Comprehensive assessment of water and sediment quality in Lake Nasser, Egypt, using various potential risk indices

by

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Abstract

Lake Nasser is a freshwater lake that supplies over 95% of Egypt's freshwater budget. Therefore, the quality of water in the lake is critical for its conservation. In addition to assessing the metal pollution load, the quality of water and sediment in the lake was assessed by collecting water and sediment samples for metal content analysis. Lake Nasser is a warm monomictic water body with a single circulation cycle in the cold months. Dissolved oxygen content in bottom water samples often dropped significantly to levels below international guidelines, reflecting reduced rates of photosynthetic activity. Although 50% of the lake's water samples contained Pb concentrations slightly above the World Health Organization's (WHO) limit for drinking water, the metal pollution index did not exceed the critical level and was classified as low metal water pollution. Based on the geoaccumulation index (I-geo), the enrichment factor (EF) and the pollution load index, the sediments of Lake Nasser are practically uncontaminated with metals. Ni has the highest EF and I-geo values, while Ni and Cd contributed the most to the ecological risk and toxic risk index. The obtained results revealed that Cd and Ni in the sediments may pose a threat to organisms living in Lake Nasser.

Key words: Lake Nasser, water quality, heavy metals, sediment analysis, potential risk indices

1. Introduction

Freshwater is necessary for human survival, and its purity has become a global problem. Egypt's national freshwater bank is represented by Lake Nasser. Water quality assessment is a critical component for any aquatic system monitoring. Therefore, this is an important technique for monitoring the most vital freshwater supply line of Egypt (Rizk et al. 2020). The quality of water in rivers and lakes has deteriorated due to the growing human population and reckless use of water resources (Muhammad & Usman 2022; Ali & Muhammad 2023). Population growth, as well as contamination through toxic wastewater and surface water runoff from urban, manufacturing, and agricultural sources, have increased pollution levels and further reduced the availability of safe water supplies (Amin et al. 2021; Abdelmageed et al. 2022).

Due to the abrupt reduction in the velocity of the main Nile River upon meeting the reservoir, huge amounts of Nile water have been stored and large volumes of sediments have accumulated in the reservoirs that have formed behind the Aswan High Dam (Goher et al. 2014). The situation is expected to change after the construction, filling, and operation of the Grand Ethiopian Renaissance Dam (GERD). Several studies (Heggy et al. 2021; Kansara et al. 2021) have shown that short-term filling scenarios (3–5 years) will result in observable water shortages in Egypt. The amount of water passing through the Aswan High Dam will be reduced to less than 55.5 km^3 per year (Egypt's proportion from 1959; Abdel-Satar et al. 2017a), especially during the initial periods of GERD filling, which could result in changes in the ecosystems of Lake Nasser and the Nile River (Heggy et al. 2021).

Lake Nasser receives a large amount of sediments brought with the flow of water from the Nile River catchments. The tunnels of the Aswan High Dam allow water to flow downstream into the Nile River, but sediments settle and accumulate in the lake, causing it to deform and reducing its storage capacity (ElKobtan et al. 2016). More than 134 million tons of Nile sediments are deposited in Lake Nasser annually (Shalash 1980). Once the GERD is operational, an estimated 90%–97% reduction in sediment accumulation in the Aswan High Dam Lake will be achieved by 2060 (Negm et al. 2018). To study all textural properties of deposits, the distributions of gravel, sand, and mud fractions are used as excellent indicators. Grain size is affected by several factors, including transport processes, sedimentation conditions, and transport-related characteristics (Farhat & Salem 2015).

Heavy metals are widely recognized as the major contaminants in aquatic environments. Lake Nasser has no direct pollution sources, but the lake receives anthropogenic heavy metals. Heavy metals enter Lake Nasser from a variety of sources, including rocks and soils directly exposed to water, decaying and dead vegetation and animal matter, dry and wet deposition of atmospheric particulate matter. In addition, other anthropogenic sources of water pollution, including discharges of various untreated wastes from different fishing boats and cruise ships, as well as domestic, agricultural, and industrial wastes are discharged directly into the Sudanese Main Nile, Blue River, and White River (Darwish 2013; Goher et al. 2019). Heavy metals can be adsorbed and stored in sediments in different forms, and under certain circumstances can be resuspended to the overlying water (Rajeshkumar et al. 2018; Muhammad 2023). In such cases, the sediments of the aquatic system become a significant source of toxins and act as a reservoir of metals. Furthermore, the biogeochemical processes and bioavailability of heavy metals are dependent on their equilibrium and transportation at the confluence of lake water and sediments (Chen et al. 2018).

The use of pollution indices is crucial for determining the degree of heavy metal contamination of water and sediment. The indices help determine whether heavy metal accumulation was caused by natural processes or anthropogenic activities (Kowalska et al. 2018). Therefore, the evaluation of heavy metal levels is important in assessing the lake environment. The objective of this study was to assess the water and sediment quality of Lake Nasser through a variety of chemical and physical tests, using various potential risk indices. The study also aimed to monitor the current state of the lake to help protect this important water source and help managers create feasible policies to protect it, especially after the GERD is filled.

2. Materials and methods

2.1. Sampling area

Lake Nasser is the second largest artificial lake in the world and a freshwater reservoir for Egypt (Fig. 1). It lies between 31°30′ and 33°15′E and 22°31′ to 23°45′N and has a total area of 6200 km^2 with an average depth of around 25 m. Lake Nasser is located in a desert area that lies between the Mediterranean and subtropical climates (Goher et al. 2014). The Aswan High Dam Lake formed one of the largest man-made lakes in Africa, which stretches 500 km south of the dam. The lake was
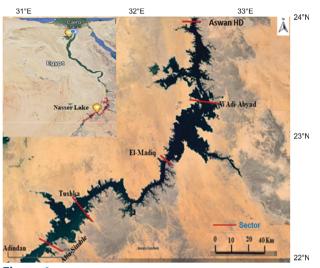
Figure 1

Map of Egypt showing Lake Nasser and the surveyed sectors (source: Google Earth 2021)

created after the Aswan High Dam was built in 1964 and completed in 1970. The lake stretches from the dam in the north to Dal Cataract in the south of Sudan. On the Egyptian side, the lake is known as Lake Nasser, whereas on the Sudanese side, it is known as Lake Nubia. Lake Nasser is extremely important to Egypt as it supplies more than 95% of Egypt's freshwater budget. It has a narrow and long shape, especially in its southern part. The shoreline of Lake Nasser is very irregular with several side channels known as khors. The lake is divided into three parts. One of them is the riverine part, which covers the southern part of Lake Nubia from the southern end to Daweishat and has year-round riverine characteristics. The second one is the semi-riverine section, which covers the northern part of Lake Nubia and the southern part of Lake Nasser, extending from Daweishat to Amada/Tushka and has riverine characteristics during floods and lacustrine conditions during the rest of the year. The final third lacustrine section covers the stretch from Amada/Tushka to the dam (El Shabrawy 2009).

2.2. Sample collection and analysis

Samples were collected twice: first in January (after the flood period) and then in July (before the flood period). Five sectors were selected to collect water and sediment from the main channel of the lake from north to south, i.e. the Aswan High Dam, Wadi-Abyad, El-Madiq, Tushka, and Abu-Simbel (Table 1). For each sector, surface and bottom water samples were collected from the eastern bank, western bank, and middle part of the main channel with a total

number of 30 samples per period. Water samples were collected using polyvinyl chloride Van Dorn plastic bottles. All samples collected for physical and chemical analysis were stored in an icebox and delivered to the laboratory within two hours.

Duplicate collocated samples were collected at the monitoring site, where the percentage difference between the field and laboratory results recorded for different samples was less than 10%. Transparency, electrical conductivity (EC), temperature, and pH were recorded in situ using a Secchi disk, conductivity meter (S.C.T.33 YSI) and a pH500/mV/Temperature Meter, respectively.

Chemical variables were estimated according to procedures outlined by the American Public Health Association (APHA 2005). Finally, water samples for total metal content analysis were digested using 65% HNO_3 according to the APHA (2005) method. The precision of the water quality analysis was controlled using triplicate readings for each analysis, and the mean was calculated with relative standard deviations of less than 5%.

Sediment samples were collected from the upper 20 cm of the bottom using an Eckman sampling device in five sectors from the eastern bank, western bank, and middle part of the main channel, with a total number of 15 samples per period. Grain size and sediment organic matter (OM) were determined by the dry sieving method (Folk 1974) and the wet oxidation method (Loring & Rantala 1992), respectively. To determine the total heavy metal content of sediment samples, 0.5 g of finely grinded samples was digested according to the Kouadia and Trefry (1987) method. Fe,

Table 1

Description of the sampling sites in Lake Nasser with GPS locations (latitude and longitude)

Sector name	Sector no.	*	Latitude	Longitude
Aswan High Dam	1	E	23° 57' 38.34"	32° 53' 53.14"
		M	23° 57' 39.40"	32° 52' 59.84"
		W	23° 57' 57.24"	32° 51' 45.25"
Wadi-Abyad	2	E	23° 22' 39.27"	32° 57' 21.50"
		M	23° 22' 17.93"	32° 56' 02.10"
		W	23° 22' 41.22"	32° 55' 13.30"
El-Madiq	3	E	22° 54' 55.41"	32°37'14.70"
		M	22° 55' 21.23"	32° 36' 43.69"
		W	22° 55' 51.28"	32° 36' 04.35"
Tushka	4	E	22° 34' 39.42"	31° 55' 38.27"
		M	22° 35' 28.23"	31° 55' 33.98"
		W	22° 35' 58.79"	31° 52' 00.53"
Abu-Simbel	5	E	22° 20' 11.31"	31° 40' 50.66"
		M	22° 20' 47.88"	31° 39' 31.38"
		W	22° 21' 10.13"	31° 37' 57.75"

* E: eastern; M: middle of main channel sector; W: western

Mn, Zn, Cu, Ni, Co, Cr, Pb, and Cd in water and sediment samples were analyzed using an inductively coupled plasma mass spectrometer (iCAP TQ ICP-MS, Thermo Scientific, Germany).

2.3. Lake Nasser water indices

The suitability of Lake Nasser water for drinking purposes based on its metal content was assessed using the heavy metal pollution index (HPI) according to the method of Mohan et al. (1996) and Prasad and Bose (2001) and the contamination index (C_d) suggested by Backman et al. (1997). Details of the indices used are presented in the supplementary material (Text S1).

2.4. Lake Nasser sediment indices

Several single and integrated indices were used to assess the metal ecological risk in Lake Nasser sediments, including the geoaccumulation index (Müller 1969), the enrichment factor (Yahaya et al. 2012), the pollution load index (PLI; Tomlinson et al. 1980), the potential ecological risk (ER) index (Hakanson 1980, 1988), the toxic unit (TU; Pedersen et al. 1998), and the toxic risk index (TRI; Gao et al. 2018; Zhang et al. 2016). Details of these indices are presented in the supplementary material (Text S2).

2.5. Statistical analysis

Data for all variables were tested for temporal and spatial significant differences using one-way ANOVA. In addition, relationships between different variables in the Lake Nasser environment were calculated using Pearson's correlation index.

3. Results and Discussion

3.1. Water analysis

Man-made Lake Nasser represents the national freshwater bank of Egypt. Table 2 shows the distribution of water quality data for all variables investigated in the lake.

Temperature affects the rates of biological and chemical processes. Temperature levels are critical to the health of aquatic species, ranging from bacteria to fish (Sharifinia et al. 2013). Surface water temperature in Lake Nasser is characterized by temporal variation, with its values varying with air temperature. Table 2 shows that the lowest temperature was recorded in winter (16.0°C) and the highest in summer (31.4°C).

Lake Nasser is a warm monomictic water body with a single circulation cycle in the cold months. Stratification is an important factor affecting water quality in relatively still and deep waters, including reservoirs and lakes. When water in a reservoir or lake stratifies, two separate bodies of different densities float on top of each other, with temperature changes causing differences in density (Abd Ellah 2020).

The pH values of the lake water were within the range of the aquatic life guidelines (6.5–9). Decreases in EC values were recorded before the flood period (summer), when low levels of total dissolved solids (TDS) were determined. The EC value of water is sensitive to changes in dissolved solids, mainly mineral salts (Othman et al. 2020), as confirmed by its highly significant correlation with TDS ($r = 0.99$, $n = 60$, $p < 0.001$).

One of the most important water quality parameters is dissolved oxygen (DO) content, as it plays an important role in aquatic life and is one of the limiting elements in water quality assessment. DO content in Lake Nasser is mainly affected by climate change and water depth. DO values decreased in the summer season, and those of bottom water samples often dropped significantly to levels below the aquatic life guidelines (5.5 mg l^{-1}) established by the Canadian Council of Ministers of the Environment (CCME). This reflects a reduced rate of photosynthetic activity, while the bottom layer is physically isolated from the atmosphere and may come into contact with decaying sediments that have a high oxygen demand. As a consequence, the bottom water usually has slightly lower oxygen content than the surface water (Abd Ellah 2020). The oxygen demand required for material decomposition depletes DO in water, posing a threat to water quality and aquatic life. In addition, an increase in water temperature increases metabolic oxygen demand and decreases oxygen solubility (Abd Ellah 2020; Sharifinia et al. 2013). The recorded values of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) increased significantly in the surface water of Lake Nasser during the hot season, while low levels of these values were recorded in bottom water samples, suggesting DO depletion.

High total alkalinity concentrations can be attributed to high carbon dioxide concentrations and the release of bicarbonate ions from the sediments. According to Sugunam (1995), total alkalinity above 40 mg l^{-1} indicates high productivity. Based on our results, the total alkalinity of the water in Lake Nasser varied in the range of 105.5–135.9 and 110.1–131.2 mg l^{-1} during the winter and summer seasons, respectively, indicating that the lake will continue to sustain good fish production. Alkalinity acts as a buffer for pH

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Table 2

Comparison of the physical and chemical variables* for Nasser Lake and Nile River and its branches downstream

Variable	Season	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	River Nile[1]	Rossetta Branch[2]	Damietta Branch[3]
Depth	Winter	49.0 (15.0-107.0)	41.0(15.0-83.0)	32.3(19.0-47.0)	51.5(13.5-71.0)	38.7(31.0-45.0)	-	1.50-7.00	-
	Summer	53.3 (29.0-100.0)	46.3(15.0-93.0)	39.7(19.0-55.0)	30.0(10.0-55.0)	50.0(30.0-65.0)	-	1.50-9.00	-
T (°C)	Winter	16.4(16.0-17.5)	18.0(16.8-18.9)	17.9(16.2-17.9)	18.2(16.4-19.5)	18.9(17.0-20.0)	17.8-18.9	15.00-17.20	18.3-31.4
	Summer	24.4(18.9-28.2)	24.9(19.1-30.3)	26.6(19.3-31.1)	28.7(19.9-31.4)	25.4(19.1-31.3)	24.5-30.7	29.00-33.00	
Trans. (cm)	Winter	336.7(300.0-400.0)	346.7(250.0-400.0)	256.7(240.0-280.0)	213.3(190.0-230.0)	181.7(180.0-185.0)	15-400	20.0-150.0	65-200
	Summer	300.0(250.0-350.0)	236.7(180.0-310.0)	266.7(200.0-330.0)	216.7(180.0-250.0)	288.3(280.0-305.0)	30-950	10.0-100.0	
EC (μS cm⁻¹)	Winter	286.0(282.0-291.0)	283.5(276.0-291.0)	276.7(269.0-285.0)	261.5(259.0-264.0)	255.8(254.0-257.0)	258-806	482-9450	371-516
	Summer	254.5(246.0-269.0)	254.8(246.0-265.0)	248.2(244.0-256.0)	240.8(234.0-256.0)	246.7(237.0-256.0)	210-621	341-1441	
TDS (mg l⁻¹)	Winter	187.0(185.3-189.2)	184.3(182.7-185.9)	181.1(179.4-182.7)	170.0(168.4-171.6)	166.3(165.1-167.1)	168-524	241.0-752.0	237-330
	Summer	165.4(159.9-174.9)	165.6(159.9-172.3)	161.3(158.6-166.4)	156.5(152.1-165.1)	160.3(154.1-166.4)	137-404	518.0-885.0	
pH	Winter	8.39(8.25-8.47)	8.51(8.22-8.64)	8.68(8.47-8.79)	8.67(8.42-8.79)	8.75(8.61-8.85)	7.3-8.5	7.27-8.27	7.92-8.54
	Summer	8.57(8.10-9.35)	8.38(8.08-8.52)	8.53(8.30-8.71)	8.48(8.00-8.74)	8.30(7.90-8.56)	7.7-8.6	7.28-8.49	
DO (mg l⁻¹)	Winter	7.34(6.25-8.83)	7.34(6.80-8.08)	7.32(5.73-8.67)	7.96(6.25-9.60)	7.78(6.51-9.28)	4.1-13.2	0.0-7.6	4.8-9.8
	Summer	4.54(2.66-6.34)	4.01(1.80-6.05)	4.36(2.52-5.74)	4.39(2.11-5.80)	4.75(2.05-8.08)	3.0-9.8	0.0-10.8	
BOD (mg l⁻¹)	Winter	1.83(1.02-2.50)	1.98(1.32-2.65)	2.35(1.90-2.80)	2.54(1.70-3.80)	2.39(1.41-3.41)	1.2-8.0	3.4-44.6	3.16-7.84
	Summer	2.49(1.62-3.33)	1.92(1.13-2.86)	1.76(1.00-2.63)	2.21(1.35-3.31)	1.76(1.52-2.16)	1.2-5.9	3.8-38.0	
COD (mg l⁻¹)	Winter	6.01(5.44-6.34)	5.67(5.28-6.12)	5.71(5.24-6.44)	5.95(5.26-6.44)	6.30(5.94-6.68)	2.9-111	6.4-23.8	1.9-5.58
	Summer	6.61(6.24-6.98)	6.18(5.84-6.48)	6.08(5.84-6.38)	6.06(5.77-6.28)	6.70(6.35-6.95)	3.4-78.5	6.2-22.5	
NH₃-N (μg l⁻¹)	Winter	180.2(153.0-210.8)	184.5(159.8-210.8)	202.9(95.2-297.5)	231.5(124.1-316.2)	222.4(185.3-256.7)	21-3403	255-24203	177-550
	Summer	259.3(164.9-343.4)	325.0(221.0-479.4)	232.6(161.5-324.7)	266.3(192.1-336.6)	338.3(210.8-447.1)	29-2237	341-13814	
NO₂-N (μg l⁻¹)	Winter	2.87(2.40-3.60)	6.22(5.20-7.20)	8.27(4.00-12.00)	5.93(4.00-8.00)	11.32(9.60-12.40)	4.4-86.4	6.8-338.7	5-37
	Summer	1.07(0.00-1.60)	1.67(1.20-2.40)	1.67(0.00-4.40)	1.27(0.00-2.80)	1.67(0.00-3.60)	4.6-694.3	2.1-192.2	
NO₃-N (μg l⁻¹)	Winter	124.8(92.8-150.4)	145.3(104.0-179.2)	114.2(20.96-182.4)	162.9(65.6-249.6)	270.3(248.0-297.6)	8-550	25.9-425.6	42-390
	Summer	22.00(12.80-32.80)	10.67(5.60-19.20)	33.33(12.80-62.40)	26.53(8.00-41.60)	63.20(25.60-146.40)	3-1864	34.1-1500.1	
PO₄-P (μg l⁻¹)	Winter	9.20(4.40-13.42)	6.42(2.20-9.90)	6.97(2.20-12.10)	5.82(4.14-8.80)	14.30(6.60-17.60)	4-176	20-1390	10-75
	Summer	4.22(2.20-8.80)	7.73(2.20-11.30)	14.24(9.40-18.70)	15.58(11.00-20.90)	13.02(6.60-27.50)	10-93	40-1100	
SiO₃² (mg l⁻¹)	Winter	6.89(5.88-7.56)	6.99(5.88-9.92)	5.74(3.40-7.72)	3.33(2.84-3.92)	5.25(4.88-6.12)	0.39-14.62	4.19-32.81	1.18-6.42
	Summer	5.40(4.04-6.92)	5.65(4.64-7.44)	5.70(4.52-7.16)	5.98(4.84-8.04)	5.17(4.40-5.88)	0.43-13.80	2.49-20.98	
SO₄² (mg l⁻¹)	Winter	7.53(6.37-9.64)	8.37(7.63-9.50)	7.78(6.37-9.27)	7.56(6.00-9.83)	7.79(6.84-9.69)	6.04-30.12	38.2-136.8	14.5-23.4
	Summer	6.58(6.26-6.81)	6.35(5.70-6.95)	6.09(5.00-6.81)	5.81(5.28-6.95)	5.58(5.26-6.09)	3.83-25.01	10.9-77.3	
Cl⁻ (mg l⁻¹)	Winter	9.58(9.41-9.69)	8.95(8.69-9.17)	9.16(8.69-9.55)	9.03(8.85-9.17)	8.73(8.69-8.82)	9.10-70.84	39.7-235.4	21.4-37.7
	Summer	10.40(9.93-10.64)	10.16(9.93-10.64)	9.99(9.93-10.28)	10.16(9.57-10.64)	10.52(9.93-10.64)	6.18-47.83	31.0-229.9	
CO₃² (mg l⁻¹)	Winter	1.60(0.90-3.00)	0.85(0.00-1.50)	1.85(0.00-3.00)	185(0.00-3.30)	3.90(1.80-6.00)	-	0.0-20.0	0-14
	Summer	1.65(0.30-3.60)	1.60(0.00-4.80)	1.46(0.00-3.60)	0.60(0.00-3.60)	2.30(0.00-4.80)		0.0-0.63	
HCO₃ (mg l⁻¹)	Winter	127.9(122.0-134.7)	128.3(124.4-132.2)	121.6(117.1-130.3)	112.9(109.3-114.7)	106.4(102.5-110.3)	106.4-284.2	140-350	121-198
	Summer	121.8(119.3-126.2)	118.4(114.4-126.1)	118.3(113.3-126.7)	123.1(109.8-131.2)	116.6(105.3-116.6)	94.1-232.3	125-260	
Ca (mg l⁻¹)	Winter	9.77(9.35-10.22)	10.08(9.87-10.42)	10.24(9.90-10.52)	10.12(9.68-10.75)	9.84(9.25-10.42)	11.92-28.62	35.3-71.4	21.7-33.9
	Summer	9.12(9.06-9.19)	8.96(8.74-9.13)	8.87(8.73-9.07)	8.76(8.64-8.87)	8.55(8.41-8.65)	9.45-19.20	30.5-60.9	
Mg (mg l⁻¹)	Winter	6.25(5.73-6.54)	5.03(4.29-5.43)	5.50(4.86-6.11)	5.81(5.05-6.56)	5.67(4.14-7.39)	7.39-32.82	24.3-53.5	11.8-17.7
	Summer	5.33(5.16-5.64)	5.11(4.98-5.28)	4.96(4.79-5.16)	5.13(5.06-5.26)	5.27(5.08-5.41)	6.08-32.89	17.9-40.4	
Hardness (mg l⁻¹)	Winter	50.1(48.3-51.9)	45.9(42.9-47.3)	48.2(45.7-49.9)	49.2(46.6-51.9)	47.9(42.4-55.3)	60.2-185	196.2-360.3	-
	Summer	44.7(44.1-46.0)	43.4(42.7-44.2)	42.6(41.5-43.5)	43.0(42.4-43.6)	43.0(42.4-43.6)	50.0-166	161.4-291.4	

*Mean (minimum-maximum); [1]Abdel-Satar et al. 2017a; [2]Othman et al. 2020; [3]El Sayed et al. 2020

changes, allowing the pH of the lake water to remain stable.

The amount of nutrients in a lake is one of the most significant factors in assessing its productivity. The relative abundance of nutrients has a major impact on the quality of lake water. By providing a food source for aquatic organisms, moderate levels of nutrients support the lake ecosystem (Tanabe et al. 2019). Due to the low concentrations of nitrogen in Lake Nasser, its nitrite and nitrate values are far below the current aquatic life guidelines. High nitrite and nitrate concentrations associated with low temperature and high DO levels were observed in winter, while high levels of ammonia were recorded during the summer season. The NH_3-N concentration in the range of 161.5–479.4 µg l^{-1} exceeded the specified limit (256 µg l^{-1}) for the protection of aquatic life in some surface water samples in the hot season. The distribution of nutrients in Lake Nasser water is controlled by DO levels. Nutrient compounds can increase in interstitial waters and diffuse from the sediments into the lower water layer when anoxic conditions occur in bottom sediments (Lawson & Anderson 2017).

Phosphorus is the limiting nutrient in freshwater aquatic environments, meaning that regardless of the amount of nitrogen available, plant growth will stop if phosphorus is depleted (Bhateria & Jain 2016). Significant spatial differences were recorded for the two study periods. The highest average PO_4^{3-}-P values were obtained at sector 5 (14.3 µg l^{-1}) in winter and at sector 4 (15.6 µg l^{-1}) in summer. Some temporal differences were also recorded ($p = 0.08$), while there were no significant differences in PO_4^{3-}-P values between surface and bottom water samples. This is due to the fact that anoxic conditions enhance the diffusion of phosphate from the sediments to the bottom water (Yousry 2017). Lake Nasser appears to have lower levels of nutrient salts compared with the Nile River and its downstream branches (Table 2; Abdel-Satar et al. 2017a; Abdel-Satar et al. 2022; El Sayed et al. 2020; Othman et al. 2020), which suffer from intense pollution.

The abundance of the main anions in the water of Lake Nasser is in the following order: $HCO_3^- > Cl^- > SO_4^{2-} > SiO_3^{2-} > CO_3^{2-}$, in terms of mass. At the water–sediment interface, chloride is possibly the most mobile element and represents a nonreactive element (Effler et al. 1990). Chloride and sulfate levels were characterized by remarkable seasonal variations ($p < 0.01$) and showed a close negative correlation in bottom water ($r = -0.73$, $n = 30$, $p < 0.01$), while silicate concentrations showed no temporal variation. Most of the analyzed bottom water samples showed a slight increase in sulfate concentrations, which may be related to the amount of OM. The availability of OM in anoxic sediments may be inadequate to sustain sulfate reduction. In addition, the ability of sulfate-reducing bacteria to reduce sulfate is also impaired by traces of oxygen. In fact, no sulfate reduction has been found in pure water in the presence of oxygen (Holmer and Storkholm 2001).

Calcium and magnesium are essential elements that are used by phytoplankton and other aquatic plants and animals for growth (Othman et al. 2020). The total hardness of Lake Nasser's water is in the range of 42.4–55.3 and 41.5–46.0 mg l^{-1} during the winter and summer seasons, respectively. The average concentrations of the metals in the lake water followed the following order: Fe > Mn > Zn > Ni ≈ Cr ≈ Cu > Pb > Co > Cd. In winter, the levels of Fe, Mn, Zn, Cr, Cu, Co, and Pb in the lake water were uniform and did not differ significantly, but Ni and Cd showed significant spatial differences. In summer, however, all metals showed spatial differences except for Cr and Co. In addition, all the studied metals showed significant temporal variations, with higher levels of metals observed in winter than in summer.

The concentrations of all the studied metals were lower than those recorded in the Nile River water (Table 3; Abdel-Satar et al. 2017a; Al-Afify & Abdel-Satar 2020). In addition to the reduction of anthropogenic sources of water pollution (i.e., industrial, agricultural, and domestic wastes), the deposition of metal salts under conditions of high pH and excess DO may be responsible for the lower levels of metals recorded in the water of Lake Nasser compared to that of the Nile River (Imam et al. 2020).

Iron is the most important metal for biological life. It has a greater biological impact than any other heavy metals (Yacoub et al. 2021). Fe concentrations in Lake Nasser water rarely exceeded the specified limits for aquatic life (CCME 2001) and drinking water (WHO 2017). Manganese is one of the most common earth metals in water from natural and anthropogenic sources (Izah et al. 2016). Mn, Zn, and Cu values were within the limits set by WHO (2017) and therefore would not pose any possible health risk, whereas Zn and Cu exceeded the CCME (2007) limits and resulted in a potentially hazardous environment for aquatic life in Lake Nasser. Levels of Ni in the water of Lake Nasser were within the limits set by WHO (2017) and CCME (2007), whereas Co levels were ten times above the CCME (2007) limit for the protection of aquatic life. Rock weathering and plant waste decomposition are all examples of natural sources of Co pollution (Kim et al. 2006). In addition, agricultural runoff is considered another source of Co for lake environments (Mohamed 2008).

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Table 3

Distribution of heavy metals (µg l⁻¹) compared to the Nile River and various guidelines, contamination index, and HPI values of Lake Nasser water

Sector		Fe	Mn	Zn	Cu	Ni	Co	Pb	Cd	Cr	HPI	Cd (Index)
Winter												
1	Range	240.0-336.0	31.1-57.8	24.00-37.40	8.00-11.20	8.35-14.85	4.20-7.80	6.10-11.33	1.20-1.80	6.90-12.13	47.5-61.5	-5.8:-4.7
1	Mean ± SD	282.9 ± 32.4	43.0 ± 10.7	29.96 ± 5.33	9.53 ± 0.98	11.30 ± 2.50	5.88 ± 1.23	8.77 ± 2.00	1.43 ± 0.21	9.88 ± 2.08	53.9 ± 5.3	-5.2 ± 0.3
2	Range	220.0-336.0	26.2-61.4	21.60-41.70	8.80-11.20	6.95-15.75	3.40-8.50	4.70-12.30	1.00-2.20	5.50-13.10	47.0-75.6	-5.6:-4.4
2	Mean ± SD	281.8 ± 34.7	45.9 ± 10.5	31.81 ± 5.92	9.78 ± 0.73	11.88 ± 2.63	6.18 ± 1.46	9.07 ± 2.48	1.81 ± 0.51	10.40 ± 2.36	63.5 ± 10.6	-5.0 ± 0.4
3	Range	243.0-342.0	32.6-61.2	24.80-40.60	8.10-11.40	8.55-15.70	4.70-8.05	7.30-13.10	0.70-1.70	8.10-13.20	33.4-69.9	-5.9:-4.3
3	Mean ± SD	283.5 ± 33.8	43.5 ± 10.4	30.44 ± 5.64	9.45 ± 1.13	11.28 ± 2.59	6.34 ± 1.36	9.91 ± 2.04	1.06 ± 0.35	10.89 ± 2.06	47.6 ± 12.2	-5.2 ± 0.5
4	Range	234.0-286.5	27.2-44.2	22.10-30.60	7.80-9.55	7.20-11.45	4.40-6.15	6.70-10.20	1.70-2.20	7.50-11.00	60.3-75.0	-5.5:-4.8
4	Mean ± SD	270.3 ± 18.1	35.5 ± 7.1	26.20 ± 3.52	9.01 ± 0.60	9.27 ± 1.76	5.61 ± 0.60	9.12 ± 1.21	2.04 ± 0.21	9.92 ± 1.21	68.9 ± 5.5	-5.1 ± 0.3
5	Range	213.0-345.0	34.2-60.4	25.60-39.20	9.13-11.60	8.95-18.60	5.73-9.70	9.37-12.30	1.00-2.30	10.17-13.10	51.8-82.1	-5.0:-4.4
5	Mean ± SD	291.9 ± 43.1	50.2 ± 10.7	33.73 ± 5.46	10.40 ± 1.01	14.04 ± 3.80	7.35 ± 1.54	10.92 ± 1.24	2.00 ± 0.45	11.72 ± 1.24	72.0 ± 9.6	-4.7 ± 0.3
Summer												
1	Range	179.0-343.0	23.2-69.4	20.10-43.20	7.80-12.10	5.05-17.35	3.90-6.70	3.63-9.55	1.00-1.60	4.73-11.20	36.2-50.3	-6.2:-5.0
1	Mean ± SD	239.9 ± 58.9	39.6 ± 16.2	28.26 ± 8.10	9.17 ± 1.52	9.61 ± 4.23	5.31 ± 1.07	6.33 ± 2.05	1.23 ± 0.21	7.71 ± 2.44	43.8 ± 6.4	-5.8 ± 0.5
2	Range	144.0-247.3	21.8-31.4	19.00-24.20	6.80-8.91	5.45-7.85	3.00-6.90	3.70-7.90	0.80-2.00	3.80-11.60	36.7-64.8	-6.3:-5.5
2	Mean ± SD	198.5 ± 31.6	27.8 ± 3.5	22.26 ± 1.96	7.90 ± 0.61	6.94 ± 0.88	5.20 ± 1.33	6.02 ± 1.84	1.61 ± 0.43	7.49 ± 3.11	51.9 ± 9.4	-5.9 ± 0.3
3	Range	226.0-319.0	29.6-60.2	23.00-38.60	8.20-11.30	7.40-15.05	4.80-6.80	6.30-10.30	0.60-1.60	7.40-11.40	28.9-61.6	-6.1:-4.8
3	Mean ± SD	263.8 ± 28.3	41.5 ± 10.1	29.19 ± 5.09	9.46. ± 0.94	10.71 ± 2.72	5.90 ± 0.62	8.50 ± 1.25	1.06 ± 0.36	9.60 ± 1.25	44.6 ± 10.8	-5.5: ± 0.4
4	Range	240.3-257.5	23.2-37.8	20.10-27.00	8.68-9.25	5.80-9.45	5.29-6.40	7.28-9.50	1.40-1.90	8.38-10.60	49.8-61.7	-5.7:-5.2
4	Mean ± SD	247.0 ± 7.4	28.9 ± 6.1	22.80 ± 2.94	8.90 ± 0.25	7.37 ± 1.48	5.71 ± 0.43	8.13 ± 0.86	1.69 ± 0.20	9.23 ± 0.86	58.3 ± 4.6	-5.4 ± 0.2
5	Range	191.0-261.0	31.6-39.8	24.30-28.40	8.00-9.37	7.95-13.95	4.60-6.90	5.90-10.50	0.80-2.10	7.00-11.60	42.9-65.9	-5.8:-5.2
5	Mean ± SD	238.8 ± 31.9	35.4 ± 3.4	26.21 ± 1.69	8.89 ± 0.62	9.89 ± 1.97	5.65 ± 0.82	7.99 ± 1.63	1.73 ± 0.44	9.09 ± 1.63	59.1 ± 7.7	-5.4 ± 0.2
River Nile[1]		199-2211	41-298	10-115	10-42	1.0-33		5-51	0.2-8	-		
River Nile[2]		196-1300	87-288	18-99	5-19	8.5-26.5	7-23	3-18	1.5-4	9-21		
WHO (2017)		300	400	4000	2000	70	-	10	3	50		
CCME (2007)		300	----	7	2	65		1	0.18*			

*According to CCME 2014; [1]Abdel-Satar et al. 2017a; [2]Al-A¬fify and Abdel-Satar 2020

The concentrations of Pb in water samples obtained during the winter season were uniform in Lake Nasser and did not differ significantly between the sites. On the other hand, Cd levels showed highly significant site variations ($p < 0.01$) in the two study periods. In addition, Pb concentrations exceeded the limit recommended by WHO for drinking water in 50% of the samples, whereas all Pb and Cd levels exceeded the CCME (2007) limit for the protection of aquatic life. These elements are nonessential and are rather toxic at high levels of consumption (Yacoub et al. 2021). There were no significant differences in Cr levels between the sites in the two study periods, and their values were below the limit recommended by WHO (2017) for drinking water (Table 3).

The study of the co-occurrence of heavy metals provides information about the sources and transportation routes of metals in aquatic ecosystems. All the studied metals were correlated with each other ($p < 0.05$) except for Cd, which showed no significant correlation with other metals (Table S3). These high correlations suggested that the metals have the same source and were transported together through geochemical processes.

3.2. Lake Nasser water assessment

As for the contamination of the lake's water with metals, the HPI for all the surveyed sectors did not exceed the critical level (HPI = 100) stipulated by WHO (2017), indicating that the water in Lake Nasser is not contaminated with metals (Table 3). According to the contamination index that expresses the cumulative effects of all metals by separately measuring the relative contamination of different metals, the water in all sectors of the lake is characterized by low metal pollution ($C_d < 1$; Table 3). These findings demonstrated that the water in Lake Nasser is free of any metal contamination.

3.3. Sediment analysis

In terms of geochemistry, the state of lake sediments can be a good indicator of the environmental health of aquatic ecosystems (Guzeva et al. 2021). The grain size and the level of OM in the sediments of Lake Nasser are presented in Table 4, and the distribution of heavy metals is shown in Table 5.

The results showed significant differences in OM ($n = 15$, $P < 0.05$) of the sediments from the eastern bank, western bank, and middle part of the main channel for the five sectors over the two periods. Sites in the middle part of the main channel showed the highest OM levels as mud deposition increased. This was confirmed by significant positive correlations between OM and percent mud content (Table S4). However, no chronological variation in OM was detected in any of the sectors. OM showed a significant correlation with heavy metals except for Mn (Table S4), reflecting the role of OM in binding and removing metals in the lake. Most metals are easily adsorbed and bind to OM to form organometallic complexes (Abdel-Satar et al. 2017b; Louhi et al. 2012).

The sediments of Lake Nasser consist mainly of gravel, sand, and mud, which vary in percentage and distribution across samples (Table 4). Nonsignificant temporal variations were recorded for the distribution of gravel, sand, and mud in the lake sediments. Histograms of grain size analysis during the two study periods are presented in supplementary Figures 1S and 2S.

Gravel contributed the lowest percentage to the composition of the lake's sediments in both periods studied. However, gravel (87.5%) was concentrated in the east of sector 1 but was completely absent at several sites (Table 4). This may be due to the fact that the water at the site is less disturbed. The source of gravel sediments in the lake are granules from igneous rock mountains around the lake (Farahat & Salem 2015). During the summer season, mud deposition increased in the middle part of the main channel sectors, whereas the sand fractions increased on the western bank, reflecting increased erosion on the western bank. These results are in agreement with the findings of Farahat and Salem (2015) for Lake Nasser.

Lake sediments play an important role in the internal metal cycle, acting as a temporary or permanent sink for metals (Maina et al. 2019). The mean concentrations of the analyzed metals in the lake sediments during the two study periods follow the order: Fe > Mn > Zn > Cr> Ni > Cu ≈ Co > Pb > Cd. The maximum concentrations of all analyzed metals were observed in the middle part of the main channel. With the exception of Cr concentrations, which showed slightly significant variation by location ($p = 0.057$) in summer, all other metals showed no spatial variation during the periods studied. In addition, only Pb and Cd showed slight temporal variation.

Pearson's correlation matrix revealed a significant positive correlation ($n = 30$, $p < 0.05$) between the studied heavy metal pairs in the lake sediments except for Mn, probably reflecting their related origin and similar accumulation and transport mechanisms (Abdel-Satar et al. 2017b). Furthermore, the percent composition of mud was significantly correlated at $p < 0.05$ for Zn and Cd in winter and for Ni, Zn, Cd, Co, and Pb in summer (before the flood period), indicating that high concentrations of heavy metals are associated

Table 4

Grain size and organic matter levels in Lake Nasser sediments

Sector		Winter					Summer				
		Gravel (%)	Sand (%)	Mud (%)	Type	OM (%)	Gravel (%)	Sand (%)	Mud (%)	Type	OM (%)
1	E	87.54	7.86	4.60	Sandy Gravel	6.16	61.90	26.20	12.00	Sandy Gravel	3.91
	M	0.00	20.21	79.79	Sandy Mud	10.90	0.20	22.30	77.60	Sandy Mud	10.36
	W	2.09	95.31	2.60	Sand	2.03	0.30	97.90	1.80	Sand	1.16
2	E	52.07	42.63	5.29	Sandy Gravel	5.53	4.10	24.30	71.60	Sandy Mud	7.95
	M	0.00	51.07	48.93	Muddy Sand	10.74	0.00	31.90	68.10	Sandy Mud	11.96
	W	0.00	30.73	69.72	Sandy Mud	7.97	20.50	39.80	39.70	Gravelly Muddy Sand	7.49
3	E	0.00	44.01	55.99	Sandy Mud	5.19	0.00	38.60	61.40	Sandy Mud	4.54
	M	0.00	15.73	84.27	Sandy Mud	9.71	0.00	15.20	84.80	Sandy Mud	10.27
	W	49.55	28.82	21.63	Muddy Sandy Gravel	7.51	0.50	83.80	15.70	Muddy Sand	3.47
4	E	81.44	16.37	2.19	Sandy Gravel	6.99	0.00	44.90	55.10	Sandy Mud	4.67
	M	0.00	50.76	49.24	Muddy Sand	10.07	0.00	31.70	68.30	Sandy Mud	10.53
	W	19.54	72.3	8.16	Gravelly Sand	3.76	19.50	77.40	3.10	Gravelly Sand	3.99
5	E	0.00	60.28	39.72	Muddy Sand	10.54	0.00	40.20	59.80	Sandy Mud	11.81
	M	0.00	67.77	32.23	Muddy Sand	10.09	0.00	40.20	59.80	Sandy Mud	11.25
	W	0.00	88.18	11.82	Muddy Sand	9.22	0.00	68.10	31.90	Muddy Sand	6.56

Table 5

Distribution of heavy metals (mg kg^{-1}) in Lake Nasser sediments compared to different standards

Sector		Fe	Mn	Zn	Cu	Ni	Co	Pb	Cr	Cd
						Winter				
1	E	20414	362.6	57.20	11.80	15.80	10.80	7.90	14.60	0.80
	M	20227	365.8	70.80	20.70	21.80	16.80	10.90	35.40	1.20
	W	12000	317.6	29.20	7.20	17.00	12.00	8.50	28.60	0.30
2	E	18238	392.5	56.40	12.60	19.60	14.60	9.80	28.20	0.90
	M	18113	387.9	87.80	29.80	23.60	18.60	13.82	43.90	1.20
	W	14240	327.2	55.90	12.80	17.00	12.00	8.50	27.95	1.00
3	E	18138	322.3	48.20	10.20	13.00	9.96	6.50	35.80	0.50
	M	18231	315.7	71.60	21.70	24.60	19.60	12.30	24.10	0.95
	W	16460	210.1	67.10	16.70	23.90	18.90	11.90	33.55	0.90
4	E	17876	366.5	56.40	15.20	23.50	18.50	11.70	28.20	0.75
	M	18836	381.1	71.20	21.30	26.00	20.00	13.03	32.60	0.90
	W	11763	284.3	51.60	9.40	16.60	11.60	8.30	29.80	0.40
5	E	17502	400.2	72.80	30.70	22.40	17.40	15.70	33.40	1.20
	M	18568	416.6	71.60	22.80	31.40	21.10	12.70	45.80	0.75
	W	16260	239.6	68.80	27.90	30.40	20.40	15.20	34.40	0.95
						Summer				
1	E	18181	348.7	37.90	10.20	11.00	10.20	4.50	18.95	0.47
	M	15655	235.8	70.80	17.20	23.90	19.90	11.90	35.40	0.80
	W	15294	322.1	24.10	10.10	13.80	9.89	6.90	18.05	0.30
2	E	14689	240.2	59.60	13.90	15.40	11.40	7.71	29.80	0.70
	M	20446	392.1	84.20	27.70	25.16	21.16	12.50	41.10	1.20
	W	15175	258.7	82.80	16.30	18.70	14.70	9.37	41.40	0.60
3	E	14801	313.3	46.80	12.30	14.00	10.00	4.20	23.40	0.20
	M	21238	330.2	69.20	18.50	22.27	18.27	11.10	34.60	0.75
	W	14171	230.2	40.00	14.60	20.60	16.60	5.30	16.00	0.30
4	E	13747	286.9	32.40	10.60	15.00	11.00	4.50	16.20	0.20
	M	18624	376.7	67.20	16.10	22.00	18.00	11.00	21.00	0.80
	W	17976	337.2	43.60	12.20	15.80	11.80	7.90	21.80	0.50
5	E	17265	340.1	70.20	12.20	22.20	18.20	14.60	35.10	1.10
	M	17364	376.3	61.20	19.70	29.30	21.30	11.60	29.60	0.90
	W	17084	386.9	83.80	21.30	25.50	21.50	12.77	41.90	0.80
EPA (2006)		20000	460	121	31.6	22.7	50	35.8	43.4	0.99
CCME (2001)	TEL	-	-	123	35.7	18	-	35	37.3	0.596
	PEL	-	-	315	197	36	-	91.3	90	3.53

TEL = Threshold effect level; PEL = Probable effect level

with finer sediments (Sayed & Abdel-Satar 2009). In the two study periods, the levels of Ni, Cr, and Cd in 63%, 17%, and 70% of the samples, respectively, exceeded the threshold effect level (TEL) cited by the CCME (2001) for the protection of aquatic life. This indicates that the conditions in Lake Nasser may have a rare adverse effect on its aquatic biota. In addition, Ni and Cd levels in 30% and 20% of the samples exceeded the freshwater sediment screening benchmarks (Table 5; EPA 2006). In general, there are different sources of metal pollution in Lake Nasser, including dry and wet deposition of atmospheric particulate matter, soils and rocks that are directly exposed to the water, dead and decaying plants and animals, and the discharge of various untreated wastes, which are mainly of agricultural origin, into the lake water (Mohamed 2008).

3.3. Lake Nasser sediment assessment

Due to metal toxicity, bioaccumulation, abundance and persistence, metal pollution in aquatic ecosystems has become a global problem in recent years (Eren et al. 2021). The contamination factor (C_f) is a key measure of the level of threat metals pose to the environment. Low retention time and high hazardous levels of metals in the environment are associated with high C_f values (Eren et al. 2021). Table 6 shows the contamination factor and PLI of Lake Nasser. The results indicate that the lake's sediments showed moderate contamination with Fe, Ni, Cr, and Cd. However, C_f increased more than 1 in some sectors during the summer and winter seasons. The highest C_f was recorded for Ni and the lowest for Pb. PLI is a useful tool for determining the overall toxicity grade of a sample due to the fact that it accounts for total metal content (Imam et al. 2020). The PLI values (< 1) for metals in the lake's sediments indicate the absence of pollution (Table 6).

EF values between 0.5 and 1.5 indicate that a metal is derived entirely from natural processes or minerals of the Earth's crust, while EF values greater

than 1.5 indicate that the sources of metals are mostly anthropogenic (Abdel-Satar et al. 2017b). The EF values for the lake's sediments were below 1.5 for all analyzed metals, suggesting their lithogenic origin (Fig. 2). Negative I-geo results for all analyzed metals at different sites according to the contamination
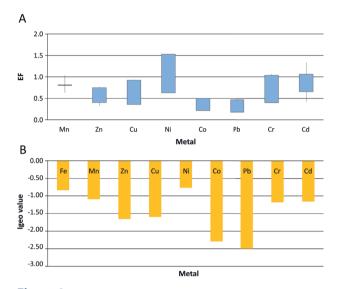

Figure 2

Average EF (A) and I-geo (B) values for different metals in Lake Nasser sediments

classification (Müller 1969) indicate that the sediments of Lake Nasser were free of heavy metal contamination (Fig. 2).

From the overall perspective of this study, the obtained average potential ER index was classified as low-grade risk (ER index < 150). The average contribution of Cd to the ER assessment was about 63.4%, while the contribution of Ni was about 14.2% (Fig. 3). The high bioaccumulative capacity of cadmium in aquatic fauna, as well as its relative solubility in water, indicates that its potential toxicity threatens aquatic species in lakes (Weldegebriel et al. 2012). In general, the trend of metal contribution to the ER in Lake Nasser follows the following order: Cd > Ni > Cu > Pb ≈ Cr > Co > Mn > Zn (Fig. 3).

The potential toxicity of Lake Nasser sediments caused by heavy metals was assessed using the TU approach. The ΣTU registered low values (< 4) of heavy metals, indicating that they have no significant toxic effect on aquatic biota in Lake Nasser (Fig. 4; Gao et al. 2018). Samples collected in the winter season recorded a higher average ΣTU (1.61) compared to those collected in the summer season (1.40). Samples collected from the middle part of the main channel recorded higher ΣTU compared to those collected
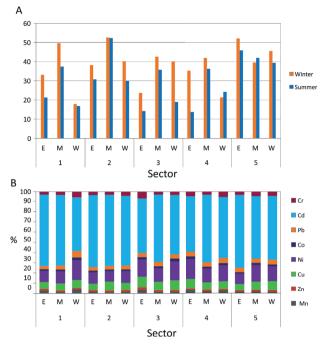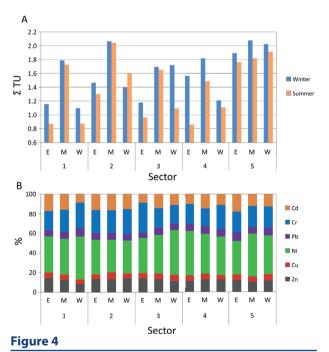
Table 6

Contamination factor (C_f) and PLI of Lake Nasser sediments

		Fe	Mn	Zn	Cu	Ni	Co	Pb	Cr	Cd	PLI
						C_f					
Winter	Min.	0.59	0.46	0.24	0.23	0.57	0.20	0.18	0.34	0.30	0.39
	Max	1.02	0.91	0.73	0.97	1.38	0.42	0.44	1.06	1.21	0.77
	Mean	0.86	0.74	0.52	0.57	0.96	0.32	0.31	0.73	0.86	0.60
Summer	Min.	0.69	0.50	0.20	0.32	0.48	0.20	0.12	0.37	0.20	0.33
	Max	1.06	0.85	0.70	0.88	1.29	0.43	0.41	0.97	1.21	0.77
	Mean	0.84	0.69	0.48	0.49	0.87	0.31	0.25	0.65	0.65	0.53

Figure 3

Potential ecological risk values (A) and average percentage contribution to the ER index (B) for metals in Lake Nasser sediments (E: eastern sector; M: middle sector; W: western sector of the main channel)

Figure 4

ΣTU values (A) and the average percentage contribution to ΣTU (B) for metals in Lake Nasser sediments (E: eastern sector; M: middle sector; W: western sector of the main channel)

from the eastern and western banks. The TU for heavy metals for the two study periods follows the order: Ni > Cr > Zn ≈ Cd > Pb > Cu. Figure 4 shows the mean contribution of each heavy metal to the ΣTU and demonstrates that Ni and Cr accounted for most of the overall toxicity of the sediments. The TRI approach was used to assess the toxic risk to aquatic organisms exposed to sediments contaminated with heavy metals in terms of both chronic and acute toxic effects (Gao et al. 2018; Zhang et al. 2016). Based on the results, TRI values were below 5, indicating no toxic risk from metals. The average TRI due to the content of metals in the sediments of the lake follows the order: Ni > Cd > Cr > Zn > Cu > Pb (Fig. 5). The significant contribution of Ni and Cd to the TRI was mainly attributed to their relatively low TEL (Fig. 5).
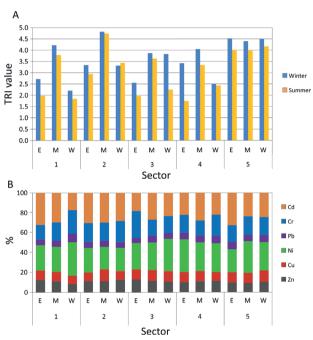

Figure 5

TRI values (A) and the average percentage contribution to TRI (B) for metals in Lake Nasser sediments (E: eastern sector; M: middle sector; W: western sector of the main channel)

4. Conclusions

The importance of Lake Nasser stems from the fact that it is the largest reservoir for the freshwater in Egypt. The use of multiple approaches to analyze metal contamination in lake water and sediments allowed for a more comprehensive assessment of the water and sediment properties of Lake Nasser in terms

of background effects and ecotoxicological concerns. Based on the water analysis, only Pb concentrations slightly exceeded the specified WHO limit for drinking water in 50% of the samples, while the HPI did not exceed the critical level (HPI = 100) for any of the sectors. In addition, based on the contamination index ($C_d < 1$), the water in Lake Nasser has low metal contamination. The results of the sediment analysis indicate that Ni, Cr, and Cd levels exceeded the TEL cited by CCME (2001) in 63%, 17%, and 70% of the samples, respectively, during the study periods. Ni and Cd levels in 30% and 20% of the samples also exceeded the limits stipulated by EPA (2006). The results revealed the highest EF, C_f, and I-geo values of Ni in Lake Nasser sediments. Moreover, Ni and Cd had the highest impact on the ER index and TRI, indicating that the conditions in Lake Nasser may have a rare adverse effect on its aquatic biota.

Acknowledgements

Availability of data and materials

The data can be available upon request.

Declaration of conflict of interest

The authors declare no conflict of interest.

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Supplementary materials

Text S1: Lake Nasser water quality assessment

Text S1.1: Heavy metal pollution index (HPI)

The suitability of Lake Nasser's water for drinking purposes with regard to metals was assessed using the heavy metal pollution index. It is based on the weighted arithmetic mean quality method and is expressed by the following equation (Mohan et al. 1996; Prasad & Bose 2001):

$$HPI = \frac{\sum_{i=1}^{n} Q_i W_i}{\sum_{i=1}^{n} W_i}$$

where Qi is the individual quality rating of the ith metal, calculated as follows:

$$Q_i = \frac{C_i}{C_s} \times 100$$

W_i is calculated as 1/Cs, where C_s is the recommended standard of the relevant metal and n is the number of metals estimated. C_i is the estimated value of metals in µg l^{-1}. The permissible standard value (C_s) for each metal was taken from WHO (2017). The critical limit of the heavy metal pollution index for drinking water is 100, above which the overall pollution level should be considered unacceptable for drinking water (Prasad & Bose 2001).

Text S1.2: Contamination index (Cd)

C_d indicates the relative contamination by different metals separately and manifests the combined effects of all metals. It is calculated according to the following equation (Backman et al. 1997):

$$C_d = \sum_{i=1}^{n} C_{fi}$$

where C_fi is calculated according to the following equation:

$$C_{fi} = \frac{C_i}{C_s} - 1$$

C_{fi} is the contamination factor for the ith metal, C_i is the measured value for the ith metal, and C_s is the upper permissible value for the ith metal. The resulting C_d values are grouped into three classes: low ($C_d < 1$), medium ($C_d = 1–3$) and high ($C_d > 3$). C_s was formerly introduced in the HPI calculations.

Text S2: Lake Nasser sediment assessment

Text S2.1: Geoaccumulation index (I-geo)

I-geo was computed as follows (Muller 1969):

$$I - geo = log_2 \left(\frac{C_n}{1.5 B_n} \right)$$

where C_n is the total metal concentration in a sediment sample, B_n is the metal background value, and 1.5 is the background matrix correction factor. Concentrations of heavy metals as defined in the freshwater sediment benchmarks (EPA 2006) were used as background. I-geo can be divided into seven classes (Table S1).

Table S1

Geoaccumulation index and enrichment factor for the analyzed elements and the contamination levels Index

Index				
Geoaccumulation index (I-geo)			Enrichment factor (EF)	
Class No.	I-geo value	Contamination level	EF value	Contamination level
0	I-geo ≤ 0	practically unpolluted	1 < EF < 3	minor enrichment
1	0 < I-geo < 1	unpolluted to moderately polluted	3 < EF < 5	moderate enrichment
2	1 < I-geo < 2	moderately polluted	5 < EF < 10	moderately severe enrichment
3	2 < I-geo < 3	moderately to heavily polluted	10 < EF < 25	severe enrichment
4	3 < I-geo < 4	heavily polluted	25 < EF < 50	very severe enrichment
5	4 < I-geo < 5	heavily to extremely polluted	EF ≥ 50	ultra high
6	I-geo ≥ 5	extremely polluted		

Text S2.2: Enrichment factor

The EF of a single trace element in the sediments was calculated as follows (Yahaya et al. 2012):

$$EF = \frac{\left(\dfrac{M}{Fe}\right)_{sample}}{\left(\dfrac{M}{Fe}\right)_{background}}$$

Fe was used as a conservative tracer to differentiate between natural and anthropogenic components. $(M/Fe)_{sample}$ is the ratio of a metal and Fe concentration in a sample in the examined environment, and $(M/Fe)_{background}$ is the ratio of a metal and Fe concentration of the background (Yahaya et al. 2012). EF values were classified as presented in Table S1.

Text S2.3: Pollution load index

PLI was calculated according to the following formula (Tomlinson et al. 1980):

$$PLI = (Cf_1 \times Cf_2 \times Cf_3 \times ...Cf_n)^{\frac{1}{n}}$$

where n is the number of elements, and Cf is the contamination factor. It is a ratio between the level of a given element (C_i) in sediment samples and its background concentration (B_i); background concentrations of heavy metals were taken from freshwater sediment benchmarks (EPA 2006):

$$Cf_i = \frac{C_i}{B_i}$$

where PLI value >1 would indicate a contaminated site, while PLI value <1 indicates no contamination.

Text S2.4: Potential ecological risk index (ER)

The potential ecological risk index (ER) was introduced to assess the degree of heavy metal pollution in sediments according to the toxicity of heavy metals and the response of the environment, where ER is calculated as the sum of all risk factors (E_r^i) for heavy metals in sediments (Hakanson 1980, 1988):

$$ER = \sum_{i=1}^{n} E_r^i \qquad \text{and} \qquad E_r^i = C_f \times T_r^i$$

where E_r^i is the monomial potential ecological risk factor, Cf is the contamination factor, and T_r^i is the toxicity response factor of a heavy metal. The factor scores on each heavy metal according to Hakanson's (1980) approach were: Mn (1), Zn (1), Cu (5), Ni (5), Co (2), Pb (5), Cd (30) and Cr (2). The pollution levels according to ER and E_r^i values are presented in Table (3).

Table S2

Pollution levels according to ER and E_r^i values

scope	Ecological risk levels for single factor pollution	ER scope	Potential ecological risk levels	TRI scope	Toxic risk levels
$E_r^i < 40$	low	$ER < 150$	low grade	TRI < 5	no
$40 \le E_r^i < 80$	moderate	$150 \le ER < 300$	moderate	TRI $5 - 10$	low
$80 \le E_r^i < 160$	considerable	$300 \le ER < 600$	severe	TRI $10 - 15$	moderate
$160 \le E_r^i < 320$	high	$600 \le ER$	serious	TRI $15 - 20$	considerable
$320 \le E_r^i$	serious	–	–	TRI > 20	very high

Text S2.5: Toxic unit (TU) and toxic risk index (TRI)

SQGs were used for qualitative assessment of potential ecological risks caused by Zn, Pb, Cu, Cd, Cr, and Ni in the sediment. The SQGs have two thresholds: the threshold effect level (TEL), below which no adverse effects on aquatic ecosystems are expected, and the probable effect level (PEL), above which adverse effects are likely to be observed. The ΣTU, defined by Pedersen et al. (1998), who suggested that the potential acute toxicity of heavy metals in sediment can be represented by the sum of ratios of the measured metal concentration to the PEL, was used to quantify toxic effects. The sediment ΣTU was calculated using the following equation:

$$\sum TU = \sum_{i=1}^{n} \frac{Ci}{PEL}$$

However, the sediment ΣTU may underestimate the potential toxicity, because it only considers PEL effects. Therefore, the TRI is used to assess the integrated toxic risk based on both TEL and PEL effects of metals (Gao et al. 2018; Zhang et al. 2016). Toxic levels according to TRI values are presented in Table 3. The TRI of the sediment is calculated using the following equation:

$$TRI = \sum_{i=1}^{n} \sqrt{\frac{\left(\dfrac{Ci}{TEL}\right)^2 + \left(\dfrac{Ci}{PEL}\right)^2}{2}}$$

Table S3

Correlation coefficient matrix between average metal concentrations in Lake Nasser water

	Fe	Mn	Zn	Cu	Ni	Co	Pb	Cd	Cr
Fe	1.00								
Mn	0.79	1.00							
Zn	0.79	1.00	1.00						
Cu	0.90	0.93	0.93	1.00					
Ni	0.77	0.95	0.95	0.89	1.00				
Co	0.77	0.79	0.80	0.84	0.77	1.00			
Pb	0.68	0.65	0.66	0.71	0.67	0.81	1.00		
Cd	-0.12	-0.13	-0.12	-0.08	-0.09	-0.08	-0.10	1.00	
Cr	0.72	0.71	0.72	0.75	0.71	0.88	0.95	-0.09	1.00

Table S4

Correlation coefficient matrix between metals in the Nasser Lake sediments

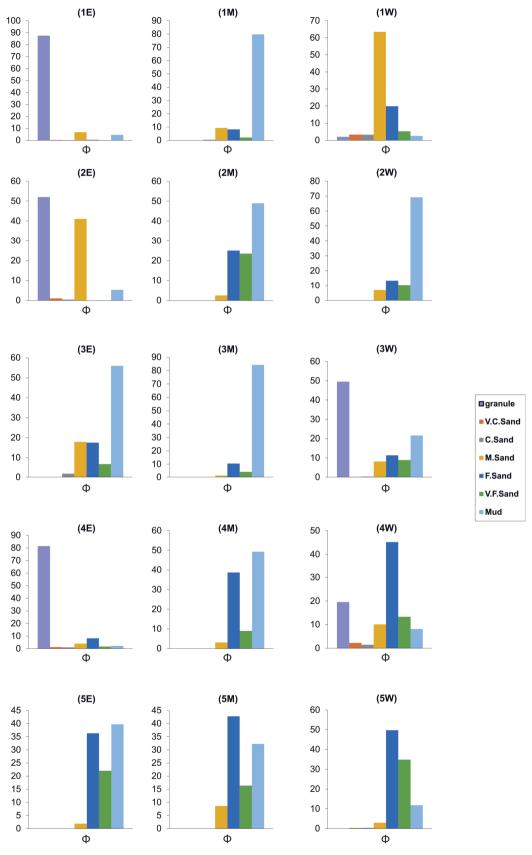| Winter											
	Fe	Mn	Zn	Cu	Ni	Co	Pb	Cr	Cd	Mud %	OM %
Fe	1.00										
Mn	0.49	1.00									
Zn	0.57	0.24	1.00								
Cu	0.41	0.22	0.88	1.00							
Ni	0.28	0.05	0.65	0.74	1.00						
Co	0.36	0.08	0.73	0.77	0.96	1.00					
Pb	0.26	0.11	0.75	0.93	0.84	0.88	1.00				
Cr	0.04	0.17	0.46	0.52	0.50	0.48	0.44	1.00			
Cd	0.57	0.27	0.83	0.77	0.42	0.53	0.65	0.21	1.00		
Mud %	0.39	0.21	0.54	0.44	0.16	0.29	0.22	0.29	0.55	1.00	
OM %	0.61	0.31	0.92	0.88	0.68	0.74	0.76	0.44	0.87	0.68	1.00
Summer											
	Fe	Mn	Zn	Cu	Ni	Co	Pb	Cr	Cd	Mud %	OM %
Fe	1.00										
Mn	0.70	1.00									
Zn	0.44	0.23	1.00								
Cu	0.54	0.39	0.78	1.00							
Ni	0.39	0.33	0.71	0.80	1.00						
Co	0.47	0.35	0.76	0.82	0.97	1.00					
Pb	0.54	0.41	0.81	0.65	0.82	0.84	1.00				
Cr	0.37	0.17	0.92	0.72	0.61	0.65	0.77	1.00			
Cd	0.63	0.45	0.80	0.71	0.74	0.79	0.92	0.74	1.00		
Mud %	0.27	-0.01	0.57	0.46	0.56	0.53	0.53	0.46	0.58	1.00	
OM %	0.53	0.28	0.79	0.65	0.75	0.76	0.82	0.66	0.89	0.86	1.00

Figure 1S

Histograms of grain size analysis for winter samples of Lake Nasser sediment
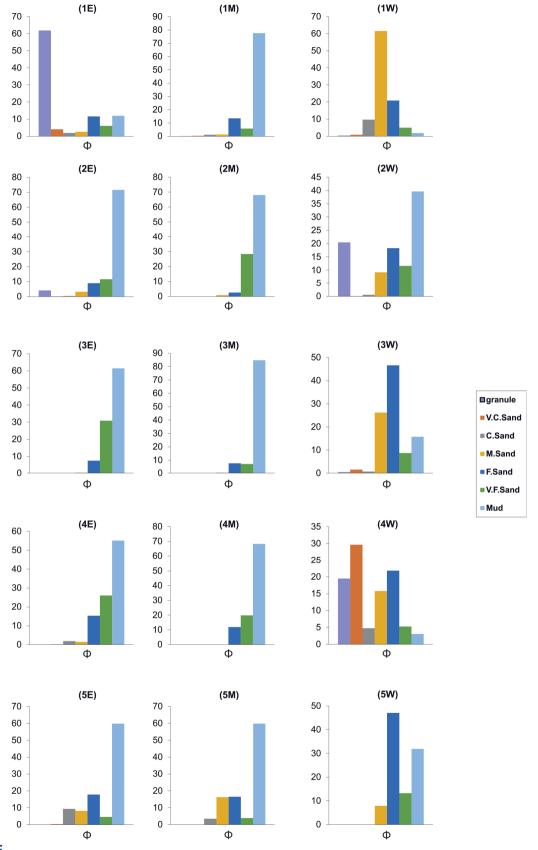
Figure 2S

Histograms of grain size analysis for summer samples of Lake Nasser sediment