Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(4): 2607 – 2631 (2025)
www.ejabf.journals.ekb.eg

Seasonal Variations in Water Quality Parameters and Their Ecological Implications in the Western Harbor of Alexandria, Egypt

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ARTICLE INFO

Article History:
Received: June 2, 2025
Accepted: Aug. 5, 2025
Online: Aug. 20, 2025

Keywords:
Water quality parameters,
Seasonal variations,
SST,
TDS,
Ecological health

ABSTRACT

The Western Harbor of Alexandria, Egypt, is a critical coastal ecosystem facing significant environmental challenges from urbanization, industrialization, and pollution. This study investigated seasonal variations in key water quality parameters—temperature, salinity, pH, dissolved oxygen (DO), total dissolved solids (TDS), conductivity, and nutrient levels (PO_4, NO_2, and NO_3)—and their ecological implications. Water samples were collected seasonally from 19 stations across the harbor, and physicochemical parameters were analyzed to assess spatial and temporal trends. Results revealed pronounced seasonal patterns: sea surface temperature (SST) peaked in summer (average 29.12°C) and dropped to its lowest in winter (average 16.19°C). The highest values of salinity and TDS were recorded in summer due to increased evaporation, while nutrient concentrations varied by season, with phosphate (PO_4) peaking in summer and nitrate (NO_3) elevating in spring. These fluctuations are largely attributed to biological activity, agricultural runoff, and wastewater discharges. The harbor's semi-enclosed nature exacerbates pollution, heightening risks of eutrophication, hypoxia, and heavy metal contamination. The ecological consequences of these seasonal changes include algal blooms, oxygen depletion, and habitat degradation, all of which threaten marine biodiversity and human health. Although this study did not directly assess biological impacts, the observed physicochemical changes highlight the urgent need for future research on marine community responses. Mitigation strategies such as reducing nutrient inputs, improving wastewater treatment, and implementing green infrastructure are essential for addressing these challenges. Regular monitoring and targeted interventions are recommended to ensure the sustainable management of the Western Harbor, safeguarding both its ecological health and economic significance. This research provides a foundation for future studies and policy actions aimed at mitigating pollution and enhancing the resilience of this vital coastal ecosystem.

INTRODUCTION

Coastal ecosystems, acting as dynamic interfaces between terrestrial and marine realms, are vital for global biodiversity and human well-being. These regions are characterized by intricate physical, chemical, and biological interactions, rendering them exceptionally productive and ecologically significant **(Kennish, 2002; Duarte *et al.*, 2020)**. However, rapid urbanization, industrial development, and agricultural intensification have placed unprecedented stress on these delicate ecosystems, leading to significant water quality degradation **(Howarth *et al.*, 2000; Cloern, 2001)**.

The Western Harbor of Alexandria, Egypt, serves as a poignant example of a coastal ecosystem grappling with these anthropogenic pressures. As a major maritime hub, it plays a crucial role in Egypt's economy, handling a substantial portion of the nation's international trade **(Nair, 2024)**. However, the harbor's semi-enclosed nature and proximity to densely populated and industrialized areas make it particularly vulnerable to pollution from various sources, including industrial effluents, domestic sewage, and agricultural runoff **(Abdallah *et al.*, 2007; Abdallah, 2008)**.

Water quality, defined by a suite of physical, chemical, and biological parameters, is a fundamental determinant of ecosystem health. Key parameters such as temperature, salinity, pH, dissolved oxygen (DO), total dissolved solids (TDS), conductivity, and nutrient levels (nitrate, nitrite, phosphate) are critical indicators of water quality and ecological integrity **(Chapman, 1996; Li *et al.*, 2021; Kumar *et al.*, 2023)**. Seasonal variations in these parameters can significantly influence the distribution, bioavailability, and toxicity of pollutants, as well as the overall health and functioning of aquatic ecosystems **(Wetzel, 2001)**.

Temperature, a critical factor influencing metabolic rates and biochemical reactions, exhibits marked seasonal fluctuations in coastal waters. In the Western Harbor, sea surface temperature (SST) is expected to peak during summer due to increased solar radiation and air temperatures, while reaching its lowest levels in winter due to reduced solar input and colder air masses **(Adam, 2009)**. These temperature variations can profoundly impact the solubility and bioavailability of pollutants, as well as the physiological processes of aquatic organisms **(Pörtner, 2010)**.

Salinity, another crucial parameter, is influenced by evaporation, precipitation, and freshwater inputs. In semi-enclosed basins like the Western Harbor, increased evaporation during summer can elevate salinity levels, while increased precipitation and freshwater runoff during winter can reduce them **(Dyer, 1997; Liu *et al.*, 2021)**. Salinity variations affect the osmotic balance of aquatic organisms and influence the distribution of marine species **(Kinne, 1971; Smith & Johnson, 2019)**. These fluctuations also have implications for local ecosystem health and biogeochemical cycles **(Thurman *et al.*, 2020)**.

pH, a measure of acidity or alkalinity, is influenced by various factors, including carbon dioxide dissolution, biological activity, and anthropogenic inputs. In marine environments, pH typically ranges from 7.5 to 8.5, with seasonal variations driven by temperature and biological processes **(Merz-Preiß & Riding, 1999; Huang *et al.*, 2022)**. Deviations from this range can have significant ecological implications, affecting the solubility and toxicity of pollutants as well as the physiological processes of aquatic organisms **(Raven *et al.*, 2020)**.

Dissolved oxygen (DO) is essential for aquatic life and varies seasonally. In the Western Harbor, DO levels are higher in winter because cold water holds more oxygen and biological activity is reduced, while in summer, warmer temperatures and increased biological demand lower DO levels **(Wetzel, 2001)**. Hypoxia, or low DO conditions, can lead to severe ecological stress, affecting the distribution and abundance of marine species **(Diaz & Rosenberg, 2008)**.

Nutrient levels, particularly nitrate, nitrite, and phosphate, play a crucial role in regulating primary productivity and ecosystem functioning. However, excessive nutrient inputs from agricultural runoff and wastewater discharges can lead to eutrophication, characterized by excessive algal growth, oxygen depletion, and habitat degradation **(Howarth *et al.*, 2000)**. Seasonal variations in nutrient levels are influenced by biological activity, agricultural practices, and wastewater discharges, with potential peaks during periods of high runoff or increased biological activity **(Cloern, 2001)**.

The Western Harbor, receiving freshwater inputs from the El-Noubaria and El-Mahmoudia Canals, along with industrial and domestic effluents, is particularly susceptible to nutrient enrichment and eutrophication **(Abdallah, 2014; El-Shafai *et al.*, 2018; Hassan *et al.*, 2021)**. The harbor's semi-enclosed nature exacerbates these issues, leading to the accumulation of pollutants and the development of hypoxic conditions **(Mostafa *et al.*, 2003)**. Furthermore, the accumulation of heavy metals in sediments poses a significant threat to the ecological health of the Western Harbor. Heavy metals such as cadmium, lead, and mercury can be released from industrial discharges, shipping activities, and atmospheric deposition **(Förstner & Wittmann, 1981)**. These metals accumulate in sediments, posing risks to benthic organisms and entering the food web through bioaccumulation and biomagnification **(Rainbow, 2002)**.

In the present study, we investigate the seasonal variations in key water quality parameters, including temperature, salinity, pH, dissolved oxygen (DO), total dissolved solids (TDS), conductivity, and nutrient levels (nitrite, nitrate, ammonium, and phosphate) in the Western Harbor of Alexandria, Egypt. Seasonal hydrographic changes and eutrophication significantly impact coastal water quality and pollutant spread, as shown by **(Koning *et al.*, 2020; Rakib *et al.*, 2021)**. This study highlights their ecological impacts, including the aggravation of eutrophication and hypoxia, aligning with prior Mediterranean assessments and providing guidance for sustainable management to prevent environmental degradation.

Two main freshwater sources feed into the harbor: the El-Noubaria Canal, which passes through Lake Maryout and connects to the Western Harbor via a water gate, and the El-Mahmoudia Canal, historically linked to the Western Harbor **(Hemeda, 1982; Rifat, 1982; Abdallah, 2014)**. These canals carry freshwater along with silt, clays, and organic/inorganic debris into the harbor. Sewage, slaughterhouse and tannery waste (mainly animal and leather residues), industrial effluents (from chlor-alkali and cement plants), and agricultural runoff via nearby drains all contribute pollutants that affect the Western Harbor **(Abdallah *et al.*, 2007; Abdallah, 2008)**.

The Western Harbor is a semi-closed basin with limited water circulation, acting as a repository for waste from land-based sources and shipping activities. While the future development and ongoing operation of Alexandria Harbor hold significant economic importance for the region, these activities may also impact its ecological functioning **(Mostafa *et al.*, 2003)**.

This study aimed to measure and analyze the physical, chemical, and environmental parameters affecting the area's environment, such as water quality, temperature, salinity, and pollutant levels, rather than focusing on living organisms or the direct effects of these conditions on them. This valuable information provides researchers and decision-makers with a foundation to conduct expanded future studies on biodiversity—whether through species monitoring, ecosystem health assessments, or the development of environmental protection strategies.

MATERIALS AND METHODS

1. Study area

The Western Harbor (W.H.) of Egypt, located at Latitude 31°12′N and Longitude 29°53′E in Alexandria, is the largest and oldest harbor on the Egyptian Mediterranean coast (Fig. 1). Covering an area of approximately 31km², the harbor handles nearly three-quarters of Egypt's international trade. Morphologically, it is a shallow, semi-elliptical, semi-enclosed basin, with most areas ranging in depth from 5 to 20m. The outer section, which forms the main part of the harbor, contains the deepest basin, reaching depths of up to 20m, where prevailing currents move in an anticlockwise direction.

The harbor connects to the open sea through a narrow inlet known as *El Boughaz*, which provides shelter from prevailing northwestern winds and ensures secure anchorage. As the primary maritime gateway for Alexandria, the Western Harbor manages about 75% of Egypt's shipborne cargo. It accommodates a wide range of imports and exports, including coal, cement, manufactured iron, fertilizers, grains, food products, textiles, chemicals, timber, crude oil, and refined petroleum **(Mostafa *et al.*, 2003)**.

The seabed is predominantly composed of mud and sandy mud, with scattered patches of sand and gravel in the inner harbor. Coarse sediments are mainly bioclastic in origin, while fine-grained deposits are largely terrigenous **(Mohamed *et al.*, 2020; El-Naggar & El-Sorogy, 2022)**.

Sample collection

A total of 19 sampling stations were selected to represent the entire Western Harbor (Fig. 1 & Table 1). Station locations were determined using a Geographic Positioning System (GPS; model C53). The study aimed to characterize these sites, measure heavy metal concentrations, and provide accurate environmental data for the Port of Alexandria.

Seasonal surface and bottom water samples were collected using 3L high-density PET (Nalgene) bottles. Prior to sampling, all bottles and analytical equipment were acid-washed with 10% ultrapure nitric acid and thoroughly rinsed with ultrapure water. During collection, *in situ* measurements were recorded for temperature, salinity, pH, and dissolved oxygen (DO).

Following collection, samples were sealed in plastic bags, stored in coolers at 4°C, and transported to the laboratory for further analysis.

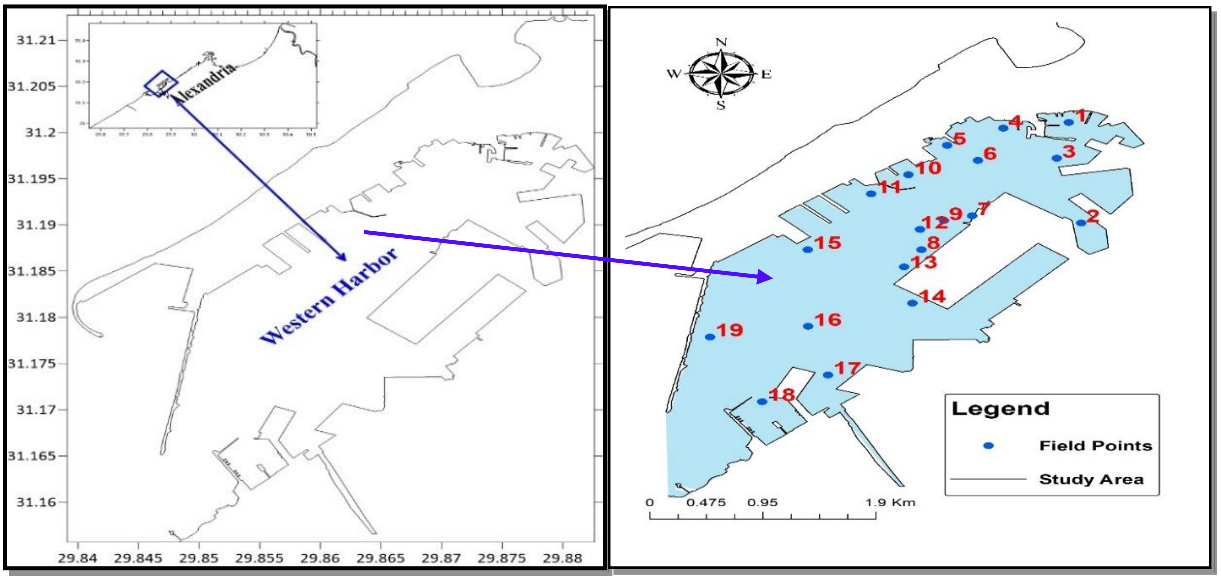


Fig. 1. A map illustrating the study area, highlighting the selected stations in the Western Harbor of Alexandria

Table 1. Sampling locations of the selected stations (Water samples) of Alexandria Western Harbor

Sample No.	Latitude (N)	Longitude (E)	Reference Position
1	31° 11 55.4	29° 52 36.8	Services berth
2	31° 11 13.3	29° 52 39.2	Containers berth
3	31° 11 38.6	29° 52 34.4	Terminal passenger berth
4	31° 11 54.6	29° 52 21.7	Restricted area
5	31° 11 49.6	29° 52 3.3	Restricted area
6	31° 11 39.7	29° 52 12.1	Inner navigation channel
7	31° 11 16.8	29° 52 10.5	In Front of Trans Misr Terminal(55-62)
8	31° 11 0.8	29° 51 58	In Front of Trans Misr Terminal(55-62)
9	31° 11 14.8	29° 52 2.8	Inner navigation channel
10	31° 11 35.8	29° 51 54.4	Restricted area
11	31° 11 25.9	29° 51 43	Restricted area
12	31° 11 11.2	29 51 56.3	Inner navigation channel
13	31° 10 55	29° 51 53.3	In Front of Trans Misr Terminal(55-62)
14	31° 10 42.7	29° 51 55.6	Side of Trans Misr Terminal
15	31° 11 3.7	29° 51 24.5	Restricted area
16	31° 10 31.1	29° 51 25.8	Inner navigation channel
17	31° 10 10.9	29° 51 28.3	Berth 85/3
18	31° 10 1.2	29° 51 15.5	Petroleum Terminal berth
19	31° 10 28.2	29° 50 55.5	Port Breakwater

1.1 Hydrogen ion concentration (pH)

Hydrogen ion concentration (pH) was directly measured at the sampling stations by the potentiometric method using pH meter model (Lovibond Senso direct 150) after calibration with buffer solutions of pH 4 and 10.

1.2 Dissolved oxygen (DO)

Dissolved oxygen (DO) was determined using the Modified Winkler Method **(APHA, 1995)**. Water samples were collected in 300mL glass-stoppered bottles with great care to avoid air bubble entrapment. Immediately after collection, 2mL of manganese sulfate ($MnSO_4$) solution was added, followed by 2mL of alkaline potassium iodide (KI) reagent. These reagents were introduced just beneath the water surface to ensure proper mixing. The bottles were then stoppered, gently inverted several times to mix, and stored in a dark box until transported to the laboratory.

In the laboratory, 2mL of concentrated sulfuric acid (H_2SO_4) was added to each sample, and the contents were thoroughly mixed. The solution was allowed to stand for at least 5 minutes to ensure complete reaction. A 100mL aliquot of the fixed sample was titrated against 0.025 N sodium thiosulfate ($Na_2S_2O_3$) solution, using starch as the indicator. The endpoint was determined by the disappearance of the blue color.

The sodium thiosulfate solution was standardized against precisely prepared 0.025 N potassium bi-iodate ($KH(IO_3)_2$). The dissolved oxygen concentrations were calculated according to the following equation:

$$\mathbf{O_2\ (mgl^{-1}) = N\ X\ V\ X\ 8\ X\ 1000\ /\ ml\ of\ sample}$$

- *Where:*

N = Normality of sodium thiosulphate

V = Volume of sodium thiosulphate

2. Physicochemical analysis

2.1 Water quality parameters

According to **Masime (2011)**, measurements were also made in the lab for water nutrient levels (nitrite nitrogen, nitrate nitrogen, ammonium nitrogen, and phosphate phosphorus) using an Atomic Absorption Spectrometer Combined Flame and Furnace (AA500FG) Graphite Furnace system model 500FG with suitable ready-to-use kits.

2.2 Calcium and magnesium hardness

Water hardness (calcium and magnesium) was determined according to **Kurtz (1961)** and **APHA (1995)**.

A) Calcium:

To determine calcium hardness, one ml of NaOH (4N) and 0.1g muroxide powder, as indicator, were added to 25ml of water samples. Samples were mixed well then titrated against EDTA (0.01M) with agitation to obtain the contrast violet endpoint color. The equation used for calculation is as follows: -

$$\mathbf{Ca^{++}\ (mgl^{-1}) = N\ X\ V\ X\ 40.08\ X\ 1000\ /\ ml\ sample}$$

Where: N = Normality of EDTA; V = Volume of EDTA titrate.

B) Magnesium:

The combined concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions was determined by complexometric titration using 0.01M EDTA solution with Eriochrome Black T (EBT) as the indicator. A 25mL water sample was mixed with 1mL of buffer solution (pH 10) and 0.5mg of EBT. The sample was titrated with 0.01M EDTA until the endpoint was reached, indicated by a distinct color change to blue.

To differentiate between calcium and magnesium, a separate titration was performed for calcium alone. The magnesium concentration was then calculated as the difference between the total hardness (Ca^{2+} + Mg^{2+}) and the calcium hardness. The equation used for calculation was as follows:

$$\mathbf{Mg^{++}\ (mgl^{-1}) = N \times V' \times 24.32 \times 1000 / ml\ sample}$$

Where: N = normality of EDTA; V' = volume of EDTA (total) – volume of EDTA (Ca).

RESULTS AND DISCUSSION

1. Calcium (Ca) and magnesium (Mg) concentrations

a. Spatial variability

Color variations in the maps (Fig. 2) indicate that Ca and Mg concentrations are not uniform across the harbor, with clear areas of higher and lower values.

Seasonal fluctuations of Ca and Mg

Seasonal color patterns reveal significant variations in both Ca and Mg.

- **High Concentrations (Summer):** Ca (>300 mg/L) and Mg (>1,500 mg/L) peaked in summer, likely due to enhanced evaporation, which reduces water volume and concentrates dissolved ions. Reduced rainfall and runoff during this season further limit dilution. Elevated temperatures may also intensify biological activity (e.g., shell formation), releasing Ca and Mg into the water.
- **Low Concentrations (Winter):** Ca (< 150mg/ L) and Mg (< 1, 100mg/ L) were lowest in winter, consistent with seasonal dilution from rainfall and freshwater inflow, as well as reduced evaporation. These findings align with **Houser *et al.* (2014)**, who reported Ca and Mg concentrations 20–30% lower in winter in the Western Harbor due to Nile discharge and urban runoff. Similar patterns were observed by **Sanford *et al.* (1990)** in Chesapeake Bay, USA, linking winter declines to freshwater input and summer peaks to hypersaline conditions.
- **Transitional Seasons (Spring/Autumn):** Intermediate Ca and Mg concentrations reflect a balance between evaporation, rainfall, and biological activity. **Kapiris *et al.* (2014)** reported comparable trends in the Gulf of Gabès (Tunisia), though they emphasized anthropogenic inputs such as industrial effluents, which are beyond the scope of this study.

2. Seasonal variations in salinity and TDS

- **Summer:** TDS exceeded 34g/ L and salinity surpassed 35‰, largely due to strong evaporation and limited water exchange.
- **Winter:** TDS dropped below 30g/ L, with most areas showing salinity <33‰, reflecting rainfall and freshwater inputs.
- **Spring/Autumn:** Intermediate TDS (30– 34g/ L) and moderate salinity dominated, showing transitional conditions.

These findings align with **Dorgham *et al.* (2004)**, who documented similar seasonal patterns in Alexandria. Importantly, such variations influence biodiversity: high salinity in summer can stress sensitive species, while lower winter salinity fosters more favorable conditions for growth and reproduction. With accelerating climate change expected to intensify evaporation and reduce freshwater inflow, these dynamics are likely to become more pronounced.

3. Seasonal variations in sea surface temperature (SST)

- **Summer:** 28.98–29.49 °C (highest).
- **Winter:** 16.0–16.4 °C (lowest).
- **Spring/Autumn:** Intermediate values, reflecting transitional warming and cooling.

These changes follow solar radiation and air temperature patterns typical of the Mediterranean.

4. Spatial distribution of salinity

- **High Salinity:** Predominant in summer, especially in poorly flushed regions.
- **Low Salinity:** Most common in winter, influenced by freshwater inflow.
- **Moderate Salinity:** Observed in spring and autumn.

5. Nutrient dynamics

5.1. Phosphate (PO_4) and nitrate (NO_3)

- PO_4 showed significant seasonal variation ($P< 0.05$): highest in summer (1.900 ± 0.62 µmol/L), lowest in winter (1.097 ± 0.44 µmol/L), with spring and autumn intermediate.
- NO_3 showed no significant seasonal differences, averaging 9.8– 11.5µmol/ L, though extreme values (>40 µmol/L) occurred sporadically across all seasons, reflecting localized inputs or sediment resuspension. High variability (SD ~9 µmol/L) underscores spatial heterogeneity.

The persistently elevated baseline of NO_3 suggests chronic anthropogenic inputs (e.g., sewage, agriculture), consistent with findings in urban estuaries such as Boston Harbor **(Howarth *et al.*, 2012)**. Localized hotspots (e.g., summer sample: 43.4 µmol/L) emphasize the need for integrating spatial with statistical analyses.

5.2. Nitrite (NO_2)

- **Summer:** Higher concentrations (7.2– 11µmol/ L), linked to enhanced microbial activity and limited mixing.
- **Winter:** Lower concentrations (1.6–4.6µmol/ L), due to dilution and possible denitrification.
- **Spring/Autumn:** Intermediate concentrations, reflecting transitional biological and physical conditions.

5.3. pH

- **Highest:** Winter (8.2–8.3).
- **Lowest:** Summer (7.9–8.1).
- **Intermediate:** Spring and autumn.

pH distribution is shaped by freshwater inflow, circulation, and biological activity.

5.4. Dissolved oxygen (DO)

DO showed strong spatial heterogeneity, with maps (Fig. 2) highlighting both oxygen-rich and oxygen-poor zones. High DO often coincided with photosynthetically active regions, while hypoxic zones developed in stagnant, poorly flushed areas.

5.5. Conductivity

- **Summer:** 50–56 mS/cm (highest).
- **Winter:** 37–39 mS/cm (lowest).
- **Spring/Autumn:** Intermediate values.

Conductivity patterns mirror salinity and TDS, confirming the dominant role of evaporation and freshwater inputs.

Synthesis

The seasonal and spatial variations observed across Ca, Mg, salinity, nutrients, pH, DO, and conductivity reflect the complex interplay of physical, chemical, and biological processes within the Western Harbor. The semi-enclosed nature of the basin amplifies these effects, creating localized hotspots of stress such as hypoxia and high nutrient loads. These conditions can trigger eutrophication, algal blooms, and biodiversity loss, highlighting the urgent need for continuous monitoring and management interventions

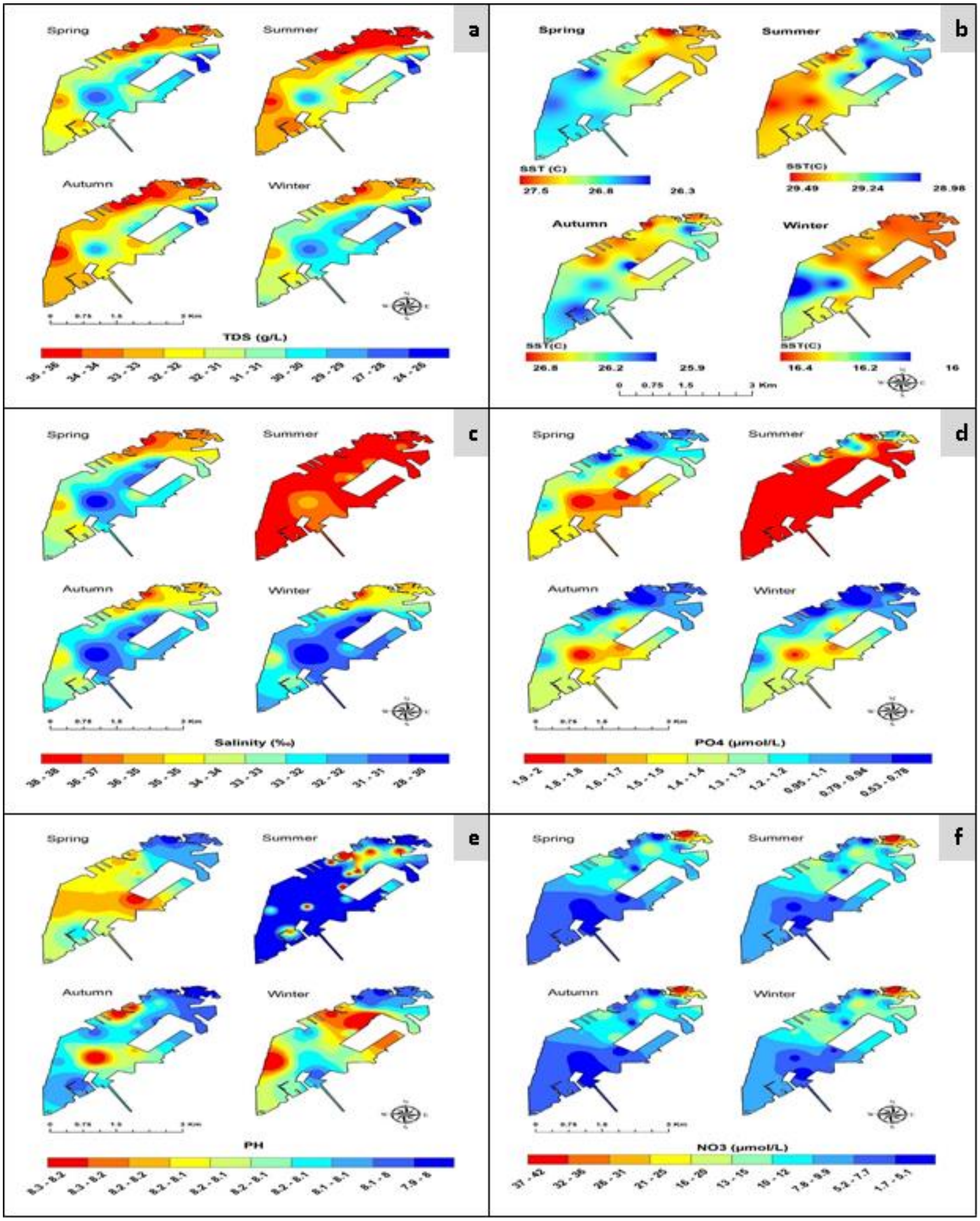
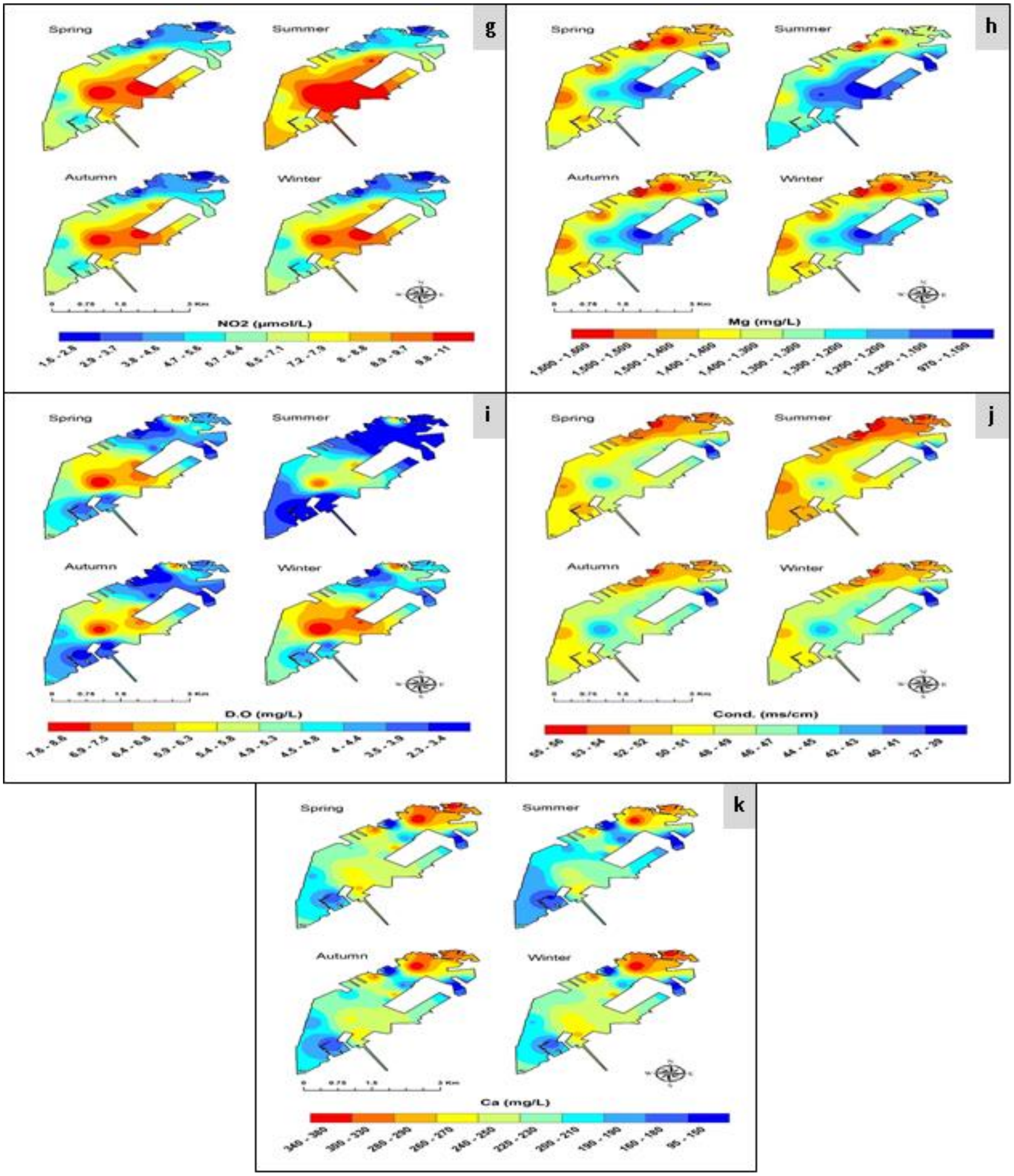


Fig. 2. A map illustrating Spatial and seasonal variability of water quality parameters in the Western Harbor of Alexandria, Egypt, with subfigures (a–k) illustrating distinct patterns: (a) summer calcium (Ca) distribution (> 300mg/ L) driven by evaporation and biological activity; (b) seasonal magnesium (Mg) variability (< 1,100mg/ L winter) due to rainfall dilution; (c) summer salinity gradients (>35‰) and TDS maxima (> 34g/ L); (d) pH fluctuations (7.8–8.5) from sewage discharge and CO_2 dynamics; (e) dissolved oxygen (DO) summer peaks (5.4– 8.6mg/ L) from photosynthesis; (f) winter DO minima (2.3– 4.8mg/ L) linked to stratification breakdown.



Continue, Fig. 2. A map illustrating spatial and seasonal variability of water quality parameters in the Western Harbor of Alexandria, Egypt, with subfigures (a–k) illustrating distinct patterns: (g) nutrient hotspots (PO_4, NO_3) from agricultural runoff; (h) conductivity trends (35.81– 57.25mS/ cm) reflecting ion seasonality; (i) anthropogenic pollution sources near inlets; (j) reduced heavy metal retention from winter dilution; and (k) pollutant retention due to limited hydrodynamic flushing. Subfigures (a–k) combine maps, diagrams, and heatmaps (auto-generated with medium confidence) to highlight climatic, biological, and anthropogenic influences.

Table (2) observations

a. Seasonal variation in sea surface temperature (SST): SST exhibited a pronounced seasonal pattern

- Summer: Highest average (29.12 °C), with maximum values of 29.5 °C recorded at stations 11 and 16.
- Winter: Lowest average (16.19 °C), with a minimum of 15.2 °C at station 19.
- Spring/Autumn: Intermediate values between summer and winter extremes.

Overall, summer consistently showed the highest SST across all stations, while winter displayed the lowest values, confirming the strong seasonal control of solar radiation and air temperature on surface waters **(Adam, 2009)**.

b. Seasonal variation in pH

pH showed only minor fluctuations across seasons, remaining within a narrow range that reflects a relatively stable marine environment.

- Summer: Highest average (8.09), though minimum pH values of 7.8 were recorded at stations 1, 2, and 17.
- Winter: Lowest average (8.06), but the maximum value of 8.5 occurred at station 7.
- Spring/Autumn: Intermediate values with no extreme deviations.

These results indicate that although small seasonal changes occur, the system maintains stable pH conditions typical of marine environments **(Merz-Preiß & Riding, 1999)**.

Table 2. Water quality parameters (SST and PH)

Sample code	SST(°C)				PH			
	Spring	**Summer**	**Autumn**	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**
1	27.1	28.68	26.8	16.34	7.99	7.8	7.89	8
2	26.9	28.85	26.4	16.36	8.05	7.9	8	8.1
3	26.9	29.1	26.2	16.36	8.04	8.2	8	8.04
4	27.6	29.35	26.7	16.34	7.93	7.93	7.98	7.95
5	26.8	28.76	26.9	16.41	8.01	8	8.02	7.97
6	26.7	28.87	26.5	16.36	8.05	8.2	8.11	8
7	27.4	28.49	26.7	16.26	8.07	8	8	8.5
8	26.8	28.74	26.8	16.24	8.09	7.9	8.02	8.1
9	27	29.2	26.7	16.24	8.11	8.21	8.03	8.2
10	26.4	29.4	26.6	16.19	8.16	8.3	8.2	8.15
11	26.6	29.5	26.8	16.24	8.16	8.23	8.23	8.2
12	26.9	29.3	26.7	16	8.15	8.2	8.11	8.2
13	27	28.9	25.9	16.41	8.12	8.3	8.08	8.15
14	26.5	29.2	26.7	16.43	8.22	8.1	8.15	8.1
15	25.8	29.4	26.8	16.34	8.14	7..9	8.01	8.05
16	26.4	29.5	26.3	15.5	8.16	8.21	8.24	8.07
17	26.2	29.3	26.5	16.24	8.12	7.8	8.1	8
18	26.3	29.26	26.2	16.1	8.08	8.17	8	8.1
19	26	29.5	26.5	15.2	8.16	8.11	8.06	8.25
Ave.	26.7	29.12	26.56	16.19	8.10	8.09	8.06	8.11
Max.	27.6	29.5	26.9	16.43	8.22	8.3	8.24	8.5
Min.	25.8	28.49	25.9	15.2	7.93	7.8	7.98	7.95
St. dev.	**0.45**	**0.32**	**0.26**	**0.32**	**0.07**	**0.17**	**0.09**	**0.13**
F	5.10	19.356	30.261	8.940	5.38	13.661	5.338	9.191
***P*-value**	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Table (3) observations

a. Seasonal variation in total dissolved solids (TDS)

Seasonal variations in TDS within the Western Harbor follow patterns observed in other coastal and estuarine environments, though local factors create distinct differences.

- **Summer:** Highest values, with an average of 32.63g/ L and a maximum of 35.66 g/L. Elevated TDS is linked to strong evaporation, limited freshwater input, and restricted circulation within the semi-enclosed basin. These findings agree with **El-Sayed *et al.* (2020)**, who reported comparable summer maxima (31.2– 37.8g/ L) in Alexandria's Eastern Harbor.
- **Spring:** Lowest recorded value (23.5g/ L), likely reflecting episodic rainfall or terrestrial runoff. Similar reductions were noted by **Abdelsalam *et al.* (2024)** in the Nile Delta estuaries (1.5– 28.7g/ L) during high-discharge events. However, TDS levels in the Western Harbor remain substantially higher than in estuarine waters, likely due to inputs from industrial effluents and maritime activities.
- **Ecological Implications:** Sustained high TDS, particularly in summer, may exacerbate osmotic stress for marine organisms. **Dong *et al.* (2022)** linked persistent elevated TDS to biodiversity declines in eutrophic harbors, suggesting potential ecological risks in the Western Harbor.

b. Seasonal variation in salinity

Salinity exhibited a clear seasonal trend consistent with TDS fluctuations.

- **Summer:** Highest average salinity (37.01 ‰), with a maximum of 38.6 ‰ (station 15).
- **Winter:** Lowest average salinity (32.18 ‰), with a minimum of 26.93 ‰ (station 16).

These seasonal shifts reflect strong summer evaporation and reduced freshwater inflows, as also noted in other Mediterranean coastal systems **(Peebles *et al.*, 2006)**.

c. Relationship between TDS and salinity

TDS and salinity are closely correlated: salinity quantifies dissolved salts (‰), while TDS includes all dissolved solids. Both parameters follow the same seasonal pattern, peaking in summer and reaching their lowest values in winter. This relationship supports observations in other semi-enclosed coastal basins **(Rebello *et al.*, 2020)**.

Table 2. Water quality parameters (TDS and Salinity)

Sample code	TDS (g/L)				Salinity(‰)			
	Spring	Summer	Autumn	Winter	Spring	Summe r	Autumn	Winter
1	34.21	36.5	34.8	33.65	36.39	37.6	35.2	35.14
2	23.5	24.85	24.3	23.6	32.99	37.8	31.5	31.74
3	32.9	34.2	32.5	31.95	34.86	36.3	33.95	33.61
4	33.44	34.98	33.5	32.55	35.47	37.4	33.98	34.22
5	35.66	37.15	34.76	34.75	38.19	38.35	37.2	36.94
6	33.46	34.2	34.4	32.96	35.49	38.4	34.75	34.24
7	29.21	30.75	30.35	28.7	30.53	34.6	30.4	29.28
8	29.11	30.55	29.9	28.95	30.41	34.55	30.25	29.16
9	29.28	30.35	30.46	28.98	30.59	37.9	30.15	29.34
10	34.32	35.6	35.6	33.82	36.53	37.7	35.25	35.28
11	33.5	35.85	34.7	32.95	35.54	36.8	35.1	34.29
12	30.62	31.8	31.35	29.98	32.16	37.2	32	30.91
13	28.85	29.97	29.88	28.25	30.11	36.7	29.5	28.86
14	31.72	32.56	32.92	30.95	33.54	37.5	32.8	32.29
15	31.53	32.7	32.73	30.97	33.22	38.6	32.98	31.97
16	27.19	28.5	28.86	27.75	28.18	34.6	28	26.93
17	30.04	31.74	31.94	29.84	31.49	36.4	30.65	30.24
18	32.52	33.6	32.9	31.9	34.39	36.9	33.85	33.14
19	33.15	34.15	34.85	32.85	35.12	37.8	34.6	33.87
Ave.	31.27	32.63	32.14	30.81	33.43	37.01	32.74	32.18
Max.	35.66	37.15	35.6	34.75	38.19	38.6	37.2	36.94
Min.	23.5	24.85	24.3	23.6	28.18	34.55	28	26.93
St. dev.	**2.96**	**3.05**	**2.76**	**2.71**	**2.68**	**1.25**	**2.44**	**2.68**
F	**3670.35**	**58.925**	**41.865**	**2438.372**	**5382.35**	**25.283**	**1918.392**	**40.117**
***P* value**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**

Table (4) observations – Nutrient concentrations

The seasonal fluctuations of phosphate (PO_4), nitrite (NO_2), and nitrate (NO_3) indicate a dynamic interplay between biological processes and environmental drivers within the Western Harbor ecosystem.

1. Phosphate (PO_4)

- **Seasonal Variation:** PO_4 exhibited a pronounced seasonal pattern, with the highest concentrations recorded in summer (average: 1.97µmol/ L) and the lowest in winter (average: 1.09µmol/ L).
- **Range:** Maximum values reached 2.95µmol/ L (stations 16 and 13, summer), while the minimum was 0.33µmol/ L (stations 5 and 11, winter).
- These patterns are consistent with nutrient cycling in semi-enclosed marine systems, where elevated summer values may be linked to evaporation, reduced dilution, and enhanced biological activity **(Rahman, 2009)**.

2. Nitrite (NO_2)

- **Seasonal variation:** NO_2 concentrations displayed moderate fluctuations, with the highest values in summer (average: 7.26µmol/ L) and the lowest in winter (average: 6.02µmol/ L).

- **Range:** Maximum 12.3µmol/ L (station 16, summer), minimum 1.88µmol/ L (station 1, spring).
- These trends suggest that microbial processes such as nitrification, influenced by temperature, solar radiation, and organic matter decomposition, drive NO_2 dynamics **(Murgulet *et al.*, 2019)**.

3. Nitrate (NO_3)

- **Seasonal variation:** NO_3 showed slight seasonal variability, with the highest mean concentration in winter (11.52µmol/ L) and the lowest in summer (11.17µmol/ L).
- **Range:** Maximum 43.67µmol/ L (station 1, winter), minimum 1.75µmol/ L (station 4, spring).
- The extremely high winter concentration at station 1 represents a local hotspot, potentially linked to runoff, sewage discharge, or sediment resuspension. Such outliers highlight the influence of localized inputs on nutrient dynamics **(Obeidat *et al.*, 2008)**.

Table 4. Nutrient concentrations (PO_4, NO_2, NO_3)

S. code	PO4 (µmol/L)				NO2 (µmol/L)				NO3 (µmol/L)			
	Spring	**Summer**	**Autumn**	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**
1	0.86	0.98	0.84	0.66	1.88	2.2	1.68	1.55	42.32	43.4	41.92	43.67
2	1.2	2.15	1.01	1	6.3	7	5.6	5.97	8.98	9.05	8.53	10.33
3	1.2	2.01	1.02	1	4.23	5.2	3.98	3.9	6.41	7.43	6.11	7.76
4	1.06	2	0.95	0.86	4.23	5.15	3.96	3.9	1.75	2.8	1.65	3.1
5	0.53	0.9	0.45	0.33	2.98	3.5	2.88	2.65	5.69	6.66	5.18	7.04
6	0.62	1.02	0.48	0.42	3.85	4.13	3.65	3.52	17.74	18.5	16.97	19.09
7	1.68	2.25	1.35	1.48	8.55	9.3	8.25	8.22	13.59	14.6	13.15	14.94
8	1.78	2.23	1.64	1.58	8.83	9.4	8.63	8.5	11.84	12.9	11.84	13.19
9	1.44	1.98	1.32	1.24	8.98	10.01	8.79	8.65	2.66	3.75	2.51	4.01
10	1.25	1.8	1.03	1.05	2.5	3.7	2.42	2.17	5.2	6.7	5.01	6.55
11	0.58	0.9	0.49	0.38	4.3	5.25	4.01	3.97	15.17	16.54	14.88	16.52
12	1.73	2.4	1.53	1.53	7.33	8.65	6.98	7	12.37	13.35	11.77	13.72
13	1,25	2.55	1,12	1.05	8.58	9.24	8.18	8.25	15.15	16.2	14.85	16.5
14	1.92	2.8	1.72	1.72	11.5	12.05	10.65	11.17	3.28	4.37	3.21	4.63
15	1.15	2.15	1.05	0.95	6.65	7.55	6.35	6.32	10.68	11.3	9.88	12.03
16	2.02	2.95	1.95	1.82	11.25	12.3	10.98	10.92	3.28	4.15	3	4.63
17	1.58	2.45	1.47	1.38	8.43	9.8	8.13	8.1	2.24	3.55	2.14	3.59
18	1.54	1.9	1.42	1.34	5.03	6.7	4.95	4.7	7.39	8.4	6.89	8.74
19	1.06	1.98	0.97	0.86	5.23	6.78	5	4.9	7.44	8.6	6.94	8.79
Ave.	1.29	1.97	1.15	1.09	6.349	7.26	6.06	6.02	10.17	11.17	9.81	11.52
Max.	2.02	2.95	1.95	1.82	11.5	12.3	10.98	11.17	42.32	43.4	41.92	43.67
Min.	0.53	0.9	0.45	0.33	2.5	3.5	2.42	2.17	1.75	2.8	1.65	3.1
St. dev.	**0.46**	**0.62**	**0.43**	**0.44**	**2.86**	**2.91**	**2.77**	**2.86**	**9.19**	**9.18**	**9.12**	**9.19**
F	**229.55**	**299.32**	**176.62**	**175.99**	**2984.25**	**56.482**	**10117.070**	**6677.199**	**20858.92**	**31603.075**	**16165.286**	**60.290**
***P* value**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**

Seasonal variations in phosphate, nitrite, and nitrate levels are driven by multiple environmental factors, including temperature, solar radiation, biological activity, and anthropogenic nutrient inputs. Elevated phosphate and nitrite concentrations during summer are associated with intensified biological processes, while higher nitrate levels in winter reflect reduced biological uptake combined with nutrient-rich freshwater inflow.

Localized hotspots of unusually high nitrate further emphasize the influence of point-source pollution, highlighting the need for site-specific investigations to identify and mitigate sources of contamination. Continuous monitoring of nutrient dynamics is essential, as imbalances can destabilize ecosystem functioning: excess nutrients may trigger harmful algal blooms and oxygen depletion, while deficiencies can suppress the productivity of key marine organisms. Understanding these patterns is critical for designing strategies that reduce nutrient loading and safeguard biodiversity in coastal ecosystems increasingly pressured by human activity.

Table (5) observations – Conductivity

Conductivity reflects the capacity of water to conduct electricity and is primarily determined by the concentration of dissolved ions (salts) **(Corwin & Yemoto, 2020)**.

- **Seasonal variation**
  - **Spring:** 49.37 mS/cm
  - **Summer:** 50.47 mS/cm
  - **Autumn:** 48.23 mS/cm
  - **Winter:** 48.12 mS/cm

As expected, summer exhibited the highest average conductivity, which may be attributed to greater ion mobility at elevated temperatures and enhanced evaporation. Conversely, winter values were slightly lower, consistent with dilution from rainfall and freshwater inflow.

- **Range:** Conductivity values varied considerably across stations, with a maximum of 57.25 mS/cm (summer) and a minimum of 35.81 mS/cm (winter). This range indicates notable spatial heterogeneity within the harbor, reflecting variations in salinity and freshwater inputs.
- **General Trend:** Conductivity showed only minor seasonal differences, with a tendency toward higher values in summer and lower values in winter. These findings are consistent with seasonal hydrographic patterns reported in other semi-enclosed marine systems **(Rahman, 2020)**.

Table 5. Water conductivity (Cond.)

Sample code	Cond. (ms/cm)			
	Spring	Summer	Autumn	Winter
1	53.99	54.6	52.84	52.74
2	37.06	36.5	36.33	35.81
3	51.93	53	50.65	50.68
4	52.71	53.6	51.25	51.46
5	56.27	57.25	55.33	55.02
6	52.81	53.9	50.9	51.56
7	46.09	47.45	45.4	44.84
8	45.9	47.5	44.95	44.65
9	46.18	47.3	44.89	44.93
10	54.23	55.4	53.55	52.98
11	52.85	53.98	51.95	51.6
12	48.29	49.65	46.9	47.04
13	45.49	46.85	44.63	44.24
14	50.21	52.01	49.75	48.96
15	49.8	51.2	47.98	48.55
16	42.84	44.43	40.9	41.59
17	47.36	48.16	45.86	46.11

18	51.37	52.5	50.45	50.12
19	52.58	53.7	51.8	51.33
Ave.	**49.37**	**50.47**	**48.23**	**48.12**
Max.	**56.27**	**57.25**	**55.33**	**55.02**
Min.	**37.06**	**36.5**	**36.33**	**35.81**
St. dev.	**4.70**	**4.85**	**4.72**	**4.70**
F	**1.40**	**763.895**	**1084.254**	**1.359**
***P* value**	**0.189**	**< 0.0001**	**< 0.0001**	**0.208**

The study reveals significant spatial and seasonal variability in water quality parameters in the Western Harbor of Alexandria, Egypt. Calcium (Ca) and magnesium (Mg) concentrations exhibited non-uniform distributions (Fig. 2), peaking in summer (> 300mg/ L Ca; > 1,500mg/ L Mg) due to evaporation-driven hypersalinity and enhanced biological activity (e.g., shell formation). Winter dilution from rainfall and runoff lowered concentrations (< 150mg/ L Ca; < 1,100mg/ L Mg), consistent with patterns reported by **Houser *et al.* (2014)** in Mediterranean systems and **Sanford *et al.* (2018)** in Chesapeake Bay. However, **Drira *et al.* (2016)** highlighted anthropogenic contributions (e.g., industrial effluents) in the Gulf of Gabès as a confounding factor, which this study did not assess, pointing to a gap in contextualizing local pollution impacts.

Salinity and TDS mirrored these seasonal patterns, with summer maxima (TDS >34 g/L; salinity >35‰) driven by evaporation and winter minima (TDS <30 g/L; salinity <33‰) associated with freshwater inputs. These findings agree with **Verney *et al.* (2006)** and **Hashempour-Baltork *et al.* (2019)**, who linked such dynamics to climatic and hydrodynamic drivers. Salinity distribution within the harbor is shaped by multiple interacting factors, including proximity to the entrance (greater exchange with the open sea), water depth (reducing vertical mixing), and circulation patterns such as tidal currents and wind-driven mixing, which collectively enhance horizontal and vertical distribution **(Florin *et al.*, 2018)**.

Sea surface temperature (SST) ranged from 29.5°C (summer) to 15.2°C (winter), largely controlled by solar radiation, atmospheric conditions, and ocean currents **(Gierach *et al.*, 2009; Gonzalez-Espinosa & Donner, 2021)**. Elevated SST in summer is closely tied to evaporation and TDS enrichment. pH remained within 7.8–8.5, peaking in winter due to reduced biological CO_2 production and freshwater dilution, consistent with **Blair (1999)**. Seasonal fluctuations are linked to biological processes (photosynthesis, respiration, decomposition), freshwater inflow, and anthropogenic inputs such as sewage and industrial discharges **(Falkowski & Raven, 2007; Doney *et al.*, 2009; Cai *et al.*, 2011; Hong Kong EPD, 2020)**. These changes in SST and pH have ecological implications for heavy metal bioavailability and speciation, influencing solubility, mobility, and bioaccumulation in marine organisms.

Dissolved oxygen (DO) ranged from 5.4– 8.6mg/ L in summer to 2.3– 4.8mg/ L in winter. The unexpectedly lower winter values contradict typical oxygen solubility patterns in cold water, suggesting eutrophication-driven hypoxia linked to organic matter decomposition, as noted by **Diaz and Rosenberg (2008)**.

Nutrients exhibited strong seasonal and spatial variability. Phosphate (0.33– 2.95µmol/ L), nitrite (1.55– 12.3µmol/ L), and nitrate (1.75– 43.67µmol/ L) peaked in summer/spring, reflecting agricultural runoff, sewage inputs, and organic matter mineralization. These findings align with **Hecky and Kilham (1988)** and **Li *et al.* (2022)**, who emphasized eutrophication risks in nutrient-enriched systems. Phosphate cycling was consistent with global estuarine studies **(Creed, 2004)**, with summer peaks from organic matter remineralization and reduced mixing, and winter declines driven by mixing and uptake. Unlike many eutrophic systems where NO_3 shows strong seasonal variability **(Rabalais *et al.*, 2009)**, the Western Harbor maintained persistently high baseline NO_3, suggesting chronic anthropogenic inputs.

Elevated nutrients, particularly phosphate, are linked to algal blooms, oxygen depletion, fish kills, and harmful algal toxins **(Watson *et al.*, 2016; Wu *et al.*, 2022)**. Nitrogen cycling dynamics (NO_2 oxidation to NO_3) reflect microbial nitrification and enhanced organic matter decomposition under warm conditions **(Pye *et al.*, 2010; Hutchins & Capone, 2022)**. The combined effects of agricultural runoff, untreated sewage, and atmospheric deposition represent major nutrient sources, as documented globally **(Hecky & Kilham, 1988)**.

Conductivity (35.81– 57.25mS/ cm) paralleled salinity trends, with higher summer values linked to evaporation and lower winter values linked to rainfall dilution, consistent with **Ouyang *et al.* (2006)** and **Rahman (2020)**. While this pattern matches broader hydrochemical studies, it underrepresents anthropogenic effects emphasized by **Al Shehhi *et al.* (2014)**. Importantly, the spatial distribution shows higher salinity and nutrient levels near pollution sources and lower values near freshwater inlets, in line with circulation-driven heterogeneity observed by **Trettin *et al.* (2021)**.

Ecological and management implications

Salinity and conductivity fluctuations can impose osmotic stress on aquatic organisms, altering species distributions, biodiversity, and biogeochemical cycles **(Yousuf *et al.*, 2022)**. Elevated nutrient inputs and seasonal peaks drive eutrophication, hypoxia, and habitat degradation, while posing risks to human health through harmful algal blooms and contaminated seafood.

To mitigate these impacts, targeted strategies are needed:

- **Agricultural management:** cover crops **(Grünberg, 2024)**, precision fertilization **(Getahun *et al.*, 2024)** and vegetated buffer strips **(Nair *et al.*, 2024)**.
- **Wastewater treatment:** upgrading plants with nutrient removal technologies **(Zhou *et al.*, 2022)**.
- **Urban solutions:** green infrastructure such as rain gardens, bioswales, and permeable pavements **(Sharma & Malaviya, 2021; Fletcher *et al.*, 2023)**.
- **Sustainable farming:** expansion of organic practices to reduce nutrient runoff **(Gamage *et al.*, 2023)**.

Ultimately, the Western Harbor's semi-enclosed morphology and limited flushing exacerbate pollutant retention, amplifying risks of eutrophication and heavy metal accumulation. Effective management requires integrating continuous anthropogenic monitoring with hydrochemical assessments, as emphasized by **Al Shehhi *et al.* (2014)**, to achieve holistic ecosystem protection and resilience.

CONCLUSION

The Western Harbor of Alexandria, Egypt, a vital coastal ecosystem under increasing pressure from urbanization, industrialization, and pollution, was assessed to evaluate seasonal water quality dynamics. Measurements of temperature, salinity, pH, dissolved oxygen (DO), and nutrient levels across 19 stations revealed pronounced seasonal variability. Summer was characterized by elevated sea surface temperatures (29.12°C), salinity, and nutrient concentrations (PO_4, NO_3, NO_2), primarily driven by evaporation, reduced water exchange, and intensified biological activity, while pH and DO levels declined. In contrast, winter conditions (16.19°C) reflected freshwater inflows and mixing, resulting in lower nutrient concentrations and higher pH and DO.

These seasonal fluctuations, shaped by agricultural runoff, wastewater discharges, and the harbor's semi-enclosed hydrodynamics, exacerbate ecological risks including eutrophication, harmful algal blooms, hypoxia, and heavy metal mobilization. Such degradation threatens biodiversity, fisheries, and public health through ecosystem collapse and toxic exposure.

Mitigation requires a multi-pronged approach: reducing nutrient runoff through precision agriculture, upgrading wastewater treatment systems, expanding green infrastructure (e.g., bioswales, rain gardens), and strengthening monitoring and regulatory frameworks. The findings highlight the urgent need for integrated, interdisciplinary management strategies to balance ecological health with economic activity, ensuring the long-term resilience of the Western Harbor as both an environmental and socioeconomic asset.

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