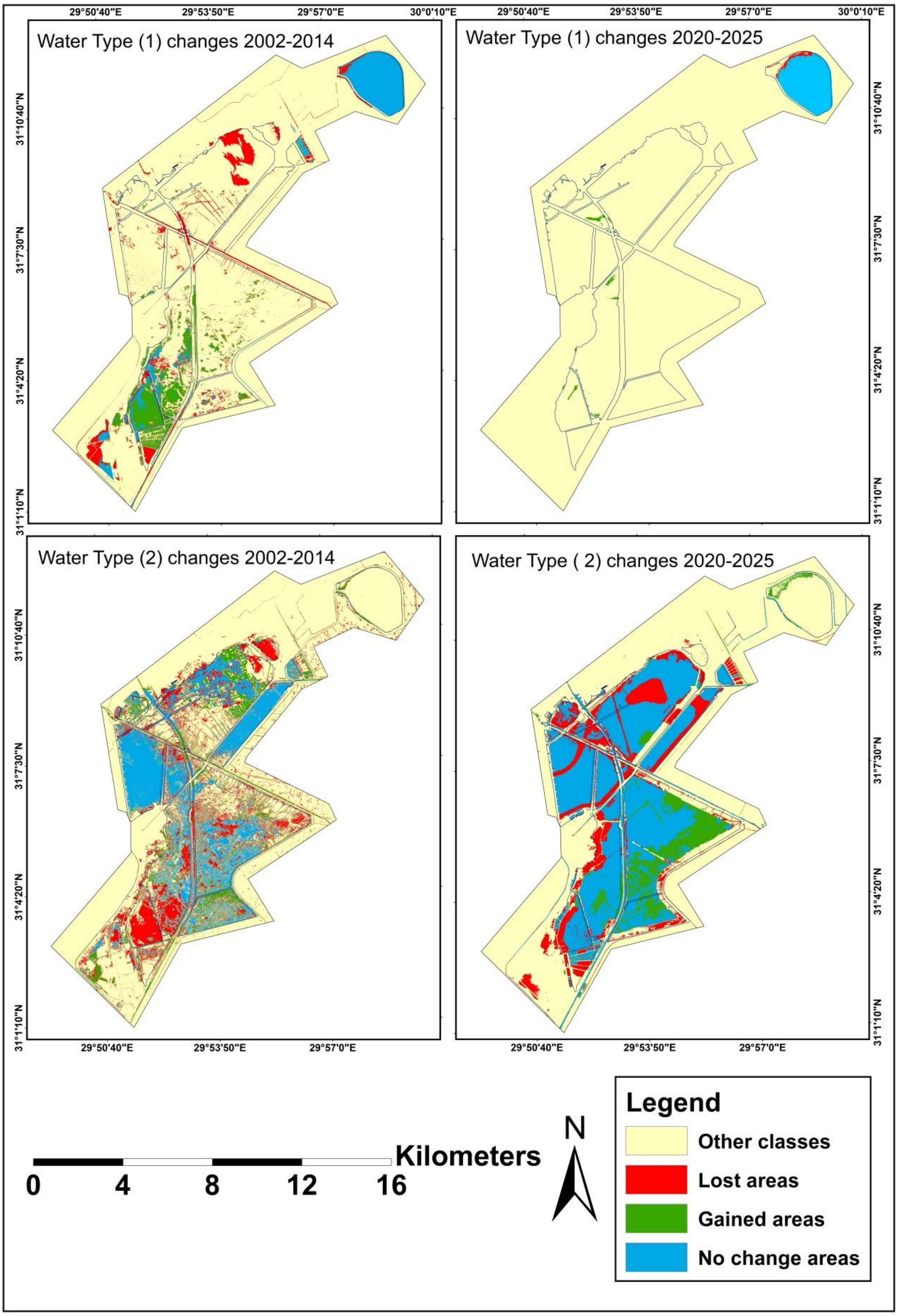

Fig. 4. Changes in Water Classes in the study area from 2002 to 2025

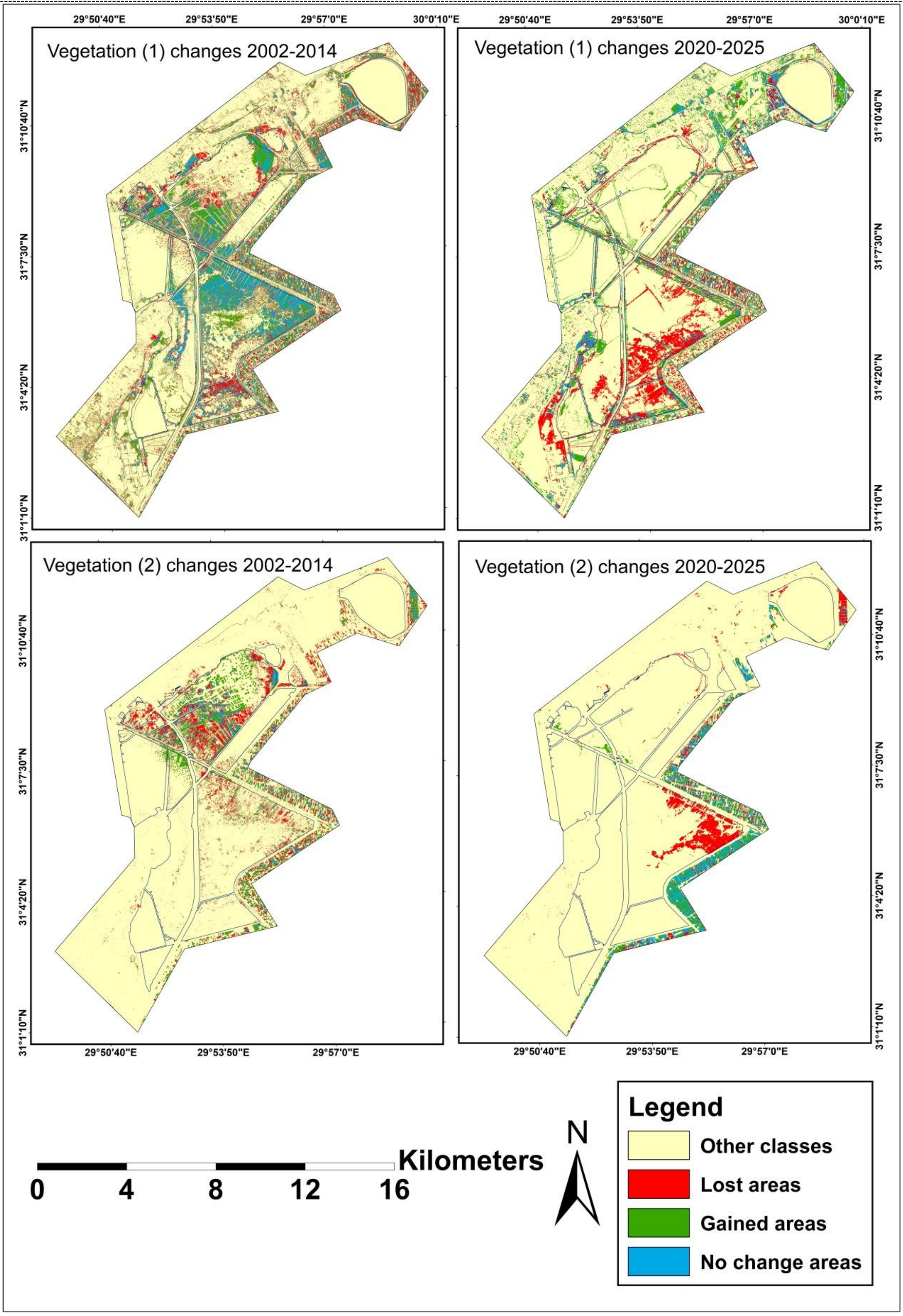

Fig. 5. Changes in Vegetation Classes (1 and 2) in the study area from 2002 to 2025

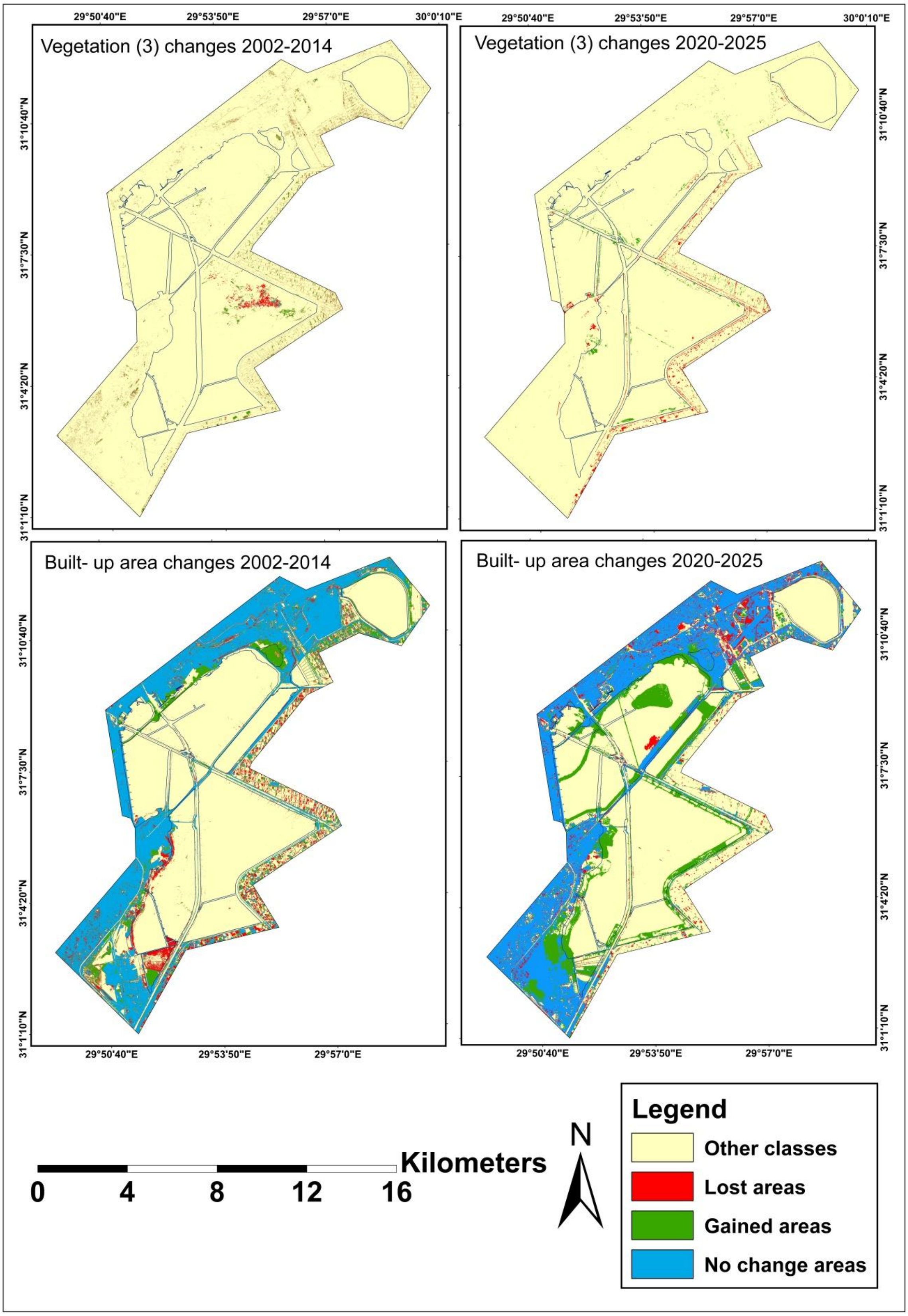

Fig. 6. Changes in Vegetation (3) and Built-Up Area classes in the study area from 2002 to 2025

Table 5
Visualization of land cover changes in Lake Maryut and surrounding areas from 2002 to 2025 (area in km²)

Water type (1)	2002-2014	2020-2025	Water type (2)	2002-2014	2020-2025
Other Classes	117	133	Other Classes	84	76.4
Lost Areas	8	0.3	Lost Areas	19	14
Gained Areas	7	0.03	Gained Areas	11	8.8
No Change	7	4.8	No Change	25	39.7
Vegetation (1)	2002-2014	2020-2025	Vegetation (2)	2002-2014	2020-2025
Other Classes	96	103.4	Other Classes	121	126.4
Lost Areas	13	15.5	Lost Areas	8	5.5
Gained Areas	18	12.6	Gained Areas	8	3.3
No Change	12	7.3	No Change	2	3.7
Vegetation (3)	2002-2014	2020-2025	Built-up area	2002-2014	2020-2025
Other Classes	135	135.7	Other Classes	84	75.2
Lost Areas	1	1.8	Lost Areas	9	6.8
Gained Areas	3	1.3	Gained Areas	10	17.5
No Change	0.0654	0.0072	No Change	36	39.5

4.1 Urban Encroachment around Lake Maryut (2002–2025)

Urban expansion has emerged as a significant driver of land cover change around Lake Maryut from 2002 to 2025, resulting in a substantial decline in the lake's area. In 2002, the lake encompassed approximately 75.9 km². By 2014, this area had contracted to 69.5 km², representing a total reduction of 6.4 km² over 12 years, which translates to an average loss rate of 0.53 km² annually. A more pronounced decline occurred between 2020 and 2025, when the lake area decreased from 67.8 km² to 52.9 km², equating to a loss of 14.9 km² at a significantly higher average rate of 3.0 km² per year. These changes are detailed in Table 6 and illustrated in Figure 7. Remote sensing analysis has revealed a continuous increase in built-up areas, expanding from 45.0 km² in 2002 to 57.0 km² in 2025.

Table 6
Changes in basin areas of Lake Maryut from 2002 to 2025

Basin	2002	2014	2020	2025	Change rate (2002-2025)Km²
Main Basin	19.7	16.2	15.3	11	-8.7
Aquaculture	4.6	4.4	4.1	2.7	-1.9
North-West	9.1	8.6	8.5	7.8	-1.3
South-East	23	20.9	21.2	16.5	-6.5
South-West	13.9	13.8	13.2	9.4	-4.5
Hydrodome Farm	5.6	5.5	5.5	5.5	-0.1
Total area	75.9	69.3	67.8	52.9	-23

This growth underscores the rapid pace of urbanization and the increasing demand for residential, industrial, and infrastructural developments in proximity to the lake. Much of this encroachment has occurred at the expense of natural land cover types, particularly water bodies and vegetation, leading to significant ecological degradation and a reduction in the lake's surface area. The spatial and temporal patterns of urban sprawl highlight the urgent need for sustainable land-use planning and the implementation of stricter regulations governing urban growth to mitigate further environmental impacts on the ecosystem of Lake Maryut. Monitoring human activities around Lake Maryut throughout this period has documented extensive land cover changes, predominantly driven by urban encroachment and land reclamation. The lake's area has diminished markedly in recent years, largely due to unauthorized landfilling and construction activities, particularly during periods of weakened governance, such as the Egyptian revolution, when enforcement of urban planning regulations was less stringent. Informal expansion by local fishermen, which includes the construction of housing along the lake’s perimeter, has further contributed to the progressive reduction of the lake's surface area. In addition to illegal encroachments, various government-sanctioned reclamation projects have also led to considerable transformations of the landscape. These include urban expansion and infrastructure development initiatives undertaken by the Alexandria Governorate.

Major projects encompass the construction and expansion of critical transportation corridors, such as the International Coastal Road, Alexandria Desert Road, El-Kabbari Road, and the Ring Road, alongside the establishment of new residential areas, commercial centers (e.g., Carrefour), and vital infrastructure projects like the Alexandria Sanitation Project. Other notable developments include the establishment of factories, Mubarak Sports City, and El-Hadeka El-Dawlia according to the *[14]*, the estimated land allocations for these projects are as follows: - 500 acres for Mubarak Sports City - 200 acres for the seventh sector of the International Coastal Road - 130 acres for El-Hadeka El-Dawlia - 40 acres for sanitation infrastructure expansion - Additional areas for the Carrefour commercial center and the Ring Road Spatially. Land loss during the 2002–2014 periods was most pronounced on the eastern and northern edges of the Main Basin, as well as in the western and southeastern portions of the South-West Basin. Between 2020 and 2025, further reductions occurred across the eastern section of the South-East Basin, south of the Aquaculture Basin, and throughout the northern, central, eastern, and southern sections of the Main Basin, in addition to the western part of the South-West Basin, as depicted in Figure 7.

Recent urban development initiatives surrounding Lake Maryut, including the *Bashaier El-Kheir 3 project* located to the north of the lake’s main basin and the *Sawari Towers complex* situated to the east have been established on areas formerly constituting the lake’s desiccated margins. These developments signify a pivotal stage in Alexandria’s westward urban expansion, whereby reclaimed wetland territories have been transformed into densely built residential and mixed-use zones. The conversion of the former lakebed into urban land reflects the city’s broader strategy to alleviate housing shortages and attract local investment. Nevertheless, this rapid urbanization has generated significant sustainability challenges, particularly concerning land subsidence, increased groundwater salinity, and the depletion of natural buffer ecosystems.

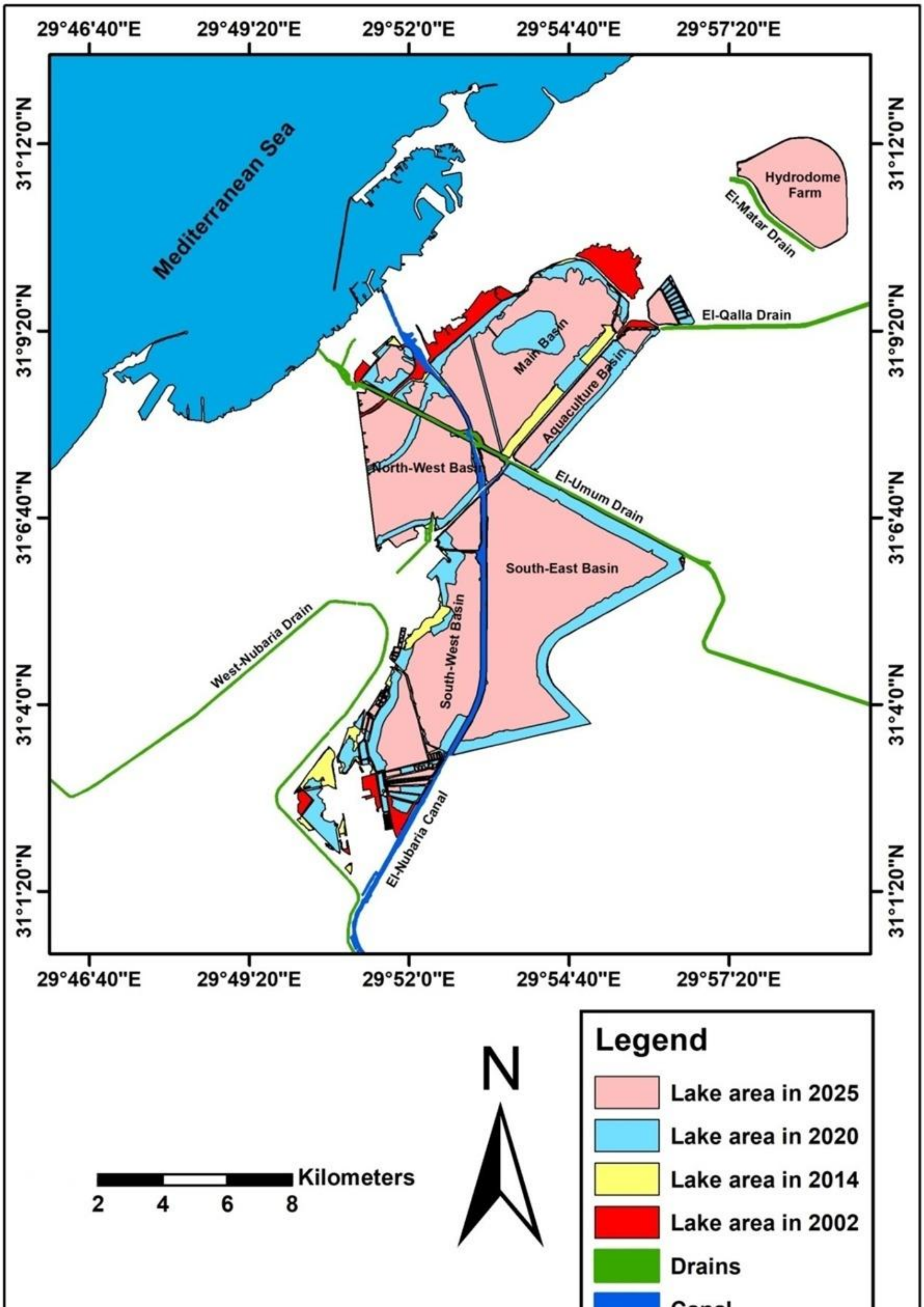

Fig. 7. Shrinkage of Lake Maryut area from 2002 to 2025

5. Conclusions and Recommendations

Due to limited available land for urban development in Alexandria and the city's rapidly growing population, Lake Maryut and its surrounding areas has become a critical zone for urban expansion and an important economic resource. As highlighted throughout this study, Lake Maryut is considered one of the environmental "hotspots" of the Alexandria Governorate and one of the most ecologically sensitive areas along the Mediterranean Sea. The use of high-resolution satellite imagery**,** combined with supervised classification algorithms and a cross-tabulation change detection approach, proved highly effective in accurately monitoring land cover changes in the study area. The temporal analysis conducted across the years 2002, 2014, 2020, and 2025 has provided valuable insights into the lake's environmental degradation, the dynamics of natural resource transformation, and the scale of urban encroachment. These findings offer crucial input for sustainable land use and environmental management strategies. Based on the results of this study, the following conclusions can be drawn:

5.1 *Significant Reduction in Lake Area:* Lake Maryut has experienced a substantial decline in surface area due to both illegal landfilling and authorized land reclamation projects for urban development, such as road construction and infrastructure expansion. The lake area decreased from approximately 75.9 km² in 2002 to 52.9 km² in 2025, marking a total loss of around 23.0 km² at an average rate of 0.95 km² per year. This sharp reduction was particularly pronounced during periods of weakened regulatory enforcement, such as during the revolution.

5.2 *Aquatic Vegetation Dynamics:* Between 2002 and 2014, the lake experienced rapid aquatic vegetation growth, driven by high nutrient loads and organic pollution from wastewater discharge. However, a noticeable decline in aquatic vegetation was recorded during the period from 2020 to 2025, which can be attributed to clean-up and restoration efforts in specific parts of the lake during this time.

5.3 *Transformation in Water Quality Indicators:* Lake Maryut exhibited a marked transformation in water quality between 2002 and 2025, reflected in a sharp decrease in the Water Type (1) class from 15.0 km² to 5.2 km², and a concurrent increase in the Water Type (2) class from 43.0 km² to 48.6 km². This shift signals a degradation of water quality, primarily driven by the continued discharge of untreated wastewater into the lake ecosystem. Based on the findings of this study, which demonstrate significant land cover change and environmental degradation in the Lake Maryut region between 2002 and 2025, the following recommendations are proposed to support sustainable management, urban planning, and ecological restoration:

1. *Strengthen Urban Planning Regulations and Enforcement:* There is an urgent need for strict enforcement of land use and urban development regulations around Lake Maryut. This includes preventing further illegal landfilling and controlling unauthorized construction activities.
2. *Implement Buffer Zones Around the Lake:* Establishing protected buffer zones surrounding the lake can limit urban encroachment and provide a safeguard for remaining wetland ecosystems.
3. *Promote Wastewater Treatment and Pollution Control:* Since water quality deterioration is a key driver of aquatic vegetation overgrowth, upgrading wastewater treatment infrastructure and reducing the nutrient load discharged into the lake are critical. This will help prevent eutrophication and restore aquatic ecosystem balance.

4. *Expand Lake Rehabilitation and Vegetation Management Programs:* Building on the success of recent cleaning operations, long-term rehabilitation programs should be developed to manage invasive aquatic vegetation (e.g., water hyacinth, torpedo grass) and to promote native species. Periodic monitoring and mechanical removal strategies can maintain open water areas and improve biodiversity.
5. *Enhance Monitoring Using Remote Sensing and GIS*: Continued use of high-resolution satellite imagery and geospatial analysis should be institutionalized to regularly monitor land cover changes, urban expansion, and environmental health. This will enable early detection of threats and more effective response planning.
6. *Involve Stakeholders and Raise Community Awareness*: Community involvement is essential for the success of environmental protection initiatives. Educational programs and stakeholder engagement, especially with local residents, fishermen, and policymakers, can foster collective responsibility and sustainable resource use.
7. *Develop an Integrated Lake Management Plan:* A comprehensive and integrated management plan should be formulated, involving local authorities, environmental agencies, researchers, and civil society. This plan should balance ecological conservation with urban development needs and include clearly defined short-term and long-term objectives.

Author Contributions

Conceptualization and methodology, Neama H. Selim; software and visualization, Neama H. Selim; data collection, formal analysis, and resources, Neama H. Selim; & Mohamed El Reay; writing—original draft preparation, Neama H. Selim; writing—review and editing, Mohamed El Reay; supervision Mohamed El Reay. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data Availability Statement

The datasets utilized in this study include QuickBird satellite imagery (2002 and 2014) obtained from Geo-Map Consultants, Cairo, Egypt; topographic maps of Alexandria Governorate (2007) provided by the Military Survey Authority, Cairo, Egypt; and publicly available Sentinel-2 satellite imagery acquired from the Copernicus Open Access Hub (https://scihub.copernicus.eu/). All data sources were used in accordance with their respective licensing and access policies.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgement

This research was not funded by any grant, and all work was conducted independently.

References

[1] Abd El-Alkhoris, Y. S., Abbas, M. S., & Abbas, M. (2020). Assessment of water and sediments pollution in Maruit Lake, Egypt. *Egyptian Journal of Aquatic Biology & Fisheries, 24*(1), 145–160. https://doi.org/10.21608/ejabf.2020.70681

[2] Abdel-Hamid, H. T., Kaloop, M. R., Elbeltagi, E., & Hu, J. W. (2023). Impact assessment of the land use dynamics and water pollution on ecosystem service value of the Nile Delta coastal lakes, Egypt. *Journal of the Indian Society of Remote Sensing, 51*, 963–981. https://doi.org/10.1007/s12524-022-01663-z

[3] Ahmed, S. M. (2021). Impact of different pollutants on some water quality aspects of Lake Mariout (Egypt). *Egyptian Journal for Aquaculture, 10*(4), 17–37.

[4] Aitali, R., Snoussi, M., Kolker, A. S., Oujidi, B., & Mhammdi, N. (2022). Effects of land use/land cover changes on carbon storage in North African coastal wetlands. *Journal of Marine Science and Engineering, 10*(3), 364. https://doi.org/10.3390/jmse10030364

[5] Ali, H. (2024). A comprehensive overview of digital image processing: Techniques, applications, and evolving technologies. *ILMA Journal of Technology & Software Management, 5*(1).

[6] Babadi Ataabadi, M., Chen, D., Pouliot, D., & Oluwadare, T. S. (2024). Comparing the performance of different classifiers for urban change detection: A case study in Kingston, Ontario. *ISPRS Archives, XLVIII-M-4*, 1–7. https://doi.org/10.5194/isprs-archives-XLVIII-M-4-2024-1-2024

[7] Beevers, L. (2020). Alexandria Lake Maryut: Integrated environmental management. In B. D. Fath & S. E. Jørgensen (Eds.), *Managing Water Resources and Hydrological Systems* (2nd ed., Chapter 29, pp. 1–15). CRC Press. https://doi.org/10.1201/9781003045045-32

[8] Cheng, G., Huang, Y., Li, X., Lyu, S., Xu, Z., Zhao, H., Zhao, Q., & Xiang, S. (2024). Change detection methods for remote sensing in the last decade: A comprehensive review. *Remote Sensing, 16*(13), 2355. https://doi.org/10.3390/rs16132355

[9] Copernicus Open Access Hub. (2020–2025). Copernicus data portal.

[10] Costa, O. P. da, Inácio, F. D., da Silva, J. E., Costa Barboza, T. O., Batista da Silva, W. H., Nunes Lacerda, L., & dos Santos, A. F. (2025). Impact of atmospheric corrections on satellite imagery for corn yield prediction using machine learning. *Smart Agricultural Technology, 12*, 101216. https://doi.org/10.1016/j.atech.2025.101216

[11] Davidson, N. C., Dinesen, L., Fennessy, S., Finlayson, C. M., Grillas, P., Grobicki, A., McInnes, R. J., & Stroud, D. A. (2019). Trends in the ecological character of the world's wetlands. *Marine and Freshwater Research, 71*(1), 127–138. https://doi.org/10.1071/MF18329

[12] Donde, O. O., Otieno, A. O., & Muia, A. W. (2023). Wetlands for remediation in Africa: Threats and opportunities. In *Wetlands: Ecology, Conservation and Management – Wetlands for Remediation in the Tropics* (pp. 175–195). Springer. https://doi.org/10.1007/978-3-031-23665-5_10

[13] Ebrahim, A., El-Mewafi, M., & Zhran, M. (2025). Studying the spatial spectral fusion models for remote sensing images. *Applied Geomatics, 17*, 483–500. https://doi.org/10.1007/s12518-025-00629-3

[14] Egyptian Environmental Affairs Agency (EEAA). (2007). *Environmental description report for Alexandria Governorate*. Cairo, Egypt.

[15] El-Gayar, E. E., El-Naggar, H. A., Elfiky, W. M., & Zuhair, R. (2023). Environmental impact assessment of aquaculture practices using zooplankton in Lake Mariout, Egypt. *Egyptian Journal of Aquatic Biology & Fisheries, 27*(4), 803–824.

[16] El-Hattab, M. M. (2002). *Environmental decision support system for a coastal area based on remote sensing and geographic information systems* (Doctoral dissertation). Alexandria University.

[17] El-Zeiny, A., & El-Kafrawy, S. (2017). Assessment of water pollution induced by human activities in Burullus Lake using Landsat 8 and GIS. *The Egyptian Journal of Remote Sensing and Space Science, 20*(Suppl. 1), S49–S56. https://doi.org/10.1016/j.ejrs.2016.10.002

[18] ERDAS IMAGINE. (2014). Product description. INTERGRAPH.

[19] Gebrehiwot, G. H., Bekitie, K. T., Yohannes, H., Anose, F. A., & Gebremichael, H. B. (2024). Time series land use/land cover mapping and change detection to support sustainable environmental management. *Environmental Systems Research, 13*, Article 33. https://doi.org/10.1186/s40068-024-00365-4

[20] Geo-Map Consultants. (2002, 2014). QuickBird satellite image. Cairo, Egypt.

[21] Keshta, A. E., Shaltout, K. H., Baldwin, A. H., Sharaf El-Din, A., & Eid, E. M. (2022). Variation in plant community composition across Egypt's major coastal lakes. *Sustainability, 14*(10), 6180. https://doi.org/10.3390/su14106180

[22] Leica Geosystems. (2006). *ERDAS Imagine – Tour guides*. Geospatial Imaging.

[23] Leica Geosystems. (2008). Geospatial IMAGINE.

[24] Military Survey Authority. (2007). Alexandria Governorate topographic maps. Cairo, Egypt.

[25] Morsy, K. M., Mishra, A. K., & Galal, M. M. (2020). Water quality assessment of the Nile Delta lagoons. *Environmental Health Insights, 14*. https://doi.org/10.1177/1178622120963072

[26] Selim, N. H. (2017). *Sustainable development of Lake Maryut using remote sensing and GIS techniques* (Doctoral dissertation). Alexandria University.

[27] Selim, N. H., & El Raey, M. (2018). EIA for Lake Maryut sustainable development alternatives using GIS, RS, and RIAM software. *Assiut University Bulletin for Environmental Research, 21*(1), 41–57. https://doi.org/10.21608/auber.2018.133202

[28] Sena, A., & Ebi, K. (2021). When land is under pressure, health is under stress. *International Journal of Environmental Research and Public Health, 18*(1), 136. https://doi.org/10.3390/ijerph18010136

[29] Shaaban, N. A. (2022). Water quality and trophic status of Lake Mariut after 8-year diversion. *Environmental Monitoring and Assessment, 194*, 392. https://doi.org/10.1007/s10661-022-10009-8

[30] Shreadah, M. A., El-Rayis, O. A., Shaaban, N. A., & Hamdan, A. M. (2020). Water quality assessment and phosphorus budget of Lake Mariut. *Environmental Science and Pollution Research, 27*(21), 26786–26799. https://doi.org/10.1007/s11356-020-08878-y

[31] Stephenson, P. J., Ntiamoa-Baidu, Y., & Simaika, J. P. (2020). Monitoring wetlands biodiversity in Africa: Challenges and opportunities. *Frontiers in Environmental Science, 8*, 61. https://doi.org/10.3389/fenvs.2020.00061

[32] Tang, Y., Li, H., Xie, G., Liu, P., & Li, T. (2024). Multi-frequency spectral–spatial interactive enhancement fusion network for pan-sharpening. *Electronics, 13*(14), 2802. https://doi.org/10.3390/electronics13142802

[33] Taylor, N. G., Grillas, P., Al Hreisha, H., Balkız, Ö., Borie, M., Boutron, O., et al. (2021). The future for Mediterranean wetlands: Key issues and research questions. *Regional Environmental Change, 21*(2), Article 33. https://doi.org/10.1007/s10113-020-01743-1

[34] Zalat, A. A., Derda, T., Welc, F., & Gwiazda, M. (2025). Environmental history of Lake Mariout… *Journal of Quaternary Science*. https://doi.org/10.1002/jqs.3686

[35] Zhang, Y., Chen, P., Guo, H., Liu, X., & Wan, Y. (2025). Generalized incremental image mosaicking with graph cuts. *ISPRS Journal of Photogrammetry and Remote Sensing, 230*, 661–674. https://doi.org/10.1016/j.isprsjprs.2025.09.030