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Evaluating the Impact of Land Use Changes on Water Quality in Lake Qarun, Egypt, Using Remote Sensing and GIS-Based Water Quality Index Modeling

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ABSTRACT

Land use and land cover (LULC) changes exert substantial impacts on freshwater ecosystems, particularly in arid and semi arid regions. This study assessed the effects of land use changes on the water quality of Lake Qarun, Egypt, by integrating remote sensing and GIS based modeling techniques. Multi temporal satellite imagery from 1985 to 2023 was analyzed using supervised classification with the Maximum Likelihood Classifier (MLC) to extract LULC classes and identify spatial patterns and trends in land use transformations. Water quality parameters including electrical conductivity (EC), turbidity, dissolved organic matter (DOM), and selected heavy metals were measured at 18 monitoring sites. The temporal analysis of LULC changes revealed significant spatial and temporal transformations, particularly in agricultural, urban, and water body classes. A Water Quality Index (WQI) was calculated and spatially modeled using GIS interpolation techniques to evaluate lake wide degradation. The results showed that WQI values in Lake Qarun ranged from 84.33 to 305.53, indicating that the lake is unsuitable for aquatic life. Water quality degradation was most pronounced in areas adjacent to intensive agricultural and urbanized zones. Urban expansion contributed higher loads of untreated wastewater, while agricultural runoff introduced excess nutrients and pesticides, both exerting a detrimental impact on the aquatic ecosystem. These findings underscore the urgent need for integrated land use regulation and pollution control measures in the Lake Qarun region to mitigate further environmental degradation.

INTRODUCTION

Water quality is a critical worldwide concern that affects human health, ecosystems, and economic progress. Inferior water quality decreases the availability of drinkable water by diminishing usable supplies, a condition worsened by insufficient wastewater treatment. Eutrophication, salinization, sedimentation, and microbiological and chemical pollution are major environmental issues contributing to global water quality deterioration. These issues have economic implications for health, the environment, water treatment, agriculture, and industry. Emerging pollutants and climate change are expected to worsen existing water quality concerns and generate new challenges, the long-term repercussions of which remain uncertain **(Du Plessis, 2017; Du Plessis, 2019)**.

Water quality is very important, yet it has been ignored across the globe, and there is evidence that it is becoming worse. Numerous countries lack reliable data on water quality, complicating the resolution of these issues **(Biswas & Tortajada, 2019)**. Alterations in land use significantly impact water quality in several regions. Urban development, agriculture, and deforestation are major contributors to water pollution **(Camara & Abdullah, 2019)**. For instance, changes in land use may significantly affect the water quality in Egyptian coastal lakes. Research conducted on Burullus and Manzala lakes demonstrates a notable decrease in water bodies, alongside a rise in agricultural land and fish farming operations **(Negm & Hossen, 2016)**. These changes are mainly due to human activities such as the drainage of agricultural land, the disposal of industrial waste, and the discharge of wastewater from residential sources **(El-behiry *et al.*, 2018)**. The influx of nutrients has led to eutrophication and alterations in phytoplankton community structures. For instance, Lake Edku has transitioned from oligotrophic to eutrophic status **(El-Sheekh & El-Kassas, 2019)**.

Remote sensing and GIS techniques are effective for analyzing the relationship between land use changes and water quality. Research conducted across several watersheds indicates that water quality deteriorates with increased urbanization and intensive agricultural practices, whereas it improves with enhanced vegetation cover. Remote sensing methodologies are effective for monitoring these changes, and supervised classification techniques provide encouraging outcomes. The degradation of vital ecosystems significantly impairs fish production, hinders biodiversity conservation, and undermines local economies. This underscores the significance of enhancing management practices and maintaining oversight **(Negm & Hossen, 2016; Elbehiry *et al.*, 2018; El-Sheekh & El-Kassas, 2019; Abd El-sadek & Negm, 2022; Shafii *et al.*, 2024)**.

GIS based research has revealed strong spatial relationships between land use categories and various water quality indicators, with notable associations between metropolitan areas and elevated pollution levels. The integration of remote sensing data, GIS, and water quality metrics facilitates efficient temporal assessments of land use changes and their impacts on water quality. Models employing export coefficients within GIS frameworks have proven effective in estimating and retrospectively assessing changes in water quality based on historical land use data. These approaches offer valuable tools for watershed management, pollution control, and informed future development planning **(Mattikalli & Richards, 1996; Yunus *et al.*, 2003; Chen *et al.*, 2020; Maurya *et al.*, 2021; Khaled *et al.*, 2025)**.

While research on the relationship between land use and water quality is expanding, significant knowledge gaps remain, particularly in arid and semi arid regions such as

North Africa. Most existing studies focus on temperate or tropical regions, where hydrological dynamics and pollution patterns differ markedly from those in desert ecosystems. Few studies have adopted an integrated approach combining remote sensing, GIS based analysis, and water quality index (WQI) modeling within a single framework. Prior research has often concentrated solely on land use analysis or on water quality modeling without incorporating spatial context **(Tong & Chen, 2002; Giri & Qiu, 2016; Punja *et al.*, 2024)**. Consequently, spatially explicit assessments quantifying the impact of LULC changes on surface water quality—particularly in endorheic lake systems such as Lake Qarun—remain scarce.

Lake Qarun, situated in Egypt's Fayoum Depression, represents an important case study for research on water quality and land change. The water quality of Lake Qarun has deteriorated significantly due to agricultural and domestic wastewater inputs contrasting with the River Nile **(Gawad *et al.*, 2022)**. The closed saline lake experiences agricultural and municipal drainage, resulting in increased levels of solids, nutrients, pesticides, and heavy metals **(Fathi & Flower, 2005; Abdel Wahed, 2015; Khalifa *et al.*, 2025b)**. The water chemistry of the lake shifts from Ca Mg HCO_3 in the headwaters to Na Cl SO_4 within the lake, due to the dissolution of soluble salts and the process of evaporative concentration **(Abdel Wahed, 2015)**. Salinity increases from east to west and is higher in summer, with an annual increase of 0.07% **(Abd Ellah, 2009)**. These studies highlight the importance of Lake Qarun for understanding water quality dynamics and land use impacts in arid environments, making it a valuable site for ongoing research and monitoring efforts.

This study enhances previous literature by presenting a unique, integrated technique to analyze the spatial interaction between land use changes and water quality dynamics in a susceptible lake system. This research employs remote sensing and GIS based Water Quality Index (WQI) modeling to provide a comprehensive and reproducible framework for managing water resources in arid and semi arid environments. Lake Qarun, which has seen considerable ecological decline in recent decades, illustrates the aggregate effects of anthropogenic pressures on aquatic ecosystems.

This research evaluates the effects of land use and land cover (LULC) alterations on the water quality of Lake Qarun, Egypt, utilizing remote sensing, geographic information systems (GIS), and Water Quality Index (WQI) modeling, and integrates spatial analytic tools with field collected water quality data to elucidate the impact of human activities on lake ecosystems in arid and semi arid regions. The study also encompasses the analysis of alterations in essential physicochemical water quality indicators, the detection and mapping of temporal land use and land cover changes using satellite imagery, and the computation of water quality index values to assess the ecological condition of the lake. The research investigates the geographical connections between land use trends and water quality degradation to identify critical areas impacted by pollution. The findings are anticipated to provide evidence based recommendations for the sustainable management of land and water resources in the Lake Qarun basin.

MATERIALS AND METHODS

1. Study area

Lake Qarun is a prominent natural landmark in the El Fayoum Oasis, a depression located in the Western Desert adjacent to the Nile River, within the Fayoum Governorate of Egypt. The lake is saline and lies approximately 44 meters below sea level. It receives drainage water from the El Fayoum Depression and has no surface water outflow. The surrounding area is predominantly agricultural, with the Bahr Yusef Canal supplying water from the Nile **(Kotb & El Semary, 2017)**. Various factors, including wastewater discharge and agricultural runoff, affect the lake's water quality and overall ecosystem health.

The geographical coordinates of the lake are between longitudes 30º 24′ and 30º 49′ E, and latitudes 29º 24′ and 29º 33′ N **(Ibrahim & Ramzy, 2013)** (Fig. 1). The lake's water originates primarily from agricultural drainage in the El Fayoum province. Being a landlocked water body, it is isolated from any marine connection and maintains a high salt content. El Qurn Golden Island, covering about 1.5 km^2, lies in the middle of Lake Qarun. This island is an important tourist destination and serves as a safe nesting habitat for wetland birds, offering protection from land-based predators. Owing to its ecological significance, Lake Qarun was declared a natural reserve in 1989 **(El-Sayed *et al.*, 2015)**.

The arid climate of the El Fayoum Depression leads to substantial evaporation from the lake's surface **(Hassan, 2018)**. Annual water loss due to evaporation is estimated at 414.5×10^6 m^3 **(Flower *et al.*, 2006)**. Rainfall in the area is infrequent during winter months. These conditions contribute to increasing salinity levels, which present a major challenge to the lake's ecological balance and biological communities **(Fathi & Flower, 2005)**.

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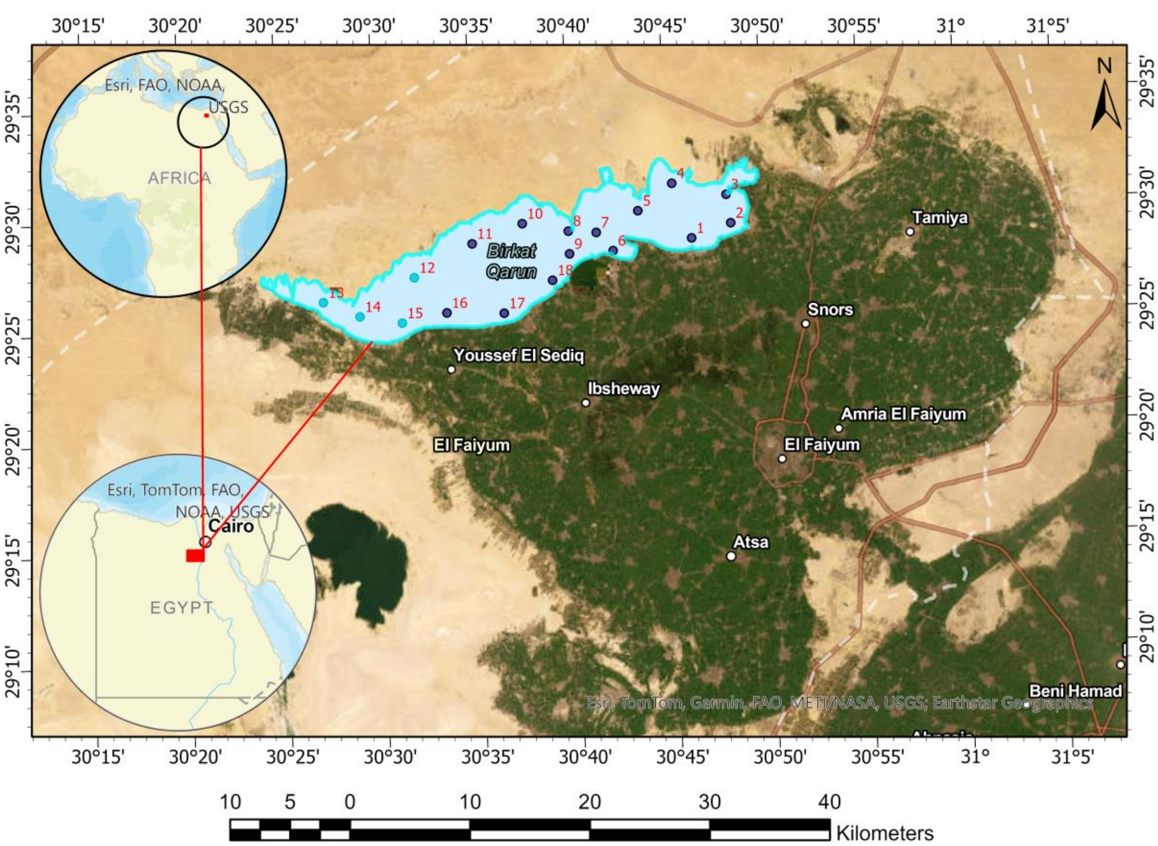

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Fig. 1. Location map of the study area in Lake Qarun, Egypt, showing water sampling sites and surrounding land use types

2. Data collection and sources

This study utilized both primary and secondary data sources to assess the impacts of land use and land cover (LULC) changes on the water quality of Lake Qarun. The collected datasets were categorized into three main groups: (1) satellite imagery, (2) field-based water quality measurements, and (3) ancillary spatial data, including land use/land cover classifications. These datasets supported multiple analytical procedures, such as satellite image processing, accuracy assessment, WQI computation, spatial interpolation, and statistical analyses, which are described in the following sections.

3. Satellite image processing

To detect LULC changes in the Lake Qarun study area, multi-temporal satellite imagery (Table 1) was acquired from multiple sources. Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI images were obtained from the US Geological Survey (USGS) Earth Explorer, while Sentinel-2A MSI images were sourced from the Copernicus Open Access Hub. These datasets were used to evaluate spatial and temporal variations in human activities and their potential impacts on water quality in Lake Qarun. Image selection criteria included minimal cloud cover and seasonal consistency—preferably during dry season months—to ensure accurate interannual comparisons.

Table 1. Satellite images used for LULC analysis in Lake Qarun (1985–2023)

ID	Year	Satellite Sensor	Spatial Resolution	Source / Platform
1	1985	Landsat 5 TM	30 m	USGS Earth Explorer
2	1990	Landsat 5 TM	30 m	USGS Earth Explorer
3	1995	Landsat 5 TM	30 m	USGS Earth Explorer
4	2000	Landsat 7 ETM^+	30 m (15 m PAN)	USGS Earth Explorer
5	2005	Landsat 5 TM	30 m	USGS Earth Explorer
6	2010	Landsat 5 TM	30 m	USGS Earth Explorer
7	2015	Landsat 8 OLI	30 m	USGS Earth Explorer
8	2023	Sentinel-2 MSI	10 m	Copernicus Open Access Hub

Note: All satellite images were selected based on minimal cloud cover (<10%) and seasonal consistency, preferably acquired during the dry season (June–August), to ensure accurate temporal comparison and reduce phenological variability.

4. Image classification and accuracy assessment

Several stages of preprocessing and image enhancement were applied to the raw satellite data to prepare them for analysis. These steps are essential for improving image quality by reducing geometric, radiometric, and atmospheric errors caused by internal and external conditions during image acquisition **(Teillet, 1986)**. For each acquisition date, multispectral bands were stacked to create composite images using ENVI (v.5.3) software, enabling visualization of vegetation, water bodies, and urban areas. To simplify analysis, improve accuracy, and reduce processing time, the images were clipped to the boundary of the study area, thereby removing data outside the area of interest and decreasing file size.

Image classification was used to categorize pixels into land cover classes based on their spectral signatures. Multispectral images were analyzed to differentiate vegetation, water bodies, barren lands, and urban areas, with each pixel's signature determined by its reflectance across various bands. Image classification is a crucial step in producing land cover thematic maps and enhancing data interpretation. Unsupervised and supervised classification are the two most commonly applied methods **(Lillesand *et al.*, 2000)**.

In this study, supervised classification was performed using the Maximum Likelihood Classifier (MLC) to extract LULC classes. Training samples were selected based on field observations, visual interpretation, and historical Google Earth imagery. The LULC classes included agricultural land, urban areas, saline flats, water bodies, and bare soil. Classification accuracy was evaluated using 200 ground truth points obtained from a combination of field GPS surveys and high-resolution imagery. These reference points were stratified across all major LULC classes to ensure balanced representation.

Classification performance was validated using a confusion matrix and Kappa statistics, achieving overall accuracies exceeding 85% for all years analyzed. ENVI 5.3 software was used to classify the images and generate cartographic representations of the LULC maps. Post-classification refinement was applied to further improve classification accuracy **(Lillesand & Kiefer, 1987; Campbell, 2002)**.

5. Water sampling and laboratory analysis

In July 2023, a Eureka Manta2 multiprobe system (Eureka Environmental Engineering, USA) was used in the field to measure water quality parameters, including temperature, pH, electrical conductivity (EC), dissolved organic matter (DOM), and turbidity. Duplicate surface water samples (0–30 cm depth) were collected from 18 representative sites across the study area (Fig. 1) following a stratified random sampling design. This approach ensured adequate spatial coverage while accounting for variations in land use zones and proximity to potential pollution sources.

Samples for heavy metal analysis (Pb, Cd, Ni, and Cr) were collected in sterile Falcon tubes and analyzed using Atomic Absorption Spectroscopy (BUCK Scientific 230ATS, USA). The geographic coordinates of each sampling point were recorded with a handheld GPS (±2 m accuracy). All samples were labeled, stored in iced coolers, and transported to the laboratory under refrigerated conditions.

This dataset builds on and extends water quality records from **Khalifa *et al.* (2023)**, ensuring continuity and validation across sampling periods. The updated dataset includes core physicochemical variables (pH, temperature, heavy metals) as well as additional parameters such as turbidity, EC, and DOM.

Spatial interpolation was performed using the Inverse Distance Weighted (IDW) method in ArcGIS (v.10.7.1) to create continuous distribution maps of water quality parameters across Lake Qarun. This geostatistical approach estimates values at unsampled locations based on nearby measurements, giving greater weight to closer points. IDW interpolation was applied to turbidity, DOM, and salinity data collected during the field surveys, enabling the visualization of spatial trends and identification of potential contamination hotspots.

6. Water quality index (WQI) computation

The Water Quality Index (WQI) is a widely used tool for evaluating and communicating overall water quality by integrating multiple individual water quality parameters into a single value **(Al-Mohammed & Mutasher, 2013)**. Originally developed by **Brown *et al.* (1972)**, the WQI has been extensively applied in water quality studies **(Puri *et al.*, 2011; Pal *et al.*, 2013; Das Kangabam *et al.*, 2017)**. It provides a comprehensive measure of water quality, aiding in pollution assessment, source identification, and management decision-making **(Abu-Ghamja *et al.*, 2018)**.

For Lake Qarun, nine parameters were used in the WQI computation: pH, turbidity, EC, DOM, temperature, Pb, Ni, Cd, and Cr. Measurements for these parameters were collected from the 18 sampling sites across the lake. The resulting WQI values were used to assess the lake's ecological condition and to examine spatial relationships between water quality degradation and LULC changes.
The mathematical formula of this WQI method is given by:

$$\boldsymbol{WQI} = \frac{\sum_{i=1}^{n} QiWi}{\sum_{i=1}^{n} Wi}$$

Where, Qi is the sub-quality index of the i^{th} parameter (or Qi is the quality rating scale of each parameter). W: weight unit of each parameter, n: number of parameters.
Calculation of Qi value:

$$\boldsymbol{Q_i} = \frac{Ci - Co}{Si - Co} \times \mathbf{100}$$

C_i = measured value of an i^{th} parameter, Si = standard permissible value of an i^{th} parameter, C_o =ideal value of an i^{th} parameter in pure water, C_o = ideal value for all parameters except for pH = 7.0 **(Tripathy & Sahu, 2005)**.

Calculation of W_i value

The computation of unit weight (W_i) for different water quality parameters exhibits an inverse relationship with the suggested standards for the respective parameters.

$$W_i \propto 1/S_i \ \& \ W_i = K/S_i$$

The proportionality constant referred to by K is employed to determine the 'weights' associated with distinct water quality characteristics.

$$K = 1/\sum_{i=1}^{n} 1/Si$$

WQI has been classified into 5 classes; the classification scheme used to interpret WQI results (e.g., excellent, good, or poor water quality) as demonstrated by **Brown *et al.* (1972)**, is depicted in Table (2).

Table 2. Classification of water quality index (WQI) and corresponding water quality rating (WQR)

WQI Value	WQR	Water Quality Grading
0-25	Excellent	A
25-50	Good	B
51-75	Poor	C
76-100	Very Poor	D
>100	Unsuitable for aquatic life	E

7. Statistical and geospatial analysis

The relationship between the Water Quality Index (WQI) and other water quality parameters in Lake Qarun was examined using a combination of statistical analyses. Descriptive statistics, including mean, standard deviation, minimum, and maximum values, were first calculated. Pearson's correlation analysis was then applied to evaluate linear relationships between WQI, turbidity, dissolved organic matter (DOM), and selected heavy metals. These analyses were conducted using Microsoft Excel 365 and IBM SPSS Statistics (v.26). Statistical significance was evaluated at two thresholds: $P < 0.05$ and $P < 0.01$ (two-tailed). This approach provided insights into the extent to which individual parameters contribute to the overall degradation of lake water quality.

In parallel, spatial analysis was performed using ArcGIS Spatial Analyst (v.10.7.1). Interpolation techniques were applied to model spatially referenced data and to address missing values for heavy metal pollution indices. The inverse distance weighted (IDW) interpolation method was used to generate continuous spatial distribution maps, allowing visualization of spatial patterns and identification of pollution hotspots across the lake.

RESULTS AND DISCUSSION

1. Land use/land cover (LULC) analysis

Remote sensing and geographical information systems (GIS) are highly effective tools for obtaining accurate and timely information on the spatial distribution of land use/land cover (LULC) changes over large areas. Based on the supervised classification of calibrated Landsat imagery, a current LULC map was produced. The Maximum Likelihood Classifier (MLC) has been widely applied in supervised classification of remotely sensed data to produce LULC maps **(Fan *et al.*, 2007; Reis, 2008)**.

According to the 2023 LULC map (Fig. 3), five categories were identified in the study area: agricultural land, urban areas, barren land, water bodies, and drains. Barren land was the most extensive type, covering 3,579.33 km². Agricultural land occupied 1,303.92 km², making it the second most abundant class. Urban areas covered 257.45 km², while water bodies spanned approximately 240 km². Lake Qarun receives inflows primarily from the El-Batts and El-Wadi drainage systems, along with contributions from

12 smaller drainage networks located in its southern catchment. El-Batts has a drainage length of approximately 50.9 km, while El-Wadi measures around 48.5 km.

The lake is surrounded by fragmented urban, residential, and industrial zones (Fig. 4). Differentiating between residential and industrial areas provided valuable insights into potential pollution sources, especially in locations with elevated heavy metal concentrations and degraded physicochemical parameters. While the northern region exhibits minimal diversity in land use and pollution sources, other parts of the lake are heavily influenced by effluents from urban, industrial, and agricultural activities. The Kom Oshim industrial zone lies east of the El-Batts drain, while the Emisal salt production facility is situated east of the El-Wadi drain (Fig. 5). The southern and eastern shores of the lake are predominantly agricultural and urban.

The LULC analysis for the period 1985–2023 (Table 3; Figs. 2, 7) revealed substantial spatial and temporal transformations, especially in agricultural, urban, and water body classes. Satellite classification results indicated continuous urban expansion, likely driven by population growth and unregulated development along the lake's margins. Agricultural land exhibited periods of both expansion and contraction, influenced by irrigation practices, land reclamation efforts, and economic conditions.

Urban areas increased steadily, particularly along the eastern and southern boundaries (Figs. 6, 7), replacing agricultural lands and encroaching upon ecologically sensitive zones. To refine the analysis, built-up areas were further subdivided into residential and industrial zones using high-resolution satellite imagery and visual interpretation. Agricultural expansion was evident during 1990–1995 due to reclamation and intensification, but some areas later declined, potentially because of urban encroachment, soil degradation, or limited irrigation water. Contrary to common regional patterns of water body shrinkage, Lake Qarun's surface area increased between 2000 and 2023, likely due to the sustained inflow of agricultural drainage and untreated wastewater. Overall, the LULC changes reflect strong anthropogenic pressures with direct implications for hydrology, water quality, and ecosystem health.

These findings align with previous research highlighting the adverse effects of urbanization and agricultural expansion on freshwater systems. In China's Erhai Lake Basin, forest and grassland were negatively correlated with water pollution, whereas built-up areas worsened water quality **(Wang *et al.*, 2020)**. In the Chaohu Lake Basin, landscape diversity also showed a negative relationship with water quality indicators **(Huang *et al.*, 2013)**. In Egypt, remote sensing and GIS have been applied to assess the impacts of LULC changes on water quality. For example, **(Azab, 2012)** integrated hydrodynamic models with GIS for water quality management in complex watersheds. Satellite imagery analyses have documented reductions in water bodies and floating vegetation, along with increases in agricultural areas and fish farms **(Abd El-sadek & Negm, 2022)**. Water quality assessments using statistical models, WQI, and trophic status indices have classified some lakes as "Very Poor" and "Hyper-Eutrophic," indicating an urgent need for recovery plans **(Mohsen *et al.*, 2023)**. Furthermore, spatial mapping of water properties, eutrophication indicators, and heavy metals has been used to monitor ecological changes in lakes **(Ahmed, 2023)**. These examples demonstrate the value of remote sensing and GIS for evaluating and managing Egyptian lakes impacted by anthropogenic activities.

Table 3. Quantitative results of area changes in each LULC category (1985–2023)

Years	Agriculture	Urban	Water body
1985	1414.11	45.76	229.35
1990	1344.182	87.5	238.07
1995	1412.3	91.7	233.11
2000	1381.85	96.69	235.58
2005	1397.95	112.7	240.51
2010	1287.88	146.34	243.55
2015	1331.1	231.5	236.02
2023	1303.92	257.45	241.26

Note: All areas are in km², and values were filled based on results classified LULC maps from satellite imagery.

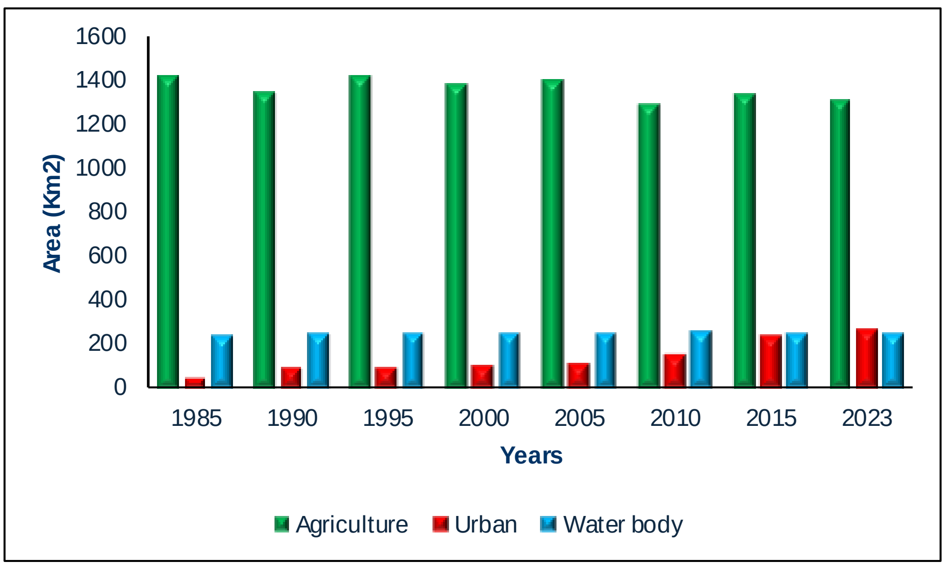

Fig. 2. Quantitative analysis of land use/land cover (LULC) area changes in Lake Qarun and its surroundings from 1985 to 2023. The figure illustrates the temporal dynamics and transformations across major LULC categories, highlighting trends in urban expansion, agricultural development, and changes in water surface area

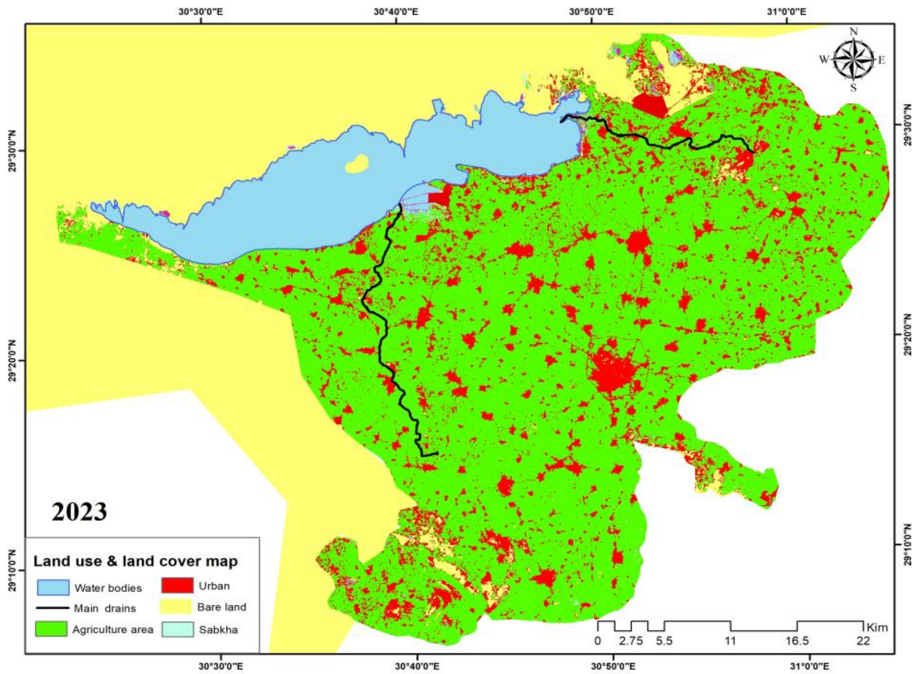

Fig. 3. Land use and land cover (LULC) map of the study area in 2023, illustrating major land use categories

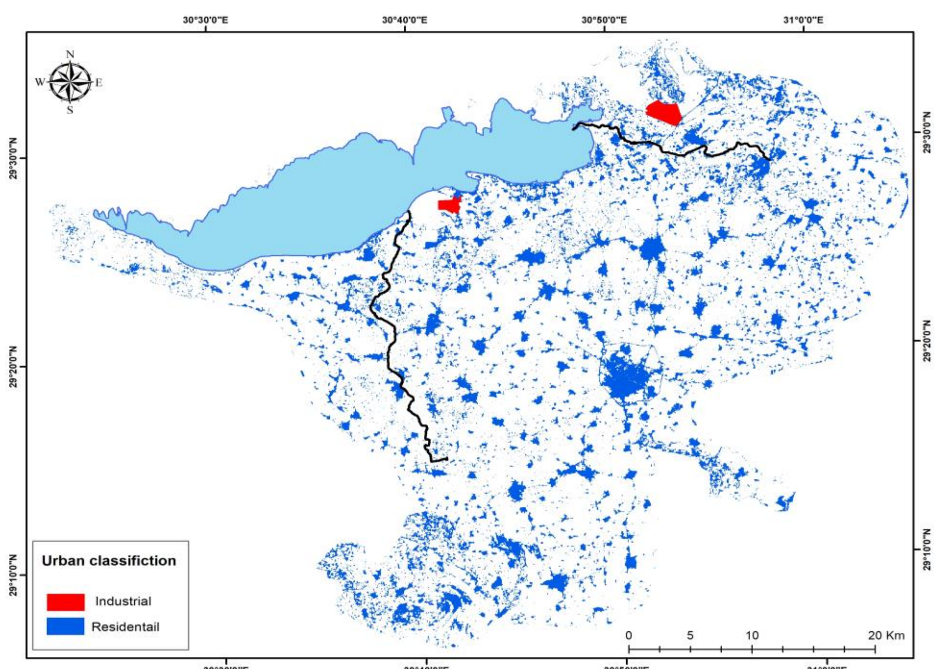

Fig. 4. Urban land use classification map distinguishing between industrial and residential areas within the study region

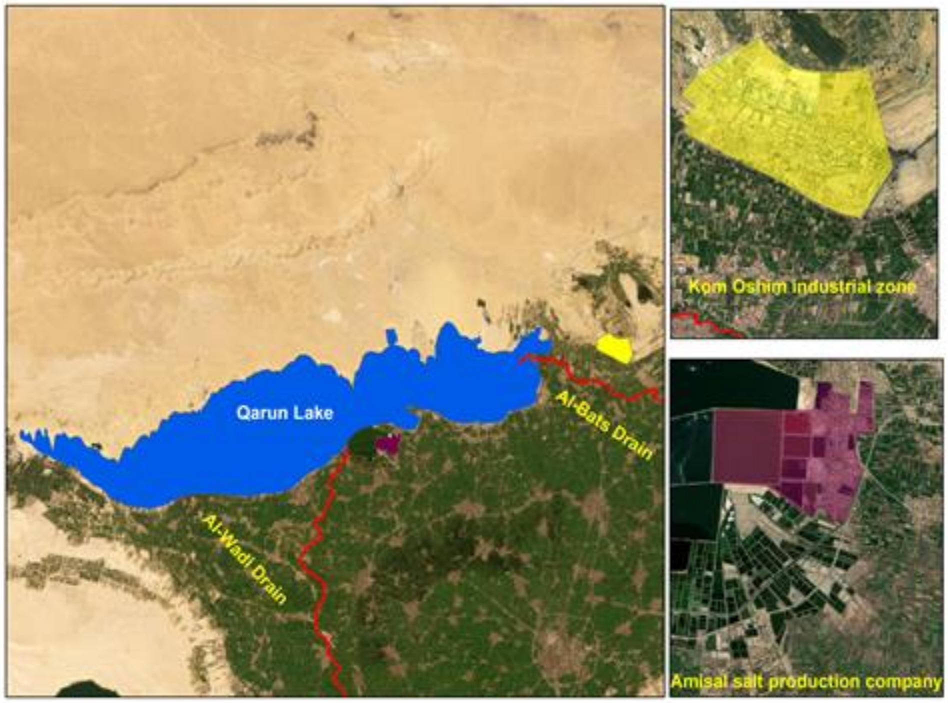

Fig. 5. A map for El-Fayoum area showing the spatial distribution of industrial regions surrounding Lake Qarun

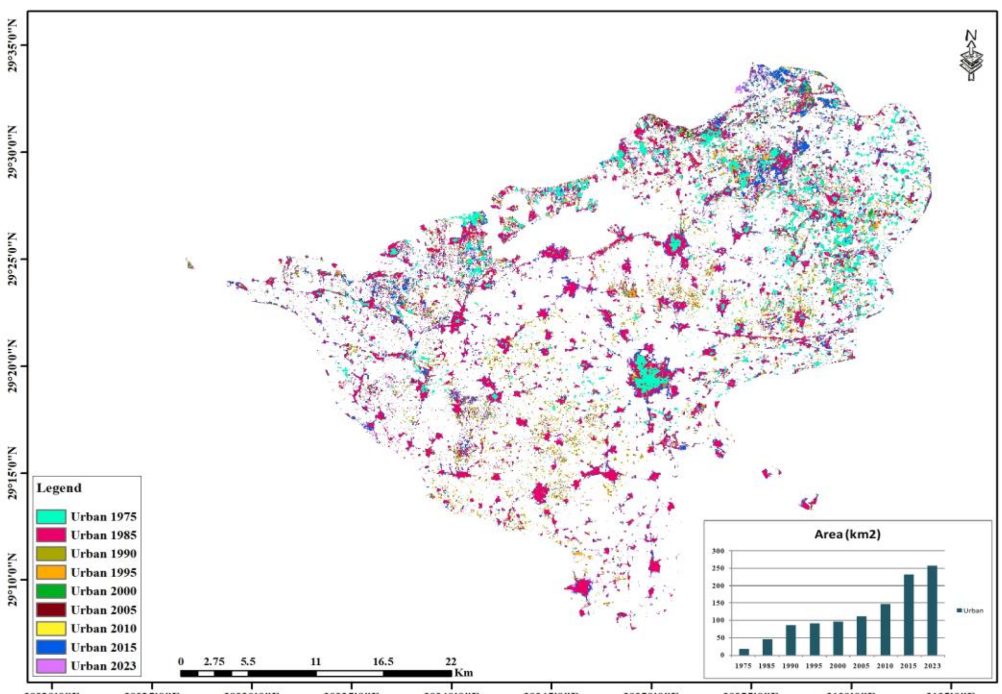

Fig. 6. Changes in urban areas in the Lake Qarun region between 1975 and 2020, showing significant expansion patterns over time

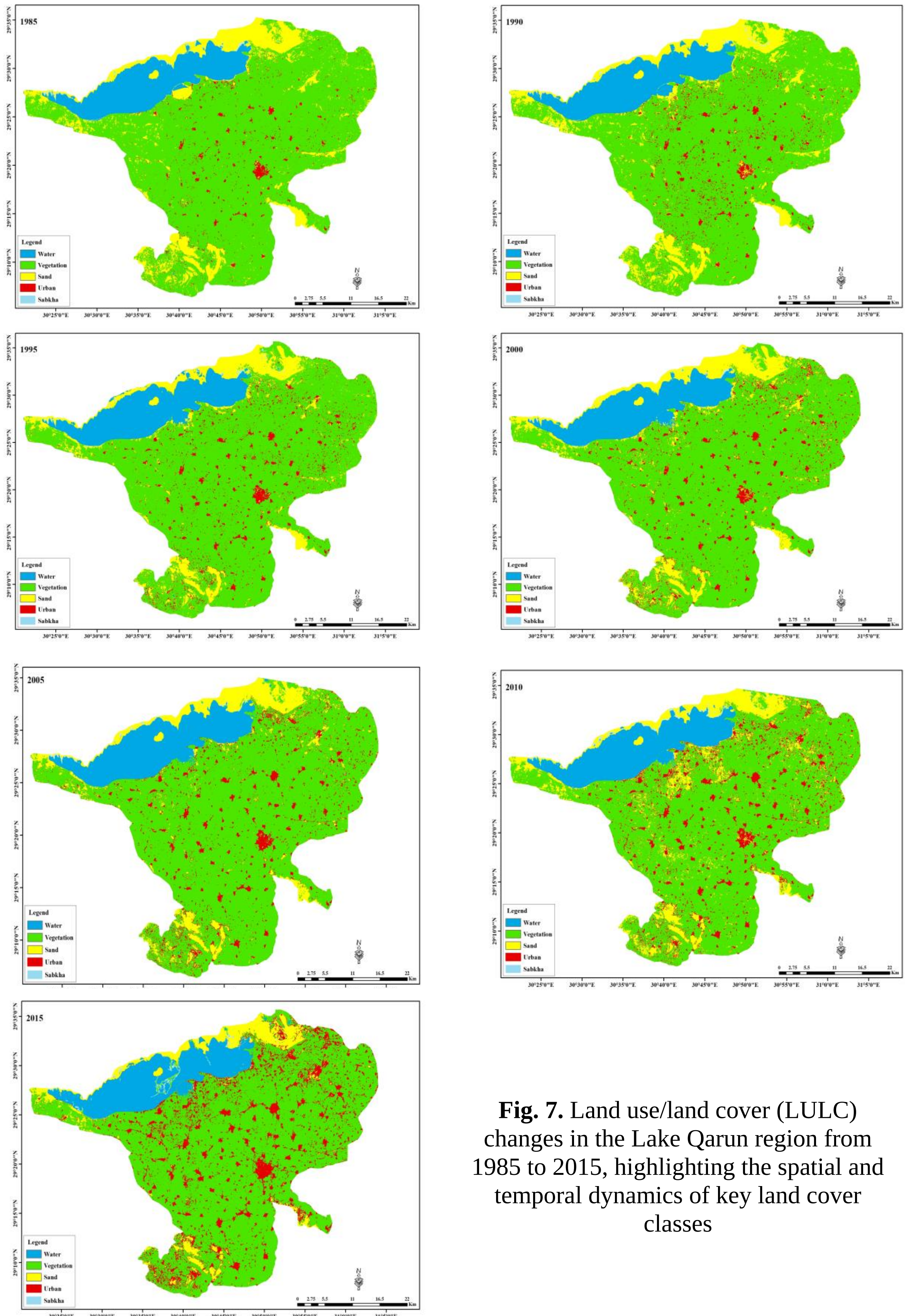

Fig. 7. Land use/land cover (LULC) changes in the Lake Qarun region from 1985 to 2015, highlighting the spatial and temporal dynamics of key land cover classes

2. Assessment of physicochemical and heavy metal parameters in Lake Qarun

This section presents the spatial and temporal variations in physicochemical parameters—temperature, pH, electrical conductivity (EC), turbidity, dissolved organic matter (DOM)—and heavy metals (Pb, Cd, Ni, Cr) measured at multiple sampling stations across Lake Qarun. Results are compared to national and international water quality standards, with trends interpreted in relation to anthropogenic activities and land use patterns.

The pH exhibited a moderately alkaline trend, ranging from 7.5 to 8.9 with a mean of 8.25. Turbidity ranged from 9.2 to 57.8 NTU, with an average of 33.1 NTU (Fig. 8). The maximum value (57.8 NTU) occurred near the El-Batts drain, consistent with **Fishar *et al.* (2005)**. According to **EPA (2017)**, Lake Qarun is highly turbid, as it exceeds the threshold of 5 NTU. Elevated turbidity is often associated with increased sediment runoff, untreated sewage, industrial effluents, and higher concentrations of pathogenic microorganisms **(Kistemann *et al.*, 2002)**.

Electrical conductivity (EC) ranged from 16.9 to 57.5 mS/cm, with a mean of 37.2 mS/cm (Fig. 10). Salinity was highest in the western part of the lake, with maximum EC (57.3 mS/cm) recorded at the western end and minimum EC (16.9 mS/cm) in front of the El-Batts drain. Stations opposite the El-Batts and El-Wadi drains exhibited lower EC values due to the dilution effect of incoming drainage water. Freshwater inflow from the El-Batts drain reduces salinity in the eastern sector, which increases westward due to evaporation and wastewater accumulation. A very strong negative correlation was found between turbidity and EC ($r = -0.90$, $P < 0.01$), consistent with **(Goher *et al.*, 2018)**.

Water temperature ranged from 19.3 to 22.0 °C, with a mean of 20.6°C. DOM concentrations varied from 1.54 to 4.53 mg/L, averaging 3.82 mg/L (Fig. 9). Values exceeding the **WHO (2011)** guideline of 2 mg/L were recorded, particularly near the El-Wadi and El-Batts drains, reflecting inputs from domestic and agricultural sources. DOM originates from the partial decomposition of organic materials such as soil humus, plant residues, and soluble biogenic particles from bacteria, algae, and macrophytes.

DOM was strongly and negatively correlated with turbidity ($r = -0.88$, $P < 0.01$), likely due to DOM oxidation by bacteria attached to suspended sediments and adsorption of DOM onto particulate matter. Significant positive correlations were observed between DOM and Ni ($r = 0.82$, $P < 0.01$), Pb ($r = 0.78$, $P < 0.01$), and Cd ($r = 0.78$, $P < 0.01$). This is consistent with the role of DOM in heavy metal migration from municipal solid waste leachates and its ability to adsorb onto metal surfaces or coat mineral particles **(Rubio *et al.*, 2000)**.

A very strong positive correlation between DOM and EC ($r = 0.84$, $P < 0.01$) suggests interactions between organic residues and dissolved salts that generate HCO_3^- and HS^- (Eq. 1). HS^- subsequently reacts with metals to produce metal sulfides (Eq. 2), explaining the positive correlation between DOM and pH (r = 0.61, $P < 0.01$) **(Jong & Parry, 2003)**.

$$SO_4^{2-} + \text{Organic matter} \longrightarrow HS^- + HCO_3^- \qquad (1)$$
$$HS^- + M^{2+} \longrightarrow MS^+ + H^+ \qquad (2)$$

The surface water of Lake Qarun was analyzed for four toxic heavy metals (Pb, Ni, Cd, and Cr), with all measurements conducted in triplicate; mean values are shown in Fig. 11. Concentrations of Pb, Ni, and Cd exceeded the **APHA (2017)** threshold limits for the protection of aquatic life, whereas Cr remained below permissible limits. Elevated Cd, Pb, and Ni levels in certain locations are likely due to industrial effluents, urban runoff, and weathering of surrounding geological formations. Such concentrations present risks of bioaccumulation in aquatic organisms and may pose health hazards to humans consuming fish from the lake **(Khalifa *et al.*, 2025a)**.

Heavy metal concentrations increased from east to west across the lake, likely driven by water circulation patterns moving from the southeastern to the northwestern basin. This directional flow, from higher- to lower-density water, facilitates the accumulation of metals—an observation consistent with earlier studies on Lake Qarun **(Goher *et al.*, 2018; El-Zeiny & Effat, 2019)**.

Strong positive correlations were found between EC and Pb (r = 0.91, $P < 0.01$), Cd (r = 0.95, $P < 0.01$), and Ni (r = 0.90, $P < 0.01$). These relationships suggest that increasing salinity, via the accumulation of salts such as $CaCl_2$, $MgCl_2$, NaCl, and Na_2SO_4, enhances heavy metal mobilization into high-salinity zones. This process is likely driven by competition between Pb, Ni, and Cd with Ca^{2+} and Mg^{2+} for sorption sites, followed by metal chloro-complexation **(Acosta *et al.*, 2011)**.

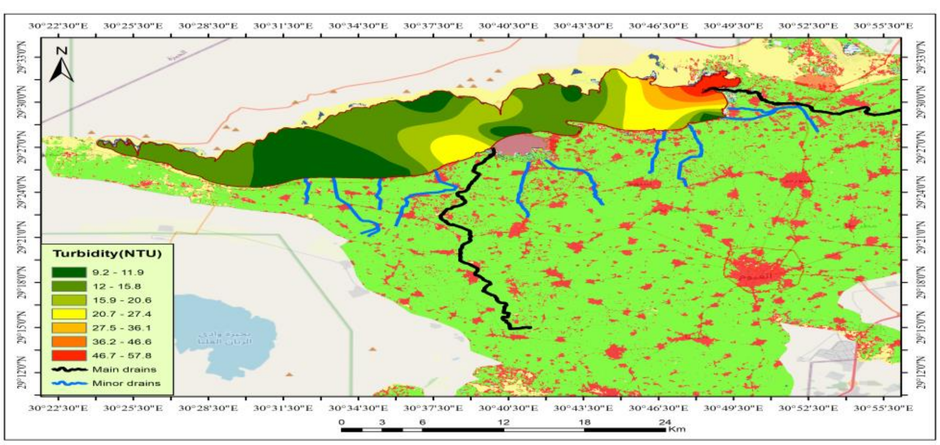

Fig. 8. Spatial distribution of turbidity levels in the surface water of Lake Qarun, overlaid with land use/land cover (LULC) data to illustrate the influence of surrounding land use patterns on water quality

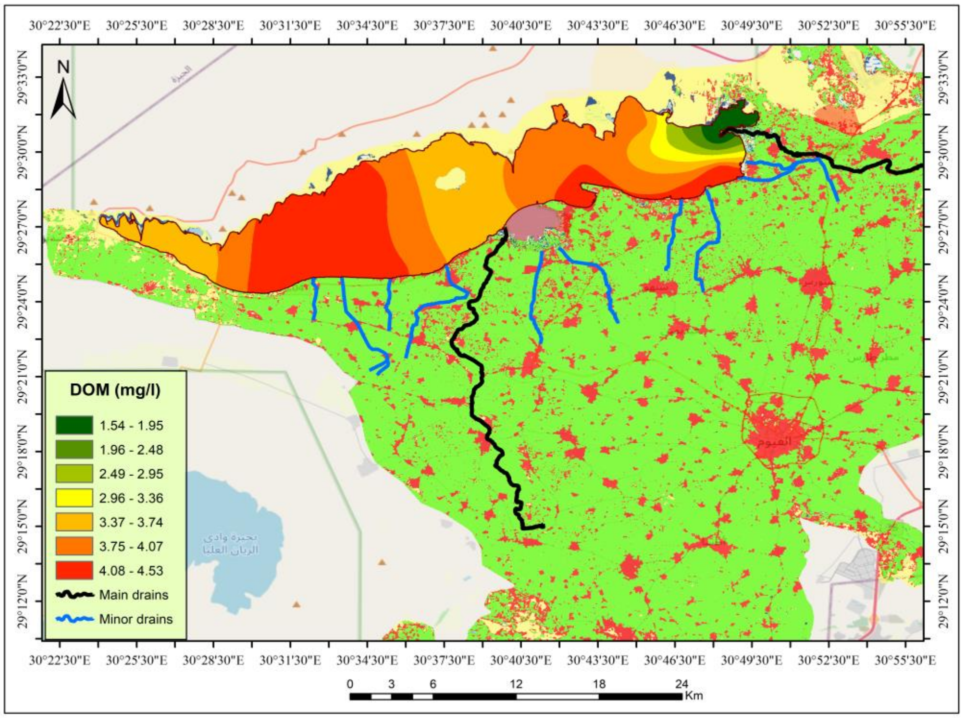

Fig. 9. Spatial distribution of dissolved organic matter (DOM) levels in the surface water of Lake Qarun, overlaid with land use/land cover (LULC) data to illustrate the influence of surrounding land use patterns on water quality

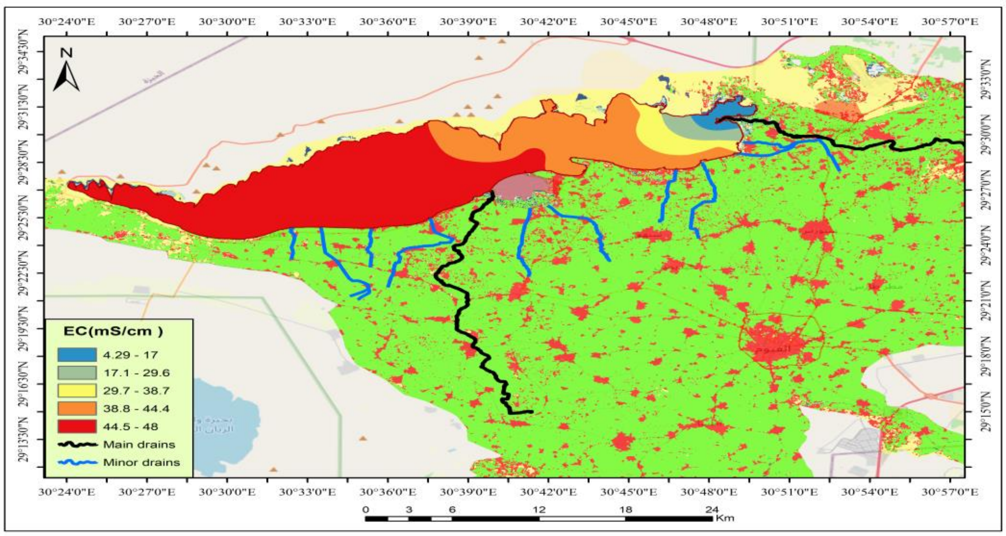

Fig. 10. Spatial distribution of electrical conductivity (EC) levels in the surface water of Lake Qarun, overlaid with land use/land cover (LULC) data to illustrate the influence of surrounding land use patterns on water quality. Elevated EC values are associated with urban, agricultural, and industrial activities in the lake's vicinity

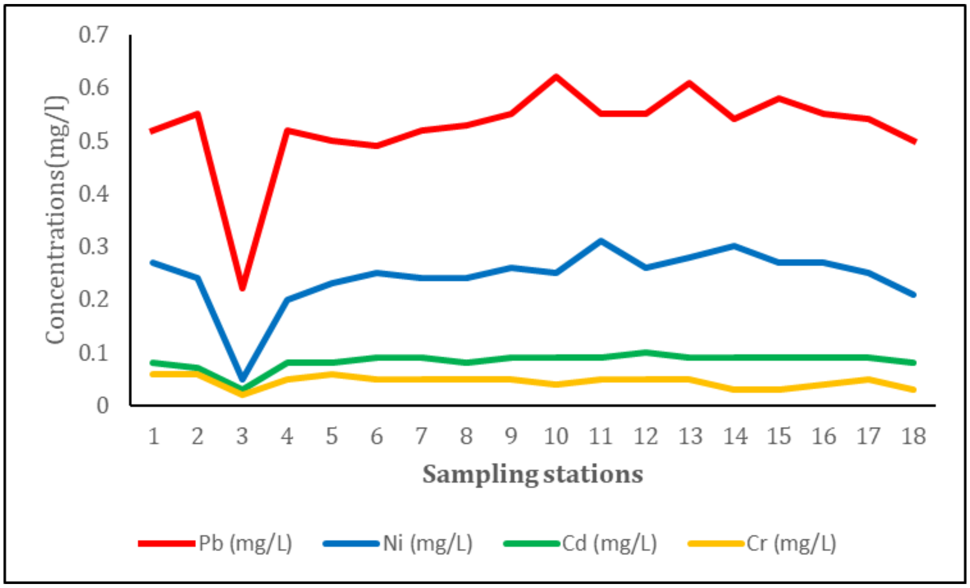

Fig. 11. Concentrations of selected heavy metals in surface water samples collected from various locations in Lake Qarun

3. Water quality index (WQI) assessment

The results of this study show that Water Quality Index (WQI) values in Lake Qarun ranged from 84.33 to 305.53. The calculated mean WQI value was 267.58, classifying the lake's water as *unfit* for the protection of aquatic life. The WQI values and corresponding water quality status are summarized in Table (4) and illustrated in Figs. (12) and (13). WQI computation followed the guidelines of the **WHO (2011)** and **EPA (2017)**. Overall, the findings confirm that water pollution in Lake Qarun has significant negative implications for both water use and ecosystem integrity.

A strong positive correlation was observed between WQI and pollutants such as Pb, Ni, Cd, EC, turbidity, and DOM (Table 5), indicating that increases in these parameters are directly associated with declining water quality. These results highlight the critical role of heavy metals, salinity, turbidity, and organic contamination in the degradation of the lake's water quality. The spatial distribution of WQI values aligns closely with the location of terrestrial pollution sources and human activities, emphasizing the influence of watershed-scale processes.

The variation in water quality across the lake underscores the value of the WQI methodology in integrating multiple parameters into a single, coherent index, thereby providing a clear and comprehensive assessment of overall ecological health. These findings reinforce the need for integrated watershed management, targeted pollution control, and ongoing monitoring programs to protect Lake Qarun's aquatic ecosystem.

Table 4. Water quality index (WQI) values and corresponding water quality status at different sampling locations in Lake Qarun

Stations	WQI	WQ Status
1	271.05	Unsuitable for aquatic life
2	243.21	Unsuitable for aquatic life
3	84.36	Very Poor
4	245.48	Unsuitable for aquatic life
5	255.48	Unsuitable for aquatic life
6	280.7	Unsuitable for aquatic life
7	278.41	Unsuitable for aquatic life
8	260.55	Unsuitable for aquatic life
9	287.14	Unsuitable for aquatic life
10	286.72	Unsuitable for aquatic life
11	305.39	Unsuitable for aquatic life
12	305.53	Unsuitable for aquatic life
13	297.19	Unsuitable for aquatic life
14	301.1899	Unsuitable for aquatic life
15	292.1877	Unsuitable for aquatic life
16	290.7954	Unsuitable for aquatic life
17	282.9705	Unsuitable for aquatic life
18	248.1201	Unsuitable for aquatic life

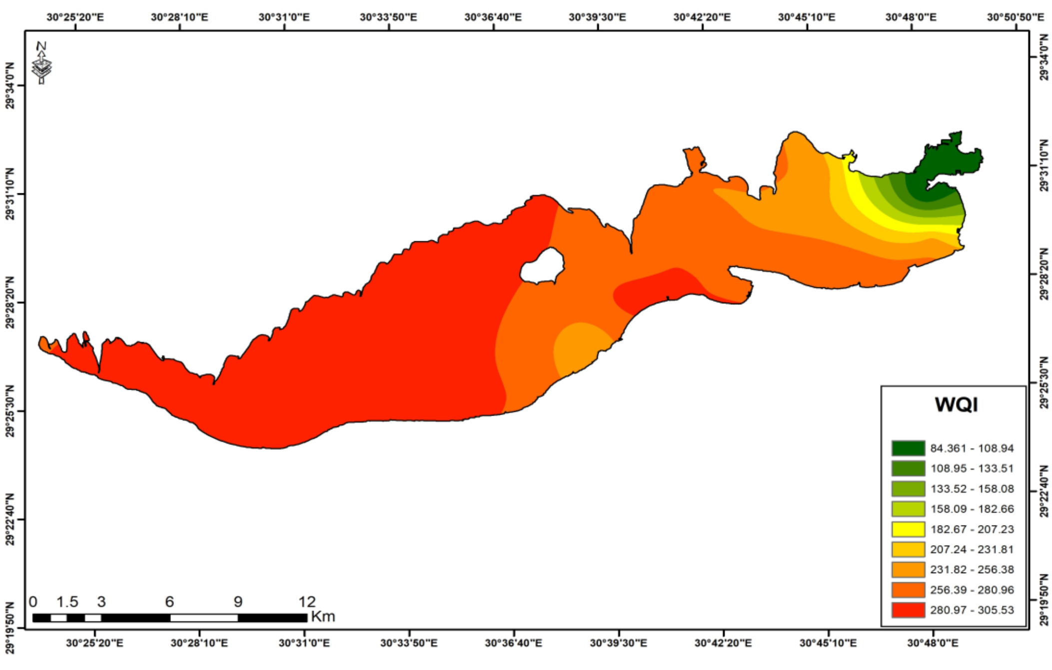

Fig. 12. Water quality index (WQI) distribution across Lake Qarun, illustrating spatial variations in overall water quality status

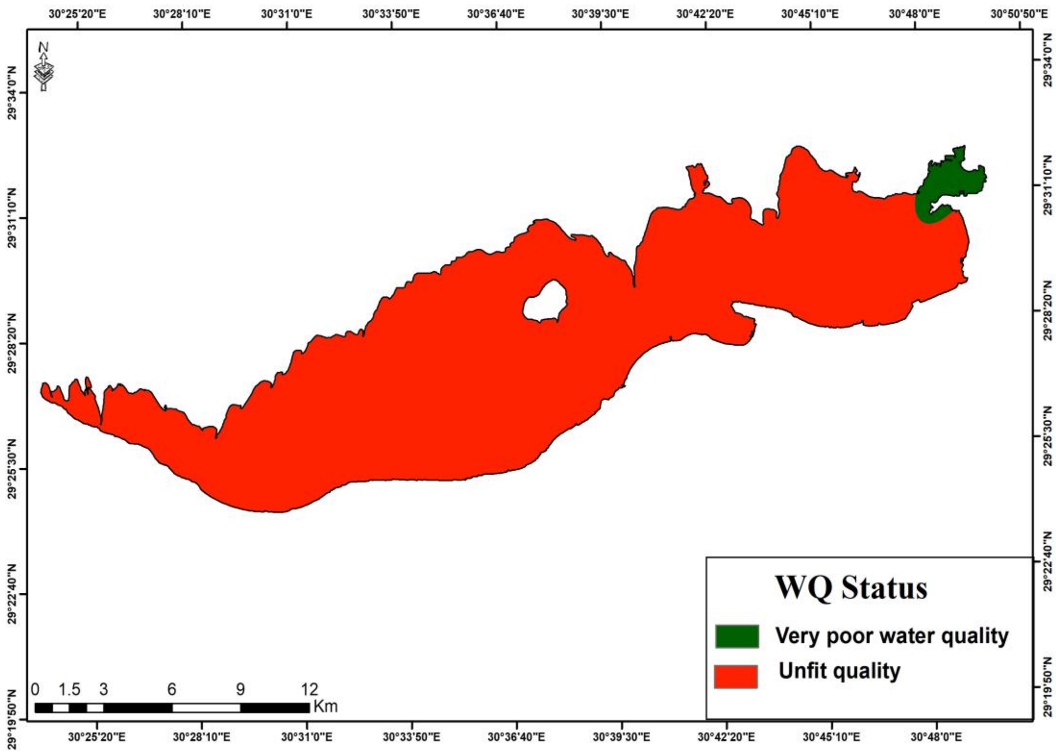

Fig. 13. Spatial distribution of water quality status across Lake Qarun, derived from the Water Quality Index (WQI). The map highlights areas with varying levels of water quality, influenced by surrounding land use activities.

Table 5. Pearson correlation coefficients between the Water Quality Index (WQI) and selected water quality parameters in Lake Qarun.

	WQI	Temperature	pH	EC	Turbidity	DOM	Pb	Ni	Cd	Cr
WQI	1									
Temperature	0.30	1								
pH	0.56*	0.11	1							
EC	0.96**	0.42	0.62**	1						
Turbidity	0.91**	-0.24	-0.56*	-0.90**	1					
DOM	0.82**	0.11	0.61**	0.82**	-0.88**	1				
Pb	0.92**	0.21	0.50*	0.91**	-0.89**	0.78**	1			
Ni	0.96**	0.17	0.46	0.90**	-0.85**	0.82**	0.88**	1		
Cd	0.98**	0.40	0.60**	0.95**	-0.89**	0.78**	0.87**	0.89**	1	
Cr	0.41	-0.26	0.42	0.37	-0.48*	0.59**	0.43	0.42	0.37	1

*Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

4. Impact of land use/land cover on water quality in Lake Qarun

This study evaluated the effects of land use and land cover (LULC) changes on water quality in Lake Qarun through remote sensing mapping and GIS-integrated water quality modeling. LULC maps were generated to identify natural resources, anthropogenic activities, and surrounding environmental factors influencing water quality **(El-Zeiny & El-Kafrawy, 2017)**. These changes are largely driven by poor management of agricultural and urban areas, resulting in serious environmental problems such as water pollution and quality degradation due to effluent discharge and waste disposal **(Paul & Meyer, 2001)**.

Agricultural and industrial sites represent major anthropogenic pollution sources, producing significant environmental impacts **(Reis, 2008; El-Zeiny & El-Kafrawy, 2017)**. Built-up and agricultural lands are strongly associated with both point and non-point sources of pollution. In agricultural zones, large quantities of livestock feces—often used as fertilizer—can contaminate surface water, while fertilizer application increases nutrient loading, potentially enhancing the survival of intestinal bacteria. Industrial operations further compound these risks. For example, the Kom Oshim industrial zone, located east of the El-Batts drain, hosts multiple factories, including the Al-Nasr Company for Intermediate Chemicals, which produces chemicals, insecticides, gases, and pesticides, posing a substantial risk of heavy metal contamination.

The results revealed spatial variability in WQI values across Lake Qarun, with notably poor water quality in areas adjacent to urban and agricultural land uses. This pattern suggests a direct link between human activities—particularly untreated wastewater discharge, agricultural runoff, and saltwater intrusion—and water quality deterioration. Analysis of LULC classifications alongside WQI distribution maps indicated that zones with higher proportions of agricultural and urban land use closely align with areas of poor water quality.

These findings support the hypothesis that LULC changes within the lake's watershed strongly influence spatial variation in water quality. The observed spatial correlations from visual and descriptive GIS analyses are consistent with results from similar lake ecosystems **(Abayazid, 2015; Donia & Farag, 2019; El-Kafrawy & Ahmed, 2020)**.

CONCLUSION

This study employed remote sensing and GIS-based Water Quality Index (WQI) modeling to assess the spatial effects of land use and land cover (LULC) changes on the water quality of Lake Qarun. The analysis revealed marked variation among sampling sites in turbidity, electrical conductivity, dissolved organic matter, and heavy metal concentrations, with the most severe degradation occurring in areas heavily influenced by urbanization and agriculture.

Elevated pollution levels were primarily linked to non-point sources such as fertilizer runoff and untreated wastewater discharge. Spatial overlay analysis confirmed a strong association between anthropogenic land uses and poor water quality, underscoring the significant impact of human activities on freshwater ecosystems. These geographic analyses provided critical insights into land–water interactions within the lake system.

The findings highlight the urgent need for sustainable land use planning, enhanced wastewater treatment, and strengthened monitoring within the Lake Qarun watershed. The integration of remote sensing and GIS proved to be an effective and transferable approach for environmental assessment, offering potential applications for other lakes facing similar pressures.

To mitigate further deterioration, local authorities should implement stricter regulations on agricultural runoff and urban wastewater, establish vegetative buffer zones, and expand wastewater treatment infrastructure. Future research should integrate multi-seasonal satellite imagery with in situ microbiological and chemical analyses to improve the accuracy of spatial prediction models and support targeted management strategies.

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