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RESEARCH ARTICLE

Water Quality Assessment, Eutrophication, and Pollution Index in Lake Edku (Nile Delta of Egypt)

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Abstract

Lake Edku is one of the most important lakes in the northern Nile Delta of Egypt. Studying the physicochemical characteristics and nutrient salts is essential for assessing water quality. pH recorded values fell within internationally permitted limits; the temperature was suitable for the growth of fish and living organisms. Electrical conductivity indicates a source of fresh water; salinity indicates that the lake water is brackish; Total dissolved solids (TDS) refers to most of the fresh water in the lake. Solid particulate matter occurred within the permissible limits according to WHO, and dissolved oxygen, and some results exceeded the permissible limit. However, biochemical oxygen demand 5 did not exceed the permissible limits. In addition, dissolved nutrients (nitrate, ammonium, nitrite, and phosphorus) did not exceed the permissible limits. The seasonal and regional water quality index ranged between good, fair, and poor water quality that was restricted to use for irrigation and industrial purposes. The water pollution index fluctuated between impure rank and polluted rank during spring and between heavily polluted rank and polluted rank during summer. The N/P ratio indicates the prevalence of dissolved phosphorus in all parts of the lake. Eutrophication level: chlorophyll ranged between eutrophic and hypertrophic. Nitrates fluctuated between oligotrophic and mesotrophic and phosphates fluctuated between hypertrophic and eutrophic.

Keywords: Chlorophyll-a, Eutrophication, Nutrient limitation, Pollution index, Water quality

1. Introduction

Lake Edku is considered the third largest northern Egyptian coastal lake in the Nile Delta, situated in the Beheira governorate, and one of the most threatened aquatic environments in Egypt due to anthropogenic activities and pollution (Omran and Negm, 2019). Its area has decreased to about half the area or more because of agricultural reclamation. It receives huge amounts of drainage water from four main drains, namely Bousaly, Edku, Berseek, and El-Khairy (Okbah and El-Gohary, 2002). The morphostructure and physiochemical composition of the lake changed very quickly because of human activities such as urbanization, industrialization, agricultural activities, and unregulated fish farming activities (Gu *et al.*, 2013). Water cleanliness and safety are essential matters for the survival of living organisms, and due to the expansion of human activities (industrial, agricultural, and population), which in turn threatens to cause significant changes in water quality parameters. It was necessary to pay attention to water quality monitoring as a vital matter. The aquatic environment contains living organisms and dissolved and insoluble substances. These substances are necessary for the process of determining water quality when they are present naturally and in a way that does not affect the aquatic environment (Chowdhary *et al.*, 2020). Anthropogenic activities (agricultural,

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industrial, and domestic) are among the most important factors that change the aquatic environment's biological, physical, and chemical properties and threaten the ecosystem's integrity. The most important of these activities are the unregulated and deliberate disposal of waste of living organisms (human and animal), the use of nonconstructive and effective treatment methods, and the use of harmful agricultural materials. It is discharged into the aqueous environment (Kennish, 2002). The physical, chemical, and biological properties control the assessment of water quality. The change in chemical factors such as the degree of salinity, sediment, salts, and harmful organic and inorganic chemicals, as well as the change in biological properties represented in the organisms that cause diseases, in addition to the physical properties such as the change in temperature and water movement. All these factors are considered causes of the deterioration of surface water ecosystems (Bhateria and Jain, 2016). Water pollution is a major global problem that needs regular assessment of water resource policy at all levels. It has been suggested that water pollution is the primary cause of death and health diseases worldwide (El-Kowrany *et al.*, 2016). There are many purposes for using water including drinking, domestic purposes, agricultural purposes, or industrial purposes, so it was important and necessary to do a water test for the purposes used (Bhateria and Jain, 2016). The present work aimed to determine eutrophication, pollution, and nutrient levels in Lake Edku water. In addition, statistical analysis for the obtained results was applied.

2. Materials and methods

2.1. Study area and sampling

Lake Edku is united by a coastal road and a railroad to Alexandria to about 42 km along the west-southwest side, in addition to the railroad to Rosetta to about 19 km to the northeast (Abd El-Hamid *et al.*, 2021). Lake Edku is located nearly 30 km east of Alexandria government between Long. 30° 16' and 30° 26' E and Lat. 31° 26' and 31° 24' N (Fig. 1). Using a Niskins bottle 5 l of surface water samples was collected below 20 cm and subsampled immediately to determine the dissolved oxygen (DO), salinity (S), suspended particulate matter (SPM), biochemical oxygen demand (BOD), total dissolved solids (TDS), chlorophyll-a (Chl-a), ammonium (NH_4), nitrite (NO_2), and nitrate (NO_3) (Mortimer *et al.*, 2013). Eight stations have been identified to cover the whole lake as illustrated in Fig. 1. Stations I, II, and III cover the southern part, stations IV, V, and VII cover the northern part, station V the middle of the Lake, and station VIII points of linkage of the Mediterranean Sea with the Lake.

2.2. Methods of analysis

The pH was determined immediately by the calibrated digital pH meter (Orion research, Model 211 digital pH meter). Temperature was determined by an ordinary thermometer graduated at 0—100 °C. DO was performed according to the Winkler titration method (Hansen, 1999). The determination of BOD and DO was measured initially, and after incubation (5 days), DO was measured in the same way. BOD is calculated from the difference between the initial DO (in mgL^{-1}) and final DO_5 mgL^{-1}. TDS (in mg/l) was determined by gravimetric methods according to Hansen (1999). Salinity was measured using an induction salinometer (Beckman, model RS7-C). The solid suspended matter (SPM in mg/l) concentration was determined according to APHA 2005. The concentration of chlorophyll-a was determined spectrophotometrically according to Park (1969) by using ethanol extraction and a centrifuge. Samples were filtrated through Whatman GF/C fine mesh filter paper (0.45 μm), and samples were centrifuged for 15 min at 3000 rpm. The clear supernatant solution was completed to 10 ml with 90% aqueous acetone and then measured spectrophotometrically using a 1 cm-cell at 630, 645, 440, 750, and 665 nm, and the concentrations were calculated according to the following formula:

$$\mathrm{Chl-a}\ (\mu g/l) = [(11.6D_{665} - 1.13D_{645} - 0.14D_{630}) \times V1] / (L \times V2)$$

D = absorbance at wavelength (630, 665, and 645 nm using a 1 cm-cell), V1 = volume of extract (mL), and V2 = volume of filtered water sample (in liter). Concentrations of nutrient salts were determined according to Hansen and Koroleff (1999). The forms of dissolved inorganic nitrogen (NO_2—N, NO_3—N, and NH_4—N) were determined using colorimetric techniques with the formation of reddish purple azo-dye, copper hydrazine sulfate reduction, and phenate methods, respectively. Reactive phosphate (PO_4—P) was determined using the ascorbic acid molybdate method.

3. Result and discussion

3.1. Physicochemical parameters

The pH is considered one of the most important parameters used as a pollution index for the lakes, which is essential to plants and animals in aquatic

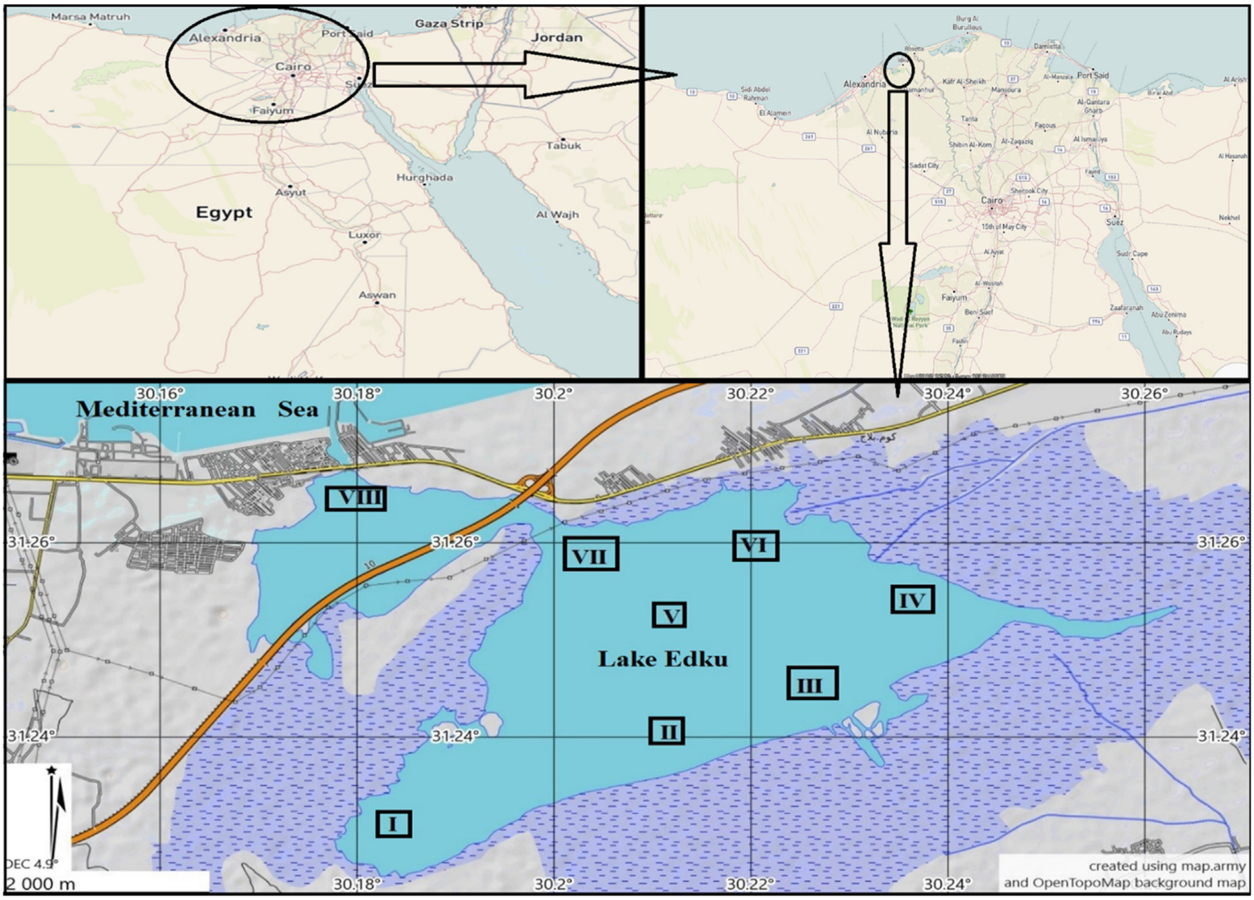

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Fig. 1. Map of sampling locations, Lake Edku.

life and affects most chemical and biological processes in the aquatic environment (Vasistha and Ganguly, 2020). pH values during the present study ranged between 7.90 at station IV and 9.0 at station I, with an average of 8.40 ± 0.39 during spring. The summer recorded a minimum value of 7.60 at station VIII and a maximum value of 8.90 at station IV, with an average of 8.33 ± 0.43 (Table 1). The standard pH value for aquatic organisms is between pH 6.5 and 9 as stated by US EPA standards. Low pH affects aquatic biota (Vasistha and Ganguly, 2020), making the results on the safe side. A low pH can cause gill damage, growth decrease, reproductive failure, and mortality). The source of high pH value may be natural sources such as alkaline geology and soils, industrial waste discharges, agricultural lime, and urban pollutants (Vasistha and Ganguly, 2020).

Temperature is a substantial factor to consider when assessing water quality. It can affect several parameters that are used to determine water quality, such as DO, BOD, metabolism, photosynthesis, salinity, density, and pH (Dey *et al.,* 2021). An increase in temperature can lead to an increase in the toxicity rate of the environmental ecosystem. The solubility of oxygen in water is inversely proportional to temperature; a higher temperature leads to a lower DO rate in the water (Karvonen *et al.,* 2010). Temperature, as shown in Table 1, during spring ranged between 23 °C at station V and 26 °C at station VII, with an average of 24.10 ± 0.93 °C during the spring season. During summer, it fluctuated between 26 °C at station VIII and 31.00 °C at station II, with an average of 28.50 ± 1.66 °C. Sunlight, or solar radiation, the atmosphere, and the transfer of heat from a higher temperature to a lower temperature are the most influential factors (Karvonen *et al.,* 2010). Turbidity increases the water temperature by absorbing the heat from solar radiation and transferring it to water molecules, which leads to an increase in the water temperature. Man-made effects, such as municipal or industrial effluents, can also affect water temperature (Irwin and Pickrill, 1982).

Electrical conductivity (EC) can be defined as the capability to pass electrical flow and is related to the concentration of ions (dissolved salts and inorganic

Table 1. Physio-chemical characteristics during spring and summer 2022 (Lake Edku).

	Min	Max	Ave	±SD
Spring				
pH	7.90	9.01	8.40	0.42
DO (mg/l)	8.70	20.30	11.72	4.00
BOD (mg/l)	15.96	30.34	24.98	5.21
Temp. (C°)	23.00	26.00	24.10	1.00
EC (μs)	2200.00	3200.00	2790.00	319.42
Salinity (g/l)	0.70	2.00	1.21	0.41
TDS (mg/l)	13.09	28.40	21.27	4.88
SPM (mg/l)	60.30	158.93	100.74	28.70
Chl-a (μg/l)	15.30	55.60	39.38	13.93
NH4/N (mg/l)	0.35	1.99	1.22	0.55
NO3/N (mg/l)	0.03	0.20	0.09	0.05
NO2/N (mg/l)	0.06	0.23	0.14	0.06
Total N (mg/l)	0.57	2.15	1.45	0.52
PO4/P (mg/l)	0.31	1.70	0.94	0.44
Summer				
pH	7.60	8.90	8.33	0.48
DO (mg/l)	9.90	19.80	13.20	3.53
BOD (mg/l)	9.98	39.61	25.13	10.18
Temp. (C°)	26.00	31.00	28.50	1.77
EC (μs)	1500.00	3800.00	2468.75	741.11
Salinity (psu)	1.54	3.05	2.23	0.52
TDS (g/l)	16.09	31.25	24.05	6.44
SPM (mg/l)	80.91	199.21	134.84	38.69
Chl-a (μg/l)	13.40	45.37	34.73	9.76
NH4/N (mg/l)	0.87	2.11	1.50	0.51
NO3/N (mg/l)	0.11	0.28	0.19	0.05
NO2/N (mg/l)	0.05	0.23	0.17	0.06
Total N (mg/l)	1.18	2.42	1.85	0.50
PO4/P (mg/l)	0.50	2.30	1.28	0.74

compounds) that are known as electrolytes in water and aquatic environments. Ions or electrolytes, when they dissolve in water, are divided into positive (cation) and negative (anion) charges. So, more ions mean higher conductivity and fewer ions mean less conductivity (Das, 2023). EC of water lakes results from the inflow of dissolved inorganic materials from many sources, such as underground inflow, river inflow, surface runoff, and precipitation. So, EC considers this a suitable indicator for identifying the main sources of water supply to lakes (Das, 2023; Borowiak *et al.*, 2020); EC for the samples that were examined (Table 1) ranged between a maximum value of 3800 mS at station VIII and a minimum value of 1500 mS at station IV during the summer, with an average of 2468.75 ± 741.11 mS. During spring EC ranged between 2200 mS at station VII and 3200 mS at station I with an average of 2790 ± 319.42 mS; conductivity between 1000 and 10 000 μS/cm is an indicator of saline water condition (Das, 2023), the results of the study suggest that the lake's water is brackish water.

Salinity is defined as the total concentration of dissolved salts (noncarbonate salts) or the total concentration of all ions in water (Lembi, 2001). Salinity can be classified into two types: primary (natural salinity) sources of salt result from watersheds or high evaporation rates, and secondary salinity (human activity) such as industrial, domestic, and agricultural activities (Musie and Gonfa, 2023); an organism can be divided into stenohaline (freshwater organisms) usually found at salinities below 3000 ppm, euryhaline (seawater organisms) usually found at salinities of 3000–10 000 ppm, and finally, there are a small number of organisms that can adapt between salt water and fresh water (Kültz, 2015). Salinity ranged between a minimum value of (1.54–0.70) g/l at stations V–VI and a maximum value of (3.05–2.00) g/l at stations (VIII), with an average of 1.21 ± 0.41 and 2.23 ± 0.52 g/l during spring and summer, respectively. Salinity values in the current study were in the order of spring less than summer. The United States Geological Survey (USGS) classified the salinity of water bodies according to their concentrations: freshwater (less than 1,000 ppm), slightly saline water (1,000–3,000 ppm), moderately saline water (3,000–10 000 ppm), and highly saline water (10 000–35 000 ppm) (Kültz, 2015), that is, make all stations during the present study slightly saline water.

TDS contains inorganic salts and organic compounds that are dissolved in water. TDS originates from many sources, such as natural sources, industrial wastewater, urban and agricultural runoff, and sewage (Vasistha and Ganguly, 2020). TDS fluctuated between a lowest value of 13.09 mg/l at station VIII during spring and a highest value of 28.04 mg/l at station I, with an average of 21.27 ± 4.56 mg/l (Table 1). During summer, values ranged between 16.09 mg/l at station VII and 31.25 mg/l as a minimum and maximum, respectively, with an average of 24.05 ± 6.02 mg/l. The permissible limit of TDS in water is 500.0 mg/l; concentrations above 1000.0 mg/l include minerals; a concentration above 2000.0 mg/l is considered too salty to drink (Herschy, 2012). According to WHO water quality guidelines, the permissible limit of TDS in drinking water for human beings is 1,000 mg/l, which makes it not drinkable.

SPM through the samples that were withdrawn fluctuated between a minimum value of 60.30 mg/l at station V during spring and a maximum value of 199.21 mg/l at station VII during summer, with an overall average of 117.79 ± 36.14 mg/l. Seasonal average recorded 21.27 ± 4.56 mg/l during spring with a minimum value of 80.91 at station III and a maximum of 199.21 at station VII with an average of 134.84 ± 36.19 mg/l as illustrated in Table 1. The variation of SPM concentration between the two seasons can be arranged descending as summer greater than spring. The source of SPM in water bodies may originate from rainfall erosion on watersheds, beds, and shorelines, erosion by water and waves, resuspension of sediment, leaf fall, macroorganisms and microorganisms such as plankton and bacteria, and detritus. Increasing SPM can lead to an increase in water temperatures, followed by a decrease in DO in the water, which can cause a depletion of oxygen levels (Alongi, 2020). WHO set the permissible limits for the concentration of suspended matter to be 10:50 mg/l (Vasistha and Ganguly, 2020), and accordingly, all concentrations during the current study exceeded the permissible limits.

DO is defined as the concentration of DO gas in the water. The main source of oxygen in water is direct absorption from the atmosphere (Sherwood *et al.*, 1991); oxygen can be released through photosynthesis processes by aquatic plants. A decrease in DO may cause death of aquatic fish (Müller *et al.*, 2012). DO below 2 mg/l can cause hypoxia, which results in a change in the diversity and biological system of the aquatic environment, which in turn may lead to economic loss (Müller *et al.*, 2012). Annual absolute DO during the present study recorded a maximum value of 20.30 mg/l at station V during spring and a minimum absolute value of 8.70 mg/l at station II during the same season, with an average of 12.46 ± 3.66 mg/l. Minutely, the spring season recorded a previous minimum and maximum value with an average of 11.72 ± 3.74 mg/l; however, DO during the summer ranged between 9.90 mg/l at station VII and 19.80 mg/l at station III with an average of 13.20 ± 3.30 mg/l. Some parameters can affect DO concentration, such as temperature, nutrients, sediments, and ammonia (Rajwa-Kuligiewicz *et al.*, 2015).

BOD is the amount of oxygen consumed by bacteria during the decomposition of organic matter under aerobic conditions. High BOD indicates the presence of large quantities of microorganisms, which indicates a high level of pollution in the water. BOD generally affects the amount of DO in aquatic environments. A greater BOD value means rapid oxygen consumption, which means less oxygen is needed for aquatic life (Vasistha and Ganguly, 2020). BOD5 recorded an annual average of 25.06 ± 5.10 mg/l with a minimum value of 15.24 and a maximum value of 33.26 mg/l. Seasonal values of BOD5 fluctuate between 15.96 at station VI and 30.34 mg/l at station IV during spring with an average of 24.98 ± 4.87 mg/l, and 9.98 at station I and 39.61 at station V with an average of 25.13 ± 9.52 mg/l during summer. Increasing BOD levels at stations IV (II, III, V, and VIII) during both seasons may be due to nearing stations from drains and grasslands. Leaves, debris, plant and animal waste, wastewater treatment plants, and urban stormwater runoff are considered the primary sources of BOD. Accordingly, the results of the study did not exceed the permissible limits.

Chl-a: The importance of chlorophyll is that it converts sunlight from the sun and carbon dioxide from respiration processes and the environment into useful organic compounds such as carbohydrates and oxygen. High chlorophyll rate means nutrient enrichment that can cause the production of harmful species such as cyanobacteria or blue-green algae that release cyanotoxins (hepatotoxins that can cause damage to the liver and neurotoxins that can cause death) that are considered very toxic and harmful to animals and humans. It is commonly used to measure and determine water quality (Pareek *et al.*, 2017). Chl-a values ranged between a minimum of 15.30 and 13.40 μg/l at station VIII and a maximum value of 55.60 and 45.37 μg/l at station V, with an average of 39.38 ± 13.03 and 37.06 ± 10.67 μg/l during spring and summer, respectively (Table 1). The variety of concentrations between stations may be located at the station nearest drains that improve a large quantity of nutrients to the lake. Many reasons can cause a rise in chlorophyll concentration, such as rainfall that is loaded with nutrients. The chlorophyll level is also increased during the summer months. In contrast, the tidal system, constructions, and breakwaters in turn affect the rate of the amount of nutrients present in the water body (Monbet, 1992). Human activity can cause a rise in nutrient levels in rivers to increase two important nutrients, nitrogen, and phosphorus, that cause an increase in Chl-a. An increase in nitrogen and phosphorus concentrations may occur due to many reasons, including agricultural inputs such as fertilizer implementation and treated sewage effluent (Monbet, 1992).

Nitrate is the essential form of nitrogen element that plants use as a nutrient to raise the level of growth. Nitrate is considered the most oxidized and stable form of nitrogen in a water system. Overloading amounts of nitrogen may result in phytoplankton or macrophytes increasing in rate, leading to aquatic system toxicity, significant problems for water quality, and eutrophication (Camacho-Cruz *et al.*, 2020). Sources of nitrates include human activities, runoff from land and animal manure storage areas, failing on-site septic systems, and industrial discharges. Permissible limits of nitrate in surface water are low (less than 1 mg/l) (HM, 2018). The seasonal average concentration of dissolved nitrates recorded

0.14 ± 0.04 mg/l with a minimum value of 0.08 mg/l at station IV and a maximum value of 0.21 mg/l at station VII; during spring, dissolved nitrates' recorded values fluctuated between 0.03 at station VII and 0.20 at station V with an average of 0.09 ± 0.05 mg/l; however, during summer, recorded values ranged between 0.11 at station IV and 0.28 at station VIII with an average of 0.19 ± 0.05 mg/l. The seasonal average values are ranged in the order: summer > spring. During spring, stations V, VIII, and II recorded the highest values: VIII > V > VII > II > VI > III > I > IV during summer. The low average nitrate content in spring is possibly due to the consumption of nitrates by phytoplankton, which increased in spring. The maximum value is obtained for the western and southern parts where the nitrate concentration increased due to the presence of agricultural sources and wastewater. All results fall below the permissible limit value of 50 mg/l.

Ammonium ions result from the product of the metabolism of animals, anthropogenic activities, and human activities. Ammonium is ionized and formulated as NH_4^+ and is harmless to aquatic organisms. The danger of ammonium to the aquatic environment lies when it is converted into ammonia, which is considered harmful. The main controller in the direction of the reaction is the pH, especially when the pH value is high. Temperature can also influence the transformation process (Hughes *et al.*, 2008). The ammonium−nitrogen (NH_4^+−N) concentration was determined in the water collected from all stations. The annual average values of ammonium−nitrogen (NH_4^+-N) ranged between a minimum of 0.68 mg/l at station VIII and a maximum value of 1.88 mg/l at station VII with an average value of 1.36 ± 0.35 mg/l; seasonal values of ammonium−nitrogen (NH_4^+-N) recorded a minimum value of 0.35 mg/l at station VIII and a maximum value of 1.22 mg/l at station VII with an average of 1.22 ± 0.51 mg/l during spring; during summer recorded a minimum value of 0.87 mg/l at station III and a maximum value of 2.11 mg/l at station I with an average of 1.50 ± 0.48 mg/l. Accordingly, summer > spring, in addition to stations VII, III, IV, and VI during spring, and stations I, VI, II, and VII recorded the highest values. Decreasing ammonium level changes in ammonium can be attributed to utilization by phytoplankton and hydrophytes; sedimentation from the atmosphere, industrial and health waste, sewage and agricultural waste, and biological decomposition of waste are also considered sources of ammonium emergence in the aquatic environment (Hughes *et al.*, 2008). Microbial activities and transformations are considered the most important sources controlled in the nitrogen cycle pathway and nitrification processes through which the oxidation of ammonium to nitrite and subsequently to nitrate occurs (Stein and Klotz, 2016).

Nitrite concentration by mg/l during the present study recorded a minimum value of 0.05 at station II and a maximum concentration of 0.23 at station VIII with an average of 0.17 ± 0.06 mg/l and arranged ascending as II, V, III, VI, I, IV, VII, and VIII during spring; however, arranged ascending as II, V, VIII, IV, VII, III, VI, and I with a seasonal average of 0.14 ± 0.06 mg/l and a maximum value of 0.23 mg/l at station VIII, and a minimum value of 0.06 mg/l at station II during summer; summer greater than spring. The increase in nitrite concentration at the shown station may be due to the proximity of these stations to agricultural, industrial, and population activities, which in turn led to the accumulation of nitrite in those stations, and this is confirmed by Eddy and Williams (1987).

Phosphate is an important nutrient essential for cellular growth; it converts sunlight into applicable energy. An increase in phosphorus concentration may lead to disturbance in the food web, including acceleration in the growth process, and therefore a decrease in oxygen concentration, which in turn leads to the death of aquatic organisms (Fadiran *et al.*, 2008). Dissolved phosphorus in Lake Edku during the spring season recorded a minimum value of 0.31 mg/l at station I and a maximum value of 1.70 mg/l at station VII with an average of 0.94 ± 0.41 mg/l; however, it recorded a minimum value of 0.50 mg/l at station II and a maximum value of 2.30 mg/l at station III with an average of 1.28 ± 0.69 mg/l during the summer; stations during the spring can be arranged to descend as VII, IV, VIII, V, VI, III, II, and I; during the summer, stations can be arranged to descend as III, V, IV, VI, VIII, I, VII, and II. There are many sources of phosphorus between natural sources, such as those resulting from rocks, soil, and surface runoff of water laden with phosphorus, and between human sources, represented in wastewater, treatment plant water, and industrial and agricultural activities (Fadiran *et al.*, ,2008). The USEPA has confirmed a suitable limit of total phosphates of 0.05 mg/l in streams that enter lakes and 0.1 mg/l for total phosphorus in flowing waters to control eutrophication. The concentrations recorded lower values than the permissible value (5 mg/l).

3.2. Overall water quality index

The overall water quality index (WQI) expresses the total water quality. The weight arithmetic WQI is a common measure of water quality and is widely used and calculated according to Tyagi *et al.* (2013).

Calculation and ranking of weighted arithmetic WQI as follows:

$$k = 1 / \Sigma \left(\frac{1}{sn} \right)$$

$$\mathrm{qn} = [(\mathrm{Vn} - \mathrm{Vio}) / (\mathrm{Sn} - \mathrm{Vio})] \times 100$$

$$Wn = K/Sn$$

$$WQI = \left(\Sigma\, Wn \times qn \right) / \Sigma\, Wn$$

Where K is the proportionality constant, Sn the standard permissible limit for parameters, qn the quality rating for all the parameters, Vn the value of the nth parameter during the present study, and Vio is the ideal value of the parameter in pure water.

Ratings of water quality are as follows: 50–100: excellent (drinking, irrigation, and industrial), 101–150: good (domestic, irrigation, and industrial), 151–200: fair (irrigation and industrial), and 201–250: poor (irrigation), above 150: very poor (restricted use for irrigation) (Table 2).

The selected 10 parameters during the present study, as shown in (Table 2), were used for the calculation of the WQI: pH, DO, BOD, Temp., EC, TDS, SPM, NH_4–N, NO_3, and PO_4. The results of the WQI ranged between a minimum of 70 and 98 at station I and a maximum of 209 and 283 at stations VII and III; stations can be arranged as VII > IV > VIII > V > III > V > II > I and III > V > VI > I > VI > VII > II > I during spring and summer, respectively. Stations III and V recorded very poor water quality. The overall average for the water lake shows that the Edku Lake water during spring and summer shows fair-quality water, which recorded a value of 175.17 and 197.89 which makes it restricted to use for irrigation and industrial use. The concentrations of dissolved phosphorus, dissolved ammonium, and BOD showed concentrations higher than the permissible value and ideal value, which makes the rank of water fair (Table 2 and Fig. 2).

Table 2. Results of water pollution index (WPIs) and water quality index (WQI) during spring and summer 2022 (Edku Lake).

St.'s	Ranking WPI	Summer	Spring	Status (WQI)	Summer	Spring
		WPI			WQI	
I	Polluted	2.76	2.80	Excellent	70	98
II	Polluted	4.12	3.98	Good	106	100
III	Impure	5.95	3.43	Good	123	283
IV	Polluted	2.25	4.34	Fair	185	225
V	Impure	6.28	5.35	Fair	148	272
VI	Impure	5.89	3.06	Fair	123	171
VII	Polluted	4.21	3.31	Fair	209	114
VIII	Impure	4.13	4.25	Good	149	133

Ranking WPI {Very Pure (≤0.3), Pure (0.3–1.0), Moderately polluted (1.0–2.0), Polluted (2.0–4.0), Impure (4.0–6.0)]. Status WQI {Excellent (50–100), Good (101–150), Fair (151–200), Poor (201–250), Very poor (Above 250)}.

3.3. Water pollution index (WPI)

The water pollution index (WPI) is a mathematical way to determine the chemical status of surface waters by comparing the mean annual observed parameters and their standard values divided by the number of observed parameters. The WPI is used to determine and monitor pollution in the water body using some water quality parameters and the defined standard values for these parameters. Water pollution level according to WPI can be determined according to Grzywna and Sender (2021):

$$WPI = 1/n \sum_{n=1}^{n} \mathrm{An}/\mathrm{T}$$

where *An* is the annual average value for each parameter; *T* is the standard threshold value for each parameter. We used the standards as zero for all parameters except pH and DO 7 and 14.6 mg/l, respectively. *n* is the number of used parameters.

The following parameters were used: pH, DO, BOD, EC, SPM, NH_4/N, and PO_4/P to measure the WPI. The results found that all stations of water from Lake Edku during spring ranged between a minimum value of 2.25 (polluted IV) at station IV and a maximum value of 6.28 (heavy impure VI) at station V, which fluctuated between polluted, impure, and heavily impure. Stations can be arranged in ascending order as follows: IV, I, II, VIII, VII, VI, III, and V. During summer, it recorded a minimum value of 2.80 (polluted IV) at station I and a maximum value of 5.35 (impure VI) at station V, which fluctuated between polluted and impure. Stations can be arranged in ascending order as follows: I, VI, VII, III, II, VIII, IV, and V, as shown in Table 2 and Fig. 3. DO, BOD, SPM, and EC were the most important parameters that affected and raised the value of WPI.

3.4. Eutrophication levels

Eutrophication can be defined as an aquatic environmental enrichment process with minerals and nutrients (nitrogen and phosphorus) that leads to an increase in productivity for phytoplankton. Eutrophication general symptoms include intense

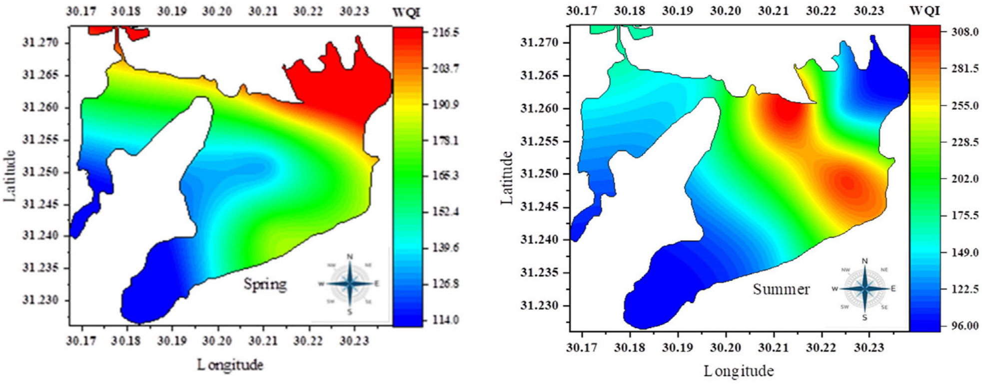

Fig. 2. Horizontal contours of water quality index (WQI) during spring and summer 2022.

algal blooms that lead to high turbidity and causing decreasing of oxygen (anoxia) in lakes and then causing fish to die (Schindler, 1975), and can be divided into three types: oligotrophic: very low nutrient concentration; mesotrophic, which refers to moderate nutrient concentration; and dystrophic or hypertrophic: very high nutrient concentration (Turner and Chislock, 2010). An increase in the process of eutrophication leads to the emergence of unpleasant odors, reduces water quality rates, reduces the appearance of some other algae, reduces growth rates, and increases the percentage of turbidity, the depletion of dissolved carbon in the water, and the high degree of acidity (Schindler, 1975). Eutrophication levels were determined according to the concentration of chlorophyll, nitrate, and phosphate in the Edku lake during the present study, based on. oligotrophic, mesotrophic, eutrophic, and hypertrophic levels for Chl-a (<2, 2: 6, 6:40,>40), for nitrate (<0.110, 0.0110: 0.290, 0.290: 0.940, >0.940), for phosphate (<0.015, 0.015: 0.040, 0.040–0.130, >0.130) (Håkanson and Bryhn, 2008).

As can be seen from Table 3), chlorophyll recorded rates with large values that made all stations during the spring and summer seasons range between eutrophic and hypertrophic, where stations I, II, III, V, and VI recorded hypertrophic conditions and stations IV, VII, and VIII recorded eutrophic conditions during the spring; during the summer, stations I, II, IV, VI, VII, and VIII and stations III and V recorded eutrophic and hypertrophic conditions, respectively. During spring, stations I, III, IV, VI, and VII recorded lower values of nitrates and ranked as oligotrophic, while other stations II, V, and VIII were ranked as Mesotrophic. During spring and summer, all stations recorded a rank of hypertrophic except for station I, which was ranked as eutrophic.

3.5. Nutrient limitation (Nutrient ratios)

Nutrient limitation is defined as controlling organism growth due to nutrient input to its environment. According to the definition, the nutrients found in the lowest concentration compared with the other nutrients will limit the growth and productivity of organisms (De Baar, 1994). The Redfield ratio is the ratio that scientists rely on in estimating the nutrient ratio, mentioning that the average of marine algae nutrients requires N and P in a molar ratio of about 16:1 (7.2:1 by weight). The N:P ratio is used to determine nutrient limitation (Redfield, 1958).

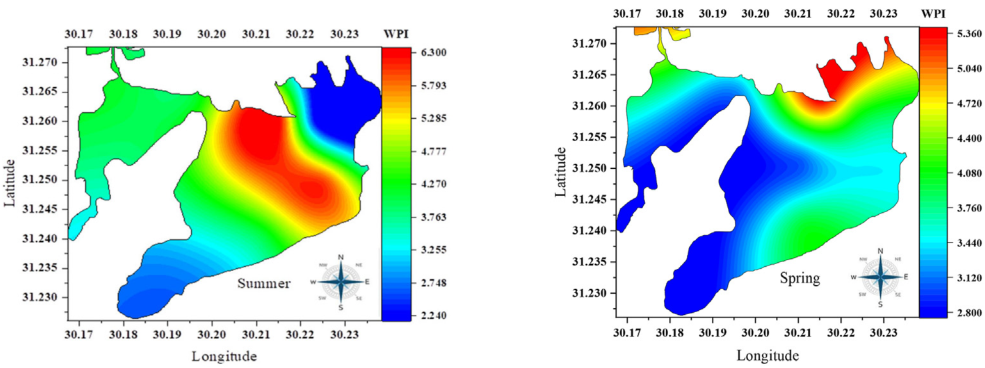

Fig. 3. Horizontal contours of water pollutionindex (WPI) during spring and summer 2022.

Table 3. Eutrophication status during spring and summer 2022 (Edku Lake).

St.	Spring			Summer		
	Chl-a (mg/l)	NO_3/N (mg/l)	PO_4/P (mg/l)	Chl-a (μg/l)	NO_3/N (mg/l)	PO_4/P (mg/l)
I	**48.20**	0.09	*0.31*	*38.20*	0.12	**0.66**
II	**45.30**	0.12	**0.55**	*35.87*	0.2	**0.5**
III	**50.10**	0.07	**0.76**	**41.21**	0.18	**2.3**
IV	*30.30*	0.05	**1.35**	*39.48*	0.11	**2.01**
V	**55.60**	0.2	**0.93**	**45.37**	0.22	**2.11**
VI	**44.30**	0.06	**0.87**	*34.11*	0.19	**1.11**
VII	*25.95*	0.03	**1.7**	*30.20*	0.21	**0.65**
VIII	*15.30*	0.11	**1.02**	*13.40*	0.28	**0.89**

Oligotrophic, Mesotrophic.
Italic values represent *Eutrophic*.
Bold values represent **Hypertrophic**.

Nutrient limitation availability for phytoplankton during the study was assessed using ratios of total dissolved inorganic nitrogen (nitrate, nitrite, and ammonium): Total phosphorus (soluble reactive phosphorus, SRP) DIN: TP. N limitation was considered probable when N:P less than 10, P limitation when N: P greater than 20, and potential co-limitation was indicated by intermediate ratios (Maberly *et al.*, 2020). By using the results of the nutritional parameters during the present study to determine the N:P ratio, which is represented in nitrate, nitrite, ammonium, and phosphorous dissolved in water, all results indicated that during the spring and summer seasons, phosphorous was prevalent in all parts of the lake under study and in all stations without exception, where the highest value was recorded 3.4. In station I, the lowest value recorded 0.6 in station VIII during the beginning of the spring season, while the lowest value was recorded at 0.5 in station III, and the highest value was recorded at 4.3 in station II at the end of the summer as illustrated in Table 4.

Table 4. Assessment of nutrient limitation using N:P ratios of DIN and SRP.

	St.'s	N:P	Status	Chl-a: TP	Chl-a: TN	Status
Spring	I	3.4	N-limited	0.16	0.05	None-limitation
	II	2.2	N-limited	0.08	0.04	None-limitation
	III	2.6	N-limited	0.07	0.03	None-limitation
	IV	1.3	N-limited	0.02	0.02	None-limitation
	V	1.3	N-limited	0.06	0.04	N-limited
	VI	1.8	N-limited	0.05	0.03	None-limitation
	VII	1.3	N-limited	0.02	0.01	None-limitation
	VIII	0.6	N-limited	0.02	0.03	None-limitation
Summer	I	3.7	N-limited	0.06	0.02	None-limitation
	II	4.3	N-limited	0.07	0.02	None-limitation
	III	0.5	N-limited	0.02	0.03	None-limitation
	IV	0.8	N-limited	0.02	0.02	None-limitation
	V	0.6	N-limited	0.02	0.03	None-limitation
	VI	2.1	N-limited	0.03	0.01	None-limitation
	VII	3.4	N-limited	0.05	0.01	None-limitation
	VIII	1.7	N-limited	0.02	0.01	None-limitation

3.6. Chlorophyll-a to nutrient ratios

Measuring the ratio of Chl-a to nutrients is an important factor as a result of the environmental impact of those nutrients. By increasing these nutrients, the rate of Chl-a increases, and vice versa. Chl-a/TP greater than 0.3 indicates P limitation and Chl-a/DIN greater than 0.042 indicates N limitation (44–45). All stations during spring and summer recorded no limitation except station I during spring which recorded N-limitation (Table 4).

3.7. Statistical analysis

3.7.1. Hierarchical cluster analysis (HCA)

HCA is a method used to identify relatively homogeneous groups of cases (variables) based on selected characteristics and build a hierarchy cluster (tree diagram) design that allows quantifying, understanding, and sorting data by calculating the strength of the perceived relationships between pairs of data (Sibson, 1973; Nielsen, 2016). In the present study, (a) single linkage clustering and (b) complete linkage clustering are the most common algorithms. Agglomerative methods are used (Drab and Daszykowski, 2014). This dendrogram was confirmed by applying two other clustering methods: (1) single linkage using the cluster method nearest neighbor with an interval Pearson correlation and (2) complete linkage using further neighbor with an interval Pearson correlation. Hierarchical cluster analysis for both the single linkages (nearest neighbor) for stations and the complete linkages (between groups) for physicochemical parameters showed similar relations between pollutants, as illustrated in Figs. 4 and 5. The hierarchical cluster analysis (dendrograms) results matched the principal component analysis (PCA). Cluster stages contain a correlation between stations V and VI at a distance of 69.58, stations III and VI at a distance of

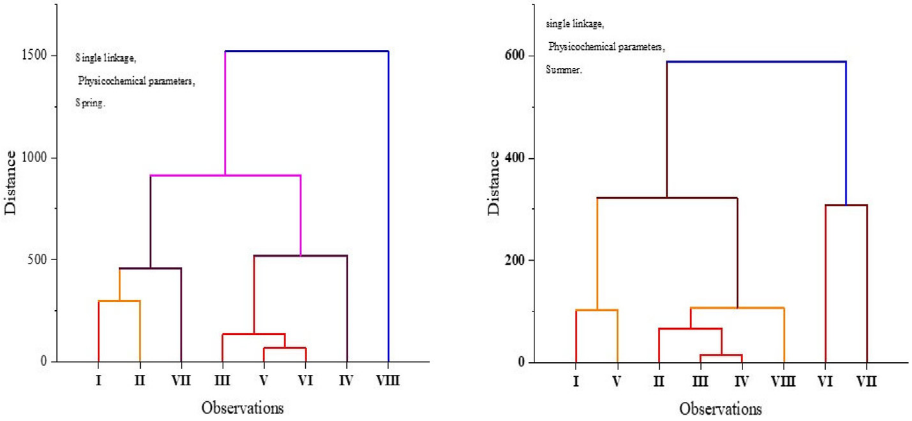

Fig. 4. Hierarchical cluster analysis Dendrogram of water samples between stations during the spring and summer 2022, Lake Edku.

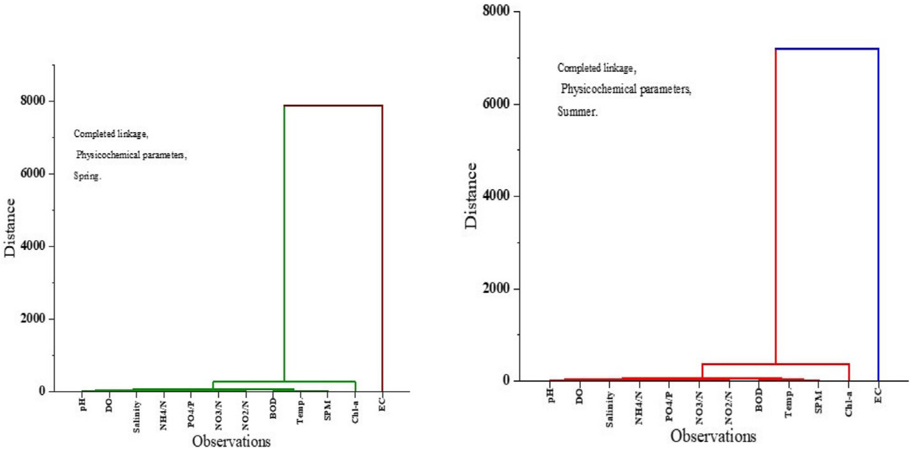

Fig. 5. Hierarchical cluster analysis Dendrogram (complete linkage) between groups of physicochemical parameters during the spring and summer 2022, Lake Edku.

135.30, stations I and II at a distance of 301.24, stations I and VII at a distance of 457.58, stations III and IV at a distance of 521.35, stations I and III at a distance of 914.40, and stations I and VIII at a distance of 1522.18 during spring. During summer, stations (III and VI) correlated at a distance of 163.31, stations (II and III) at a distance of 67.20, stations I and V at a distance of 103.70, stations II and VIII at a distance of 107.82, stations VI and VII at a distance of 308.25, stations I and II at 322.27, and stations I and VI at a distance of 588.56. Stations II and IV were considered the most representative observations, while stations VIII and VII were considered the least representative observations during spring and summer, respectively.

3.8. Conclusion

One of the most significant lakes in Egypt's northern Nile Delta is Lake Edku. To evaluate the quality of water, one must examine its physicochemical properties as well as its nutrient salt content. The temperature was appropriate for the growth of fish and other living things, and the pH values that were recorded were within internationally allowed bounds. TDS denotes the majority of the fresh water in the lake; electrical conductivity points to a freshwater source; and salinity indicates that the lake's water is brackish. While some results were above the allowable limit, solid particulate matter was found within the WHO and DO's permissible limits. BOD5 did not, however, surpass the allowable limits. Furthermore, the allowed limits for dissolved nutrients (phosphorus, ammonium, nitrite, and nitrate) were not exceeded. Only good, fair, and poor water quality—which could only be used for industrial and agricultural purposes—was included in the seasonal and regional WQI. In the spring, the WPI alternated between impure and polluted ranks, and in the summer, it alternated between heavily polluted and polluted ranks. The N/P ratio shows how common dissolved phosphorus is throughout the entire lake. The range of chlorophyll was between hypertrophic and eutrophic. Phosphates varied between hypertrophic and eutrophic and nitrates between oligotrophic and mesotrophic. When comparing the current results for Lake Edku with those reported in 2002 (Okbah and El-Gohary, 2002), we find a difference in the estimated values, perhaps due to changing environmental conditions surrounding the lake. During 2002, the average concentrations of ammonium fluctuated between 0.09 and 0.25 mg/l and decreased in the range from 0.005 to 0.03 mg/l in the present study, this is probably due to the utilization of NH4—N by phytoplankton. The concentration of nitrate fluctuated between 021 and 0.63 mg/l during 2002 and decreased in the range from 0.03 to 0.28 mg/l. Interestingly, increased values of reactive phosphate were identified in the current study (ranging between 0.31 and 2.30 mg/l) while in 2002 they ranged between 0.25 and 0.46 mg/l. The results of the N/P ratio in 2002 showed that the ratio ranged from 2.4 to 8.8, while in the current study, it was in the range of 0.6—4.3. Low values of the N/P ratio may be the result of an allochthonous condition of wastewater discharge.

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Author contributions

Idea and protocol design: Mohamed A. Okbah, Mahmoud S. Ibrahim, Mohammed E.M. Nassar, Maie I. El-Gammal, Methodology and experimentation: Mahmoud S. Ibrahim, Mohammed E.M. Nassar, Maie I. El-Gammal. Data analysis: Mohamed A. Okbah, Mahmoud S. Ibrahim, Tarek O. Said, Mohammed E.M. Nassar, Maie I. El-Gammal, All authors shared draft writing. All authors approved the submission.

Ethical information

The present manuscript is not submitted to more than one journal for simultaneous consideration. The submitted work is original and has not been published elsewhere in any form or language (partially or in full). The results are presented, honestly, and without fabrication, falsification, or inappropriate data manipulation. Authors adhere to discipline-specific rules for acquiring, selecting, and processing data. All authors agreed with the content that all gave explicit consent to submit and that they obtained consent from the responsible authorities at the institute/organization where the work was carried out before the work was submitted. The authors are responsible for the correctness of the statements provided in the manuscript. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Declaration of Competing Interest

The authors have no competing interests to declare.

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