Benthic diatoms and macroinvertebrates status with relevant to sediment quality of islands shores in the Nile River, Egypt

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Abstract

Sediments are utilized as a marker for events that endure long enough to manifest their environmental impacts and determine the contamination levels. The purpose of the present study was to highlight the current sediment quality of four Nile islands shores by utilizing a variety of physical, chemical, and biological aspects and indices. In addition, the status of benthic diatoms and macroinvertebrates, as well as their responses to sediment variables were investigated. The metals followed a decreasing concentration order: $Al > Fe > Mn > Zn > Ni \approx Cr > Cu > Co > Pb > Cd$. The outcomes of metal pollution indices revealed some localized contaminated sites, by mostly Ni and Cd. In addition, a moderate toxic risk from metals was observed for El-Keratten shores, while the sediments of El-Warraq, El-Zamalek, and El-Manial islands shores were at low toxic risk. A total of 112 diatom species belonging to 24 genera were identified in the total sample set, where most of the diatoms encountered were cosmopolitan. Metals had a remarkable impact on the composition, distribution, and dominance of diatom assemblages, but had little effect on diatom diversity, while there was a noticeable effect of grain size on diatom distribution and diversity. Thirty-four species of benthic invertebrates were identified in the collected samples from the islands shores. The dominant taxa and groups of benthic invertebrates at different islands were affected by various sediment parameters, where the levels and types of such variables differed from one species to another.

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Graphical abstract

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1 Introduction

Freshwater is necessary for human survival, and its purity is a global problem. The Nile River is Egypt's lifblood and the primary supply of freshwater for nearly all drinking and irrigation needs in Egypt (Abdel-Satar et al. 2017a). In Egypt, there are no systematic monitoring systems for recognizing and determining different types of contaminants in the Nile River ecosystem, where numerous types of organic and inorganic pollutant loading are prevalent (Al-Afify and Abdel-Satar 2020; Othman et al. 2021; Shalaby et al. 2018). The Nile River water quality are influenced not only by water management interventions such as the hydrodynamic regimes regulated by the Nile barrages, but also, by the land and water use, including agricultural return, industrial, municipal and river ships wastewaters. Because of the increase of industrial, agricultural, and recreational activities and a poorly constructed drainage and sewerage infrastructure, the quality of Nile water is a severe concern

(Abdel-Satar et al. 2017a). As a result of upstream dam projects on the Nile River, water use by neighboring nations, and population increase, Egypt's Nile River is seriously environmental changed (Hussein et al. 2021).

From Aswan to the Mediterranean Sea, the Nile River features hundreds of islands. The deposition of coarse material from the suspended load resulted in the formation of the fluvial island. The island arose as a result of the river's inability to transfer the bed load, so it gathered to create the early stage of the island, after which it received fresh deposits, causing it to grow in length and width. Aswan High Dam (AHD) construction has resulted in significant changes in hydrological properties downstream of the dam, impacting river morphology, including islands type and formation. The number and size of the islands have shrunk as a result of the operation of the AHD, which has lowered the rate of suspended sediment transfer by limiting the flow rate downstream of the dam. Where the merging of islands with the east or west bank occurred and resulted in a reduction in the number of islands.

Fig. 1 Egypt Map showing the four selected islands

In certain circumstances, islands have been merged to form a single island (Raslan and Salama 2015).

Permanent islands remain unchanged without being attached to the banks, have permanent vegetation, and have distinct sand bars, while the islands that appear during low water levels and then become submerged during high water levels are seasonal (Sadek 2013). The majority of the permanent Nile River islands have seen rapid changes in land usage in recent years (Taha 2014). The urbanization trend continues, resulting in significant increases in metropolitan areas and a decrease in green space, where the built-up area has expanded due to agricultural land use. As a result, the morphology of the Nile River around the islands has changed (Raslan and Salama 2015). River islands have economic value, since they have a lot of potential for development. The Nile River islands in Great Cairo are regarded as a true breathing space (Farg et al., 2013). They've become one of Egypt's most important waterbird wintering grounds. Migratory birds use these islands as a layover. In addition, the islands are used for seasonal agriculture, fish farming, and wildlife refuges (Sadek 2013).

Sediment is essential in river limnological and environmental studies, because they have a long residence time for interaction with biotic components in the ecosystem and also act as a buffer for dissolved metals control (Abdel-Satar 2005). Sediment serves as a sponge for pollutants in rivers, such as heavy metals, but it also serves as a secondary source of pollutants in river water, and is thus used as a measure of aquatic environment quality (Abou El-Anwar

et al. 2021). Heavy metal contamination of aquatic systems has attracted public attention in recent decades due to its toxicity, persistence, and non-degradability in the environment (Al-Afify and Abdel-Satar 2020; Yacoub et al. 2021). Metals accumulate in the sediment due to a variety of external environmental variables including pH, ionic strength, redox potential, the concentration and type of inorganic and organic chelators, and the accessible surface area for adsorption caused by grain size distribution variation (Nazeer et al. 2016). Metals in sediment can be transmitted directly into aquatic ecosystems and can be easily adsorbed by plant roots and organisms and, therefore, enter the food chain, posing major environmental and health problems (Tang et al. 2020).

Diatoms are used to monitor the ecological state of aquatic systems, they respond rapidly to any shift of environmental condition (Pandey et al. 2017). The relationship between diatoms and heavy metal concentration has gained more attention in recent years, where diatoms respond to high metal concentrations in different ways. Shifting in dominant taxa towards more tolerant species is recorded; also the same species show different frustule and cell morphology when subjected to the high concentration of metal and leading to cell deformations (Lavoie et al. 2017). Diatoms also help metals such as Pb, Zn, and Fe bioaccumulate, making them valuable contributors to global nutrient recycling (Long et al. 2019).

Benthic macroinvertebrate assemblages have been utilized to assess the ecological implications of heavy metal

Table 1 GPS coordinates for the River Nile islands, and the characteristics of Nile island water

Island	Site code	Latitude (E)	Longitude (N)	Surface area (Km ²)	Water depth (m)	Trans Cm	EC $\mu\text{S cm}^{-1}$	pH	DO mg/l
El-Kerateen	K1	30° 09' 05.3"	31° 09' 23.0"	2.6	< 1–10.2	80–110	370–418	7.6–8.6	6.1–10.0
	K2	30° 09' 34.2"	31° 09' 04.1"						
	K3	30° 10' 04.7"	31° 08' 37.1"						
	K4	30° 09' 21.0"	31° 08' 40.0"						
	K5	30° 09' 54.6"	31° 07' 57.0"						
	K6	30° 10' 33.0"	31° 07' 36.3"						
El-Warrak	W1	30° 05' 33.5"	31° 13' 53.1"	7.3	< 1–17.2	90–120	370–416	8.3–8.6	7.2–10.1
	W2	30° 06' 35.4"	31° 14' 22.4"						
	W3	30° 07' 48.5"	31° 13' 05.7"						
	W4	30° 06' 24.6"	31° 13' 15.8"						
	W5	30° 07' 13.0"	31° 12' 49.5"						
	W6	30° 07' 55.2"	31° 11' 48.6"						
El-Zamalek	Z1	30° 02' 14.5"	31° 13' 25.2"	3.6	< 1–13.6	85–100	368–423	7.6–8.5	7.1–10.6
	Z2	30° 02' 59.5"	31° 13' 42.9"						
	Z3	30° 03' 37.2"	31° 13' 32.0"						
	Z4	30° 03' 00.9"	31° 13' 05.4"						
	Z5	30° 03' 48.8"	31° 12' 54.6"						
	Z6	30° 04' 25.5"	31° 13' 22.5"						
El-Manial	M1	30° 00' 23.1"	31° 13' 29.7"	2.1	1–12.6	80–105	313–434	7.8–8.6	6.6–11.6
	M2	30° 00' 55.1"	31° 14' 40.8"						
	M3	30° 01' 43.9"	31° 13' 49.9"						
	M4	30° 00' 59.7"	31° 13' 16.3"						
	M5	30° 01' 43.8"	31° 13' 21.3"						
	M6	30° 02' 09.7"	31° 13' 40.4"						

Trans.: transparency, EC: electrical conductivity, DO: dissolved oxygen

contamination in the aquatic system, because they contain species with varying sensitivity to pollutants. Metal contamination can diminish the number of species of benthic macroinvertebrates also, their growth, density, and production may be affected (Qu et al. 2010).

There are no studies about the Nile islands shores environment and biodiversity to improve their local environment, where the present study is considered the first one. The study aimed to: (a) use a variety of physical, chemical, and biological indices to assess the current sediment quality of four Nile island shores; (b) investigate the status of benthic diatoms and macroinvertebrates relevant to the sediment quality of island shores in the Nile River, Egypt.

2 Materials and methods

2.1 Sampling area

The Nile islands in Great Cairo are characterized by high fertility and suitability for agricultural activities (Taha 2014). The current research focuses on four permanent

islands in Great Cairo (Fig. 1): El-Manial and El-Zamalek, which are largely residential regions, as well as El-Warrak and El-Keratten, which are mostly agricultural land with limited residential areas. Table 1 lists the descriptions of Nile island sites as well as the features of Nile island water.

2.2 Samples collection and analysis

The samples were collected twice, in summer and winter seasons from the selected islands in 2020. Six sites were chosen in each island for samples collection. Eckman Dredge sampling equipment was used to gather sediment samples from the top 15 cm of the bottom layer. For metal analysis, the sediment samples were taken to the lab and air-dried. The dried sample was then passed through a 2-mm sieve to remove any stones or plant pieces, where 0.5 g of sediment samples were digested according to Kouadia and Trefry (1987) method. Cd, Pb, Cr, Co, Ni, Cu, Zn, Mn, Fe and Al were estimated in the digestive sediment samples using Inductively Coupled Plasma Mass Spectrometry (iCAP TQ ICP-MS) Thermo Scientific-Germany. Triplicate readings were used to ensure precision in metal analysis, and

Table 2 Results of grain size, organic matter and carbonate (%) for the sediment in Nile islands shores

Island/site	Winter						Summer						
	Gravel %	Sand %	Mud %	Type	OM %	Carbonate %	Gravel %	Sand %	Mud %	Type	OM %	Carbonate %	
El-Kerateen	K1	20.94	23.46	55.6	Gravelly sandy mud	14.53	7.42	0.59	91.35	8.06	Muddy Sand	2.39	0.00
	K2	1.07	29.34	69.59	Sandy mud	13.63	5.81	0.10	34.05	65.85	Sandy mud	6.25	7.42
	K3	0.41	27.97	71.62	Sandy mud	13.16	6.77	0.89	9.04	90.07	Sandy mud	7.53	13.55
	K4	9.78	54.68	35.54	Gravelly muddy sand	8.12	6.13	0.46	48.56	50.98	Sandy mud	6.82	6.77
	K5	3.00	22.67	74.33	Sandy mud	12.89	6.13	0.17	11.39	88.45	Sandy mud	9.14	6.13
	K6	1.72	53.18	45.10	Muddy sand	10.01	4.52	0.13	90.02	9.85	Muddy Sand	2.62	1.29
	M±SD	6.2±8.0	35±15	59±16		12.1±2.5	6.1±1.0	0.4±0.3	47±37	52±37		5.8±2.7	5.9±4.9
El-Warrak	W1	0.09	87.51	12.40	Muddy sand	4.24	1.94	0.17	90.73	9.10	Muddy Sand	2.80	0.00
	W2	0.00	25.77	74.23	Sandy mud	12.48	3.55	0.34	60.23	39.43	Muddy Sand	4.70	3.23
	W3	1.28	82.89	15.83	Muddy sand	6.65	0.97	0.06	39.58	60.36	Sandy mud	5.80	0.00
	W4	0.32	55.98	43.7	Muddy sand	7.38	1.94	6.32	42.06	51.62	Sandy mud	3.79	16.13
	W5	5.16	89.28	5.56	Sandy	2.31	0.00	3.48	96.36	0.16	Sand	0.82	0.00
	W6	1.50	49.16	49.34	Sandy mud	9.89	3.23	14.02	85.95	0.03	Gravelly sand	0.51	0.00
	M±SD	1.4±1.6	65±61	34±37		7.2±7.6	1.9±1.9	4.1±4.7	69±66	27±30		3.1±3.1	3.2±3.8
El-Zamalek	Z1	0.42	99.51	0.07	Sand	1.86	0.00	0.31	99.45	0.24	Sand	0.83	0.00
	Z2	23.84	74.47	1.69	Gravelly sand	3.28	0.00	0.49	6.14	93.37	Sandy mud	5.55	0.32
	Z3	5.58	92.16	2.26	Sand	3.29	0.00	7.10	90.64	2.26	Gravelly sand	1.46	5.16
	Z4	0.69	99.27	0.04	Sand	1.20	0.00	0.93	98.98	0.09	Sand	0.66	0.00
	Z5	3.19	94.86	1.95	Sand	3.81	0.00	0.45	99.26	0.29	Sand	0.98	0.00
	Z6	0.80	93.07	6.13	Sand	4.30	0.00	0.25	60.64	39.11	Muddy Sand	4.53	0.65
	M±SD	5.8±6.6	92±91	2.0±2.3		3.0±3.1	0.0±0.0	1.6±1.8	76±72	23±26		2.3±2.6	1.0±1.2
El-Manial	M1	3.97	96.01	0.02	Sand	0.30	0.00	0.91	98.99	0.10	Sand	0.29	0.00
	M2	5.96	91.02	3.02	Sand	2.76	0.00	0.32	99.64	0.04	Sand	0.41	0.00
	M3	5.46	92.61	1.93	Sand	3.40	0.00	0.0	99.00	1.00	Sand	1.53	0.00
	M4	2.91	86.60	9.59	Muddy sand	5.18	0.32	2.54	95.40	2.06	Sand	1.68	0.00
	M5	6.63	92.98	0.39	Sand	1.12	0.00	0.35	99.62	0.03	Sand	0.45	0.00
	M6	3.94	56.45	39.61	Muddy sand	8.23	3.23	32.41	60.55	7.04	Gravelly sand	2.94	0.00
	M±SD	4.8±5.0	86±84	9.1±10.6		3.5±4.0	0.6±0.7	6.1±7.0	92±91	1.7±2.0		1.2±1.4	0.0±0.0

M±SD: Mean ± Standard deviation

the mean value was calculated with relative standard deviations of less than 5%. The dry sieving technique (Folk 1974) was used to assess grain size; the wet oxidation method was used to determine sediment organic matter (OM) (Loring and Rantala 1992) and carbonate percent was measured as reported in American Society of Agronomy (1982).

To evaluate the metal ecological risk in islands sediment; single and integrated indices were used including pollution load index (PLI) (Tomlinson et al. 1980); enrichment factor (EF) (Yahaya et al. 2012); geoaccumulation index (I-geo) (Muller 1969); modified contamination degree (mCd) (Abraham and Parker 2008); potential ecological risk index (ER) (Hakanson 1980, 1988); toxic risk index (TRI) (Gao et al. 2018; Zhang et al. 2016) and finally the toxic unit (TU) (Pedersen et al. 1998). The supplementary information (Text S1) provides more information about these indices.

Diatom microscope slides were prepared according to ANS (2002), in which 2 g of air-dried sediment sample was digested using 98% sulphuric acid and 65% nitric acid in the ratio of 1:2, till complete decomposition of organic matter. The samples were then washed many times until pH to be > 6.5. The diatom samples were pipetted onto cleaned coverslips, where microscope slides were prepared with Naphrax and viewed under Zeiss light microscope at a 40X magnification.

Three replicate samples for macrobenthic invertebrate community assessment were collected from the shores of the Nile islands using Ekman Grab bottom sampler. The samples were washed to remove any adhering sediments or mud through a sieve screen of 500 µm mesh diameter. The samples were fixed with a 10% neutral formalin solution. In the laboratory, the samples were washed again in a net of 500 µm mesh diameter. The samples were classified using a binuclear dissecting microscope. Population density (PD) was calculated and expressed as organisms /m². Macrobenthic invertebrate fauna were identified using Brinkhurst (1966), Brinkhurst and Jamison (1971), Brown et al. (1984), Pennak (1953), and Wirth and Stone (1963).

2.3 Statistical analysis

The data for sediment were tested for spatial and temporal significant differences using one-way ANOVA. In addition, the Pearson correlation index was used to calculate the correlations between different variables in the sediment of Nile islands shores. Canonical correspondence analysis (CCA) was used to evaluate the relationship between the abundance of diatoms and macrobenthos sequences with sediment variables in Nile shores using Canoco for Windows version 4.5 (ter Braak 1987). The diversity index and evenness for diatom at all sampled sites were calculated using primer software version 5 (Clarke and Gorley 2001). The nonparametric multiplicative regression (NPMR) was applied to predict the

relationships between different indices through the Microsoft Excel program.

3 Results and discussion

3.1 Sediment analysis

The bottom sediments of rivers have a significant impact on aquatic life and water quality (Abou El-Anwar et al. 2021). The grain size of sediments is an essential factor influencing the metal mobility and dispersion in a river system (Abdel-Satar 2005). Table 2 summarizes the grain size distributions for sediment samples collected from four Nile islands shores. Grain size analysis has shown that El-Keratten sediments were mainly composed of mud, reflect the agricultural activity on the island, while El-Manial, El-Zamalek, and El-Warraq islands sediment possessed sand with an average percent 89, 84, and 67%, respectively.

The average OM values for the sediment of El-Manial, El-Zamalek, El-Warraq, and El-Keratten islands were 2.4, 2.6, 4.1, and 8.9%, respectively, Table 2. OM showed a significant correlation with mud percent in all islands sediment, Table S3, where the particle composition of the Nile islands sediment and the organic load entering the Nile with various wastes control the organic content distribution in the Nile sediments (Abdel-Satar 2005). Because of the formation of complexes between the metals and OM, the availability of metals to organisms will be reduced (Abdel-Satar et al. 2017b). OM showed significant correlations ($n = 12$, $p < 0.05$) with metals (Mn, Zn, Cu, Pb, and Cd) for different islands sediments samples (Table S3), reflecting the role of OM in the bioavailability and mobility of metals (Qu et al. 2019). The stability of natural humic complexes generally follows the Irving-Williams order for divalent trace elements complexation: $Hg > Cu > Pb > Zn > Cd > Fe$ in Nile sediments (Abdel-Satar 2005).

Carbonate content was completely depleted in most sediment samples for El-Manial and El-Zamalek islands, while the increase of carbonate percent in El-Warraq and El-Keratten samples may be related to the mud content, Table 2. The significant correlations were observed between mud and carbonate contents (Table S3), where the fermentation processes, which may occur in sinking dead organisms, generating OM and releasing calcium carbonate to surface sediment (Abdel-Satar 2005).

3.2 Metals abundances

Because sediments show less fluctuation over time than dissolved metals in overlying water columns, they are favored as a monitoring method (Badawy et al. 2021). pH

Table 3 Basic statistics of heavy metals ($\mu\text{g g}^{-1}$) in the sediment of Nile islands shores

Metal	Season		El-Kerateen	El-Warrak	El-Zamalek	El-Manial	EPA (2006)	MacDonald (2000)	
								PEL	TEL
Al	W	Range	11,897–35,765	10,831–24,209	17,561–29,251	13,169–35,506	–	–	–
		Mean $\pm$ SD	20,859 $\pm$ 8421	16,067 $\pm$ 5775	22,958 $\pm$ 4814	22,642 $\pm$ 9926			
	S	Range	23,158–78,427	18,712–71,833	17,388–60,614	11,755–39,395			
		Mean $\pm$ SD	53,701 $\pm$ 22,975	48,675 $\pm$ 21,444	40,690 $\pm$ 17,252	22,818 $\pm$ 9978			
Fe	W	Range	11,288–17,786	12,907–16,764	13,859–22,458	13,071–20,970	20,000	–	–
		Mean $\pm$ SD	14,693 $\pm$ 2391	14,445 $\pm$ 1689	17,284 $\pm$ 3647	16,458 $\pm$ 3111			
	S	Range	13,849–48,562	13,295–51,563	13,797–37,472	12,289–31,596			
		Mean $\pm$ SD	30,586 $\pm$ 14,132	32,612 $\pm$ 16,359	26,978 $\pm$ 8798	16,822 $\pm$ 7288			
Mn	W	Range	592.1–2203	406.8–1329	335.4–825.5	125.9–1237	460	–	–
		Mean $\pm$ SD	1084 $\pm$ 620	840 $\pm$ 421	591 $\pm$ 161	478 $\pm$ 392			
	S	Range	774.5–1898	174.3–1679	416.3–997.6	273.1–849.9			
		Mean $\pm$ SD	1194 $\pm$ 416	793 $\pm$ 523	702 $\pm$ 204	433 $\pm$ 219			
Zn	W	Range	55.1–175.8	57.3–197.8	75.3–98.1	45.6–193.8	121	123	315
		Mean $\pm$ SD	96.7 $\pm$ 43.8	121.3 $\pm$ 60.1	86.3 $\pm$ 8.0	124.8 $\pm$ 62.9			
	S	Range	102.2–186.3	79.9–147.1	75.3–157.8	45.0–185.5			
		Mean $\pm$ SD	141.0 $\pm$ 32.1	101.2 $\pm$ 24.4	97.6 $\pm$ 30.8	86.5 $\pm$ 52.0			
Cu	W	Range	40.11–66.33	22.23–53.98	21.36–40.06	10.73–44.82	31.6	35.7	197
		Mean $\pm$ SD	53.7 $\pm$ 10.9	39.4 $\pm$ 12.7	32.9 $\pm$ 6.5	25.3 $\pm$ 12.7			
	S	Range	39.67–106.5	19.12–54.75	24.87–42.97	15.37–35.25			
		Mean $\pm$ SD	64.4 $\pm$ 25.4	34.5 $\pm$ 12.0	32.7 $\pm$ 8.0	23.2 $\pm$ 6.8			
Ni	W	Range	31.23–102.2	32.72–59.84	34.30–94.08	12.56–64.43	22.7	18	36
		Mean $\pm$ SD	56.9 $\pm$ 27.4	40.1 $\pm$ 11.2	51.3 $\pm$ 21.6	32.8 $\pm$ 17.6			
	S	Range	74.11–182.2	21.38–103.8	47.94–99.11	21.29–62.30			
		Mean $\pm$ SD	101.9 $\pm$ 40.1	63.7 $\pm$ 29.4	74.2 $\pm$ 21.4	33.6 $\pm$ 15.4			
Co	W	Range	11.04–33.83	13.01–25.64	12.85–21.04	8.04–25.52	50	–	–
		Mean $\pm$ SD	21.2 $\pm$ 9.6	16.7 $\pm$ 5.1	18.4 $\pm$ 2.9	13.5 $\pm$ 6.4			
	S	Range	30.06–41.54	8.26–41.36	20.47–31.53	8.98–26.04			
		Mean $\pm$ SD	33.6 $\pm$ 4.3	25.9 $\pm$ 12.1	23.9 $\pm$ 4.4	13.6 $\pm$ 6.5			
Pb	W	Range	9.26–27.26	12.94–26.65	5.86–12.12	7.58–12.98	35.8	35	91.3
		Mean $\pm$ SD	18.8 $\pm$ 6.1	19.1 $\pm$ 6.1	10.0 $\pm$ 2.3	10.2 $\pm$ 2.0			
	S	Range	5.58–29.12	6.92–16.06	6.22–11.14	5.22–11.36			
		Mean $\pm$ SD	15.2 $\pm$ 8.0	10.1 $\pm$ 3.40	8.1 $\pm$ 1.7	8.2 $\pm$ 2.4			
Cr	W	Range	19.01–126.8	21.32–88.15	24.25–96.86	22.96–83.55	43.4	37.3	90
		Mean $\pm$ SD	49.6 $\pm$ 43.0	34.5 $\pm$ 17.1	57.6 $\pm$ 29.2	45.1 $\pm$ 21.6			
	S	Range	71.93–147.7	22.65–163.0	36.03–133.5	16.35–100.4			
		Mean $\pm$ SD	103.7 $\pm$ 27.8	93.8 $\pm$ 50.7	86.7 $\pm$ 32.1	48.3 $\pm$ 34.4			
Cd	W	Range	1.02–2.18	1.19–4.12	1.47–4.44	1.16–4.88	0.99	0.596	3.53
		Mean $\pm$ SD	1.6 $\pm$ 0.4	1.99 $\pm$ 1.20	2.39 $\pm$ 1.09	2.06 $\pm$ 1.43			
	S	Range	1.12–2.02	1.14–2.68	1.26–3.12	1.02–3.94			
		Mean $\pm$ SD	1.61 $\pm$ 0.37	1.62 $\pm$ 0.55	2.00 $\pm$ 0.88	1.87 $\pm$ 1.09			

W: winter, S: summer, SD: standard deviation, TEL: threshold effect level, PEL: probable effect level

of Nile water was in the alkaline side (Table 2) that promotes the metal precipitation and possibly increases the metal levels in sediments (Abdel-Satar 2005). During the two study periods, the examined metals followed a decreasing average concentration order $\text{Al} > \text{Fe} > \text{Mn} > \text{Zn} > \text{Ni} \approx$

$\text{Cr} > \text{Cu} > \text{Co} > \text{Pb} > \text{Cd}$ in the Nile islands shores sediment, Table 3. The average concentrations maxima for all metals analyzed were in the El-Keratten Island sediment. All metals did not show any spatial variations during the studied periods for different islands.

Al and Fe showed significant temporal variations for El-Zamalek, El-Warraq and El-Keratten sediment samples. No criteria have been established for Al, which is generally not harmful to biota. The average levels of Al and Fe were the lowest in El-Manial shores (22,730 and 16,640 $\mu\text{g g}^{-1}$, respectively), while the highest levels were recorded in El-Keratten and El-Warraq sediment, reflecting the agricultural wastes discharges containing high levels of metals. Fe concentrations in sediment of islands shores surpassed the freshwater guidelines (EPA 2006) on some samples especially in El-Keratten and El-Warraq and during summer season, Table 3.

Metals (Mn, Zn, and Cu) are essential micronutrients and have been demonstrated to be vital in plant and animal metabolism. Due to increased contamination of the world's surface waters and broad transmission of airborne contaminants, their concentrations may eventually approach lethal levels (Goldman 2009). The ranges of Mn, Zn, and

Cu concentrations in sediment Nile islands shores were 125.9–2202.6, 45.0–197.8, and 10.7–106.5 $\mu\text{g g}^{-1}$, respectively. The studied sediment showed high levels of metals and their levels overstepped the freshwater sediment benchmarks (EPA 2006) on most samples, Table 3. The agricultural runoff, fertilizer leaching, and disposal of domestic sewage lead to an increase in the metals load to Nile River islands shores. These metals have limited solubility and are not biodegradable, but they commonly interact with inorganic and organic substances before settling to the bottom sediments of water bodies (Maina et al. 2019).

Ni is an essential element for microorganisms and plants, where it is a component of various enzymes that play critical roles in oxygen, nitrogen, and carbon cycling (Mulrooney and Hausinger 2003). In addition, Co acts as a catalyst in nitrogen fixation in different types of algae and is required for vitamin B-12 synthesis (Goldman 2009). The average Ni concentrations were 79.36, 53.25, 62.72,

Table 4 Pollution load index (PLI), modified contamination degree (mCd), potential ecological risk index, toxic unit (TU) and toxic risk index (TRI) for Nile islands shores sediment*

Island	Season	PLI	mCd	ER	Σ TU	TRI
El-Kerateen	Winter	0.76–1.73 (1.07)	0.91–2.43 (1.38)	51.9–116.3 (78.6)	2.14–6.06 (3.37)	5.10–12.72 (7.53)
	Summer	1.12–1.82 (1.48)	1.41–2.74 (1.92)	65.7–122.5 (93.6)	4.08–8.22 (5.38)	8.22–15.69 (11.03)
El-Warrak	Winter	0.67–1.29 (0.94)	0.76–1.62 (1.18)	79.8–83.0 (81.5)	2.05–3.95 (2.96)	4.63–9.26 (6.88)
	Summer	0.51–1.91 (1.13)	0.60–2.36 (1.38)	45.8–129.0 (76.1)	1.66–6.37 (3.88)	3.93–13.49 (8.21)
El-Zamalek	Winter	0.76–1.07 (0.92)	0.93–1.57 (1.21)	79.1–80.7 (79.9)	2.42–4.62 (3.29)	5.76–10.81 (7.73)
	Summer	0.87–1.38 (1.08)	1.08–1.82 (1.42)	63.7–130.6 (90.6)	2.93–5.44 (4.16)	6.20–11.92 (8.88)
El-Manial	Winter	0.47–1.01 (0.76)	0.58–1.42 (1.00)	79.7–81.4 (80.3)	1.62–3.80 (2.63)	3.86–9.56 (6.35)
	Summer	0.53–1.11 (0.71)	0.64–1.38 (0.92)	43.7–134.2 (73.4)	1.79–3.89 (2.48)	4.10–8.29 (5.90)

*minimum–maximum (mean)

Fig. 2 Average contribution percentage of metals to ER and Σ TU in Nile islands shores

and $33.18 \mu\text{g g}^{-1}$ for El-Keratten, El-Warraq, El-Zamalek, and El-Manial shores, respectively, while the averages Co values were 27.42, 21.35, 21.12, and $13.57 \mu\text{g g}^{-1}$, respectively, El-Keratten showed the highest levels and El-Manial had the lowest. Ni concentrations in about 94% of samples overstepped the EPA (2006) guidelines at the two studied periods (Table 3), where domestic wastewater effluents are the most common cause of Ni contamination in aquatic habitats, as acidic beverages can dissolve Ni from pipes. Cr levels in Nile shores ranged from 16.35 to $163.1 \mu\text{g g}^{-1}$. The highest level was recorded at El-Warraq Island, while the minimum was observed at El-Manial. The average concentration of Cr showed the highest level in El-Keratten and the lowest in El-Manial. The concentrations of Cr are significantly higher than the amounts in the freshwater sediment guidelines (EPA 2006), such concentration is an indicator of high Nile islands activities, Table 3. Cd and Pb are hazardous metals with significant implications for the environment and human health. The presence of other metals, such as zinc, may aggravate cadmium toxicity (Rzetała et al. 2016). The levels of Pb were within the freshwater benchmark (EPA 2006) in all studied islands samples, while Cd overstepped the guidelines in all Nile shores samples, Table 3.

According to the correlation matrix based on Pearson's coefficient the mud % and studied metals in El-Manial (Cu, Pb, Cd), El-Zamalek (Fe, Zn, Cu), El-Warraq (Mn, Cu, Pb, Cd), and El-Keratten (Cu, Pb, Cd) showed significant correlations ($n = 12$, $p < 0.05$), Table S3, implying that finer-grained sediments are linked to elevated heavy metal concentrations (Sayed and Abdel-Satar 2009). The results of correlation matrix ($n = 12$, $p < 0.05$) for studied metals pairs in different islands shores illustrated common sources, Table S3.

Because of their toxicity, non-degradability, and biomagnification, which can pose a threat to ecosystems, heavy metals are an effective indicator of ecological environmental quality assessment (Abou El-Anwar et al. 2021). The ecologically adverse hazards of metals in Nile shores sediments were assessed using the threshold effects level (TEL) and probable effects level (PEL) according to MacDonald et al. (2000), Table 3. In the two studied periods, almost all islands sediment showed high levels of Ni and Cd exceeded the TEL. While, Zn, Cu, and Cr levels in Nile samples surpassed the TEL in El-Keratten shores in 42, 100 & 67% of samples, respectively, while for El-Warraq shores in 25, 50 & 58% of samples, respectively. In addition, El-Zamalek and El-Manial shores in 8, 33 & 92% and 25, 8 & 58%, of samples showed high levels of Zn, Cu, and Cr, respectively, reflecting rare adverse effects on aquatic biota inhabiting the Nile shores. In general, various metals sources to Nile shores include dry and wet fallout of air particle matter, decomposing of dead plants and animals, in addition to the discharge of various untreated wastes, including agricultural wastes, especially into El-Keratten shores.

3.3 Sediment indices of Nile shores

The sediment quality indices application can help to evaluate the detrimental effects of numerous anthropogenic contamination sources and is considered a suitable approach for monitoring water quality (Unda-Calvo et al. 2020). Average I-geo values for tested metals according to contamination classification (Müller 1969) indicated that El-Keratten sediment was virtually contaminated by Mn, Cu, Ni, and Cd, El-Warraq and El-Zamalek shores were contaminated by Ni and Cd, and finally, El-Manial sediments had Cd contamination only (Fig. S1).

Fig. 3 Diatom diversity index at sites of four Nile islands during winter and summer. Note: Diatoms at sites K3, K5, Z3 and Z4 in winter and W6 in summer were not analyzed

Fig. 4 Diatom evenness value at sites of four Nile islands during winter and summer

Fig. 5 Ordination diagram showing the result of CCA analysis for diatoms in the four studied islands

Table 5 Coded diatom species included in the CCA and recorded with relative abundance $\geq 1\%$ at the four islands shores

K	W	Z	M	Species name
Species code				
			S1	<i>Achnanthes lanceolata</i> Oestrup
S1			S2	<i>Achnanthes lanceolata</i> var. <i>rostrata</i> * <i>Planothidium rostratum</i> (Ostrup) Lange-Bertalot
S2	S1	S1	S3	<i>Achnantheidium minutissimum</i> (Kützing) Czarnecki
	S2	S2	S4	<i>Amphora fogediana</i> * <i>Amphora eximia</i> (Krammer) Carter
S3	S3			<i>Amphora lybica</i> Ehrenberg
	S4	S3	S5	<i>Amphora ovalis</i> Kützing
S4				<i>Amphora perpusilla</i> Grunow
S5	S5	S4	S6	<i>Amphora venta</i> * <i>Halamphora veneta</i> (Kützing) Levkov
		S5		<i>Bacillaria paradoxa</i> * <i>Bacillaria paxillifera</i> (O.F.Müller) T.Marsson
S6	S6	S6	S7	<i>Cocconeis placentula</i> Ehrenberg
S7	S7	S7	S8	<i>Cyclotella glomerata</i> * <i>Lindavia glomerata</i> (H.Bachmann) Adesalu & Julius
S8	S8	S8	S9	<i>Cyclotella meneghiniana</i> Kützing
S9	S9	S9	S10	<i>Cyclotella ocellata</i> * <i>Pantocsekiella ocellata</i> Pantocsek
S10	S10	S10	S11	<i>Cyclotella operculata</i> * <i>C. distinguenda</i> (Kützing) Hustedt
		S11	S12	<i>Cyclotella stelligera</i> Cleve & Grunow
S11		S12	S13	<i>Cymbella affinis</i> Kützing
		S13		<i>Cymbella caespitosa</i> * <i>Encyonema cespitosum</i> Kützing
		S14		<i>Cymbella hustedtii</i> Krasske
S12				<i>Cymbella leporeros</i> * <i>Cymbella neoleptoceros</i> Krammer
S13	S11	S15	S14	<i>Cymbella microcephala</i> * <i>Encyonopsis microcephala</i> (Grunow) Krammer
S14	S12	S16	S15	<i>Cymbella silesiaca</i> * <i>Encyonema silesiacum</i> (Bleisch) Mann
S15	S13	S17	S16	<i>Epithemia sorex</i> Kützing
S16	S14	S18	S17	<i>Eunotia</i> sp
S17			S18	<i>Fragilaria biceps</i> Ehrenberg
S18	S15	S19	S19	<i>Fragilaria construens</i> (Ehrenberg) Grunow
S19	S16	S20	S20	<i>Fragilaria ulna</i> (Nitzsch) Lange-Bertalot
S20				<i>Gomphonema angustatum</i> (Kützing) Rabenhorst
S21				<i>Gomphonema gracile</i> Ehrenberg
S22	S17	S21	S21	<i>Gomphonema minutum</i> Agardh
S23	S18		S22	<i>Gomphonema olivaceum</i> Hornemann
S24	S19	S22	S23	<i>Gomphonema parvulum</i> Kützing
S25		S23		<i>Gomphonema tergestinum</i> (Grunow) Fricke
S26	S20			<i>Gomphonema truncatum</i> Ehrenberg
S27				<i>Hantzschia amphioxys</i> (Ehrenberg) Grunow
S28	S21	S24	S24	<i>Mellosira granulata</i> * <i>Aulacoseira granulata</i> (Ehrenberg) Simonsen
S29	S22	S25	S25	<i>Mellosira granulata</i> var. <i>angustissima</i> * <i>Aulacoseira granulata</i> var. <i>angustissima</i> (O. Muller) Simonsen
	S23		S26	<i>Navicula accomoda</i> * <i>Craticula accomoda</i> (Hustedt) Mann
S30	S24	S26	S27	<i>Navicula anglica</i> var. <i>subsalsa</i> (Grunow) Cleve
	S25	S27		<i>Navicula digitoradiata</i> Gregory
S31			S28	<i>Navicula diluviana</i> * <i>Cymbellafalsa diluviana</i> (Krasske) Lange-Bertalot
				<i>Navicula gastrum</i> * <i>Placoneis gastrum</i> (Ehrenberg) Mereschkovsky
S32		S28		<i>Navicula harderii</i> * <i>Sellaphora harderii</i> (Hustedt) J.Foets & C.E.Wetzel
	S26	S29	S29	<i>Navicula heufferi</i> var. <i>leptocephala</i> ((Brebisson) Patrick * <i>Navicula erifuga</i> Lange-Bertalot
		S30		<i>Navicula incerta</i> Grunow * <i>Navicula salinicola</i> Hustedt
	S27		S30	<i>Navicula incomposita</i> var. <i>minor</i> Hagelstein
	S28		S31	<i>Navicula kriegeri</i> * <i>Geissleria kriegeri</i> (Krasske) Lange-Bertalot
			S32	<i>Navicula mutica</i> Grunow
S33	S29	S31		<i>Navicula parva</i> * <i>Pinnularia microstauron</i> (Ehrenberg) Cleve
	S30			<i>Navicula phyllepta</i> Kützing

Table 5 (continued)

K	W	Z	M	Species name
Species code				
	S31	S32		<i>Navicula plathii</i> Brockm
	S32		S33	<i>Navicula pupula</i> * <i>Sellaphora pupula</i> (Kützing) Mereschkovsky
		S33		<i>Navicula radiosa</i> Kützing
S34	S33	S34	S34	<i>Navicula salinarum</i> Grunow
S35				<i>Navicula salinarum</i> var. <i>intermedia</i> Grunow * <i>Navicula capitatoradiata</i> Germain
S36	S34	S35	S35	<i>Navicula viridula</i> Kützing
	S35			<i>Neidium bisulcatum</i> var. <i>baicalense</i> (Skvortsov & K.I.Meyer) Reimer
S37	S36	S36		<i>Nitzschia agnita</i> Hustedt
	S37		S36	<i>Nitzschia amphibia</i> var. <i>rostrata</i> Hustedt
S38	S38	S37		<i>Nitzschia dissipata</i> (Kützing) Rabenhorst
		S38		<i>Nitzschia fonticola</i> (Grunow) Grunow
		S39	S37	<i>Nitzschia frustulum</i> (Kützing) Grunow
S39				<i>Nitzschia frustulum</i> var. <i>bulnheimiana</i> * <i>Nitzschia bulnheimiana</i> (Rabenhorst) H.L.Smith
S40	S39	S40	S38	<i>Nitzschia liebetruthii</i> Rabenhorst
S41	S40	S41	S39	<i>Nitzschia palea</i> (Kützing) Smith
S42	S41			<i>Nitzschia paleacea</i> Grunow in Van Heurck
S43			S40	<i>Nitzschia prolongata</i> var. <i>hoehnkii</i> (Hustedt) Lange-Bertalot
S44				<i>Nitzschia umbonata</i> Ehrenberg
			S41	<i>Rhopalodia gibba</i> Ehrenberg
S45	S42	S42	S42	<i>Synedra ulna</i> var. <i>ramesii</i> * <i>Fragilaria ulna</i> var. <i>ramesi</i> (Héribaud-Joseph) Hustedt
S46	S43			<i>Synedra tenera</i> * <i>Fragilaria tenera</i> (W.Smith) Lange-Bertalot
			S43	<i>Tabellaria binalis</i> var. <i>elliptica</i> * <i>Oxyneis binalis</i> var. <i>elliptica</i> (R.J.Flower) J.C.Kingston

K: El-Keratten Island, W: El-Warraq Island, Z: El-Zamalek Island, M: El-Manial Island

EF values of more than 1.5 indicated that the metal's sources are mainly anthropogenic, whereas EF in the range of 0.5–1.5 suggested the metals come entirely from natural processes or crustal minerals (Al-Afify and Abdel-Satar 2020). Except for Cd, the studied metals in all islands shores showed minor enrichment. According to average EF values, El-Keratten, El-Warraq, and El-Zamalek shores registered severe enrichment by Cd, while El-Manial shores have very severe enrichment, indicating anthropogenic sources for Cd (Fig. S2).

PLI is a valuable method for determining a sample's overall toxicity grade due to total metals content effects (Badawy et al. 2021). According to average PLI values for metals, El-Keratten shores has pollution stress during winter and summer seasons, while El-Warraq and El-Zamalek shores showed pollution level in summer season and no pollution indicated in winter. Finally, El-Manial shores did not show any pollution level during the two seasons (Table 4). The average mCd values found for the analyzed metals suggests nil contamination for all islands shores in the two studied periods (mCd < 1.5) except for El-Keratten in summer seasons, it showed low pollution level ($1.5 \leq \text{mCd} < 2$), Table 4.

The average potential ecological risk (ER) for all islands shores was classified as low-grade risk ($\text{ER} < 150$), Table 4.

The average contribution of Cd to the ecological risk assessment was ranged from 58 to 75% in the islands shores, while the Ni contribution was in the range of 11–20% (Fig. 2). El-Keratten shores had the highest accumulative capacity for Ni (20%) and Cu (11%), whereas El-Manial shores sediment recorded the highest Cd capacity (75%). In general, the metallic contribution to the ecological risk trend in Nile shores follows the order; $\text{Cd} > \text{Ni} > \text{Cu} > \text{Cr} > \text{Pb} > \text{Mn} > \text{Zn} > \text{Co}$ (Fig. 2). Significant Cd bio-accumulative capacity in aquatic bottom fauna, furthermore, its relative solubility in water, indicated that Cd potential toxicity will threaten the aquatic species in Nile islands shores (Weldegebriel et al. 2012).

TU and TRI approaches are used to assess the toxic risks in aquatic biota exposed to heavy metals contaminated sediment and consider the TEL and PEL (Gao et al. 2018; Zhang et al. 2016). If the sediment ΣTU for metals was minimal (< 4), no significant harmful effect on aquatic organisms is registered (Gao et al. 2018). The summer season samples recorded higher average ΣTU for all Nile shores compared with winter season, where El-Keratten, El-Warraq and El-Zamalek shores recorded high ΣTU (> 4) with significant harmful effect on aquatic biota, Table 4. Figure 2 showed the average contributions of each metal to the ΣTU and

Fig. 6 Nonparametric multiplicative regression exhibiting the relationship between the diversity diatom index and metal indices at all studying sites of the four islands

declared that Ni, Cr and Cd accounted for the majority of the overall toxicity of the shores sediment. According to the average TRI, moderate toxic risk from metals was observed for El-Keratten shores in summer season, where their values were more than 10, while El-Warraq, El-Zamalek, and El-Manial shores sediments were at low toxic risk in the two studied periods, Table 4.

3.4 Attached diatoms community

A total of 112 diatom species (including species and varieties) belonging to 24 genera were identified in the total samples set, most of the diatoms encountered in the study were cosmopolitan. The most diverse genera were *Navicula*

(25 species) and *Nitzschia* (20 species). *Achnantheaceae* and *Fragilariaceae* were the most frequent pinnate genera, while *Cyclotella* and *Mellosira* were the most frequent centric genera.

According to diversity Shannon index, the recommended season for sampling diatoms was summer, as winter samples possessed many taxa with less dominance. In general, the species diversity was higher in summer at most sites than in winter samples (Fig. 3). During the winter and summer, site Z1 had the lowest diversity value of 1.75 and 1.08, respectively, while the maximum diversity was recorded at site W1 in the winter with a value of 3.92 and W2 in the summer with a value of 4.79. The high levels of diversity at some sites, such as K6 and Z6, were linked to high levels of sedimentation.

The evenness values in winter were in the range of 0.33–0.66, where the lowest value was recorded at site Z5 and reflected the high dominance of *Cyclotella ocellata* which represented 73% of total species abundance and was associated with a high Cd level (Fig. 4). In summer, the values ranged between 0.48 and 0.69, where the minimum value was observed at site M2 and reflected the high dominance distribution between *Cyclotella ocellata* and *Fragilaria construens* which represented 41% and 42% of total abundance, respectively, and was associated with a high percentage of sand sediment texture 99.6%.

Diatom assemblages (expressed as the relative abundance of species that had minimum relative abundances $\geq 1\%$ so, rare species were not included in the analysis) were correlated with sediment texture, carbonate, OM and metal levels. The CCA applied on samples of El-Keratten Island revealed that sediment variables represented 47.6% of the variance in the weighted averages of diatom assemblage. As a result, Fig. 5 depicted the observed distribution based on sediment variables. *Amphora lybica*, *Fragilaria ulna*, *Gomphonema angustatum*, *Mellosira granulata* var. *angustissima* and *Navicula viridula* was close to Ni and Co points and so on. The full name of species abbreviation in Fig. 5 was listed in Table 5. Most species were sensitive to high metal levels, where metal as Mn and Pb in addition to OM and gravel texture negatively correlated to species axis 1 with weighted correlation matrix of -0.2 , -0.4 , -0.7 , and -0.6 , respectively. For El-Warraq Island samples the sediment variables represented 47.8% of the variance in the weighted averages of diatom assemblage. The most impactful variable, Al, had a weighted correlation matrix of 0.70 with species axis 1, followed by OM and Pb, which had weighted correlation matrix of -0.64 and -0.57 , respectively (Fig. 5). In El-Zamalek Island, the sediment variables represented 52.8% of the variance in the weighted averages of the diatom community. Most variables demonstrated high correlations with species axis 1, such as Mn, Ni, Co, and Cd with a weighted correlations matrix of -0.5 , -0.55 , -0.6 , and 0.45 , respectively.

Table 6 Presence and absence of the recorded benthic invertebrates in the studied sites of Nile shores

Taxa	El-Kerateen	El-Warrak	El-Zamalek	El-Manial	Taxa	El-Kerateen	El-Warrak	El-Zamalek	El-Manial
Mollusca:					Arthropoda:				
<i>Melanoides tuberculata</i>	6+	6+	6+	5+	<i>Chlamidothica unispinosa</i>	3+	1+	–	–
<i>Valvata nilotica</i>	5+	5+	1+	1+	<i>Chironomidae pupae</i>	–	5+	1+	3+
<i>Cleopatra bulmoides</i>	5+	4+	4+	5+	<i>Chironomidae larvae</i>	5+	6+	6+	6+
<i>Bulinus truncatus</i>	4+	2+	1+	–	<i>Cainus</i> sp	2+	1+	2+	3+
<i>Bellyma unicolor</i>	2+	1+	2+	2+	<i>Ostracoda</i>	1+	1+	–	–
<i>Gyraulus ehrenbergi</i>	4+	–	–	–	<i>Cardina nilotica</i>	2+	–	–	–
<i>Pirenella conica</i>	4+	6+	5+	4+	<i>Libellula</i> sp.	1+	–	–	–
<i>Ferrissia</i> sp.	2+	1+	–	–	<i>Ischnura</i> sp	1+	–	–	–
<i>Pisidium pirothi</i>	–	–	1+	1+	<i>Trichoptera larvae</i>	1+	–	1+	2+
<i>Lymnaea</i> sp	4+	–	–	–	Annelida:				
<i>Theodoxus niloticus</i>	3+	4+	4+	4+	<i>Limnodrilus udekemianus</i>	6+	5+	5+	4+
<i>Lanistes carinatus</i>	3+	–	–	–	<i>Limnodrilus hoffmeisteri</i>	6+	5+	4+	5+
<i>Helisoma duryi</i>	–	4+	–	–	<i>Branchiura sowerbyi</i>	1+	–	1+	–
<i>Gabbiella senaariensis</i>	5+	5+	3+	3+	<i>Pristina</i> sp.	1+	2+	3+	1+
<i>Spharium simile</i>	2+	4+	4+	1+	<i>Helobdella conifer</i>	3+	2+	2+	2+
<i>Corbicula fluminalis</i>	6+	5+	6+	6+	<i>Barbronia</i> sp	2+	–	–	–
<i>Cealatura prasidense</i>	2+	1+	3+	2+					
<i>Cealatura teretiuscula</i>	–	1+	1+	3+					
<i>Mutela</i> sp	–	–	1+	–					

+ : present; – : absent; number beside + : number of sites

Samples of sites 1, 2, and 5 at El-Manial Island were did not collected in the summer season

Fig. 7 Average population density of macrobenthic invertebrates at the studied islands. Note: M1, M2, and M5 not collected during summer

Table 7 Distribution of total number of organisms (organisms /m²) and the most dominant taxa of macrobenthic invertebrates (MBI), and the percentage of the dominant taxa to their phylum

Island	Season	Annelida		Arthropoda		Mollusca				Total MBI
		Total Ann	% Lim	Total Arth	% Chi. l	Total Mol	% Cor	% Cle	% Mel	
El-Keratten	Winter	1387	85.15	390	77.18	1431	12.86	11.74	15.02	3208
	Summer	614	68.08	86	44.19	1524	12.86	5.38	22.64	2224
	Average	1001	76.61	238	60.68	1478	12.86	8.56	18.83	2716
	% to MBI	36.86		12.16		54.42				
El-Warraq	Winter	3483	27.22	1039	46.29	874	64.53	3.32	6.86	5396
	Summer	440	97.95	108	85.19	1447	24.95	2.83	41.60	1995
	Average	1962	62.59	574	65.74	1161	44.74	3.08	24.23	3696
	% to MBI	53.08		8.76		31.41				
El-Zamalek	Winter	323	87.31	618	97.41	583	61.41	0.00	22.30	1524
	Summer	82	85.37	105	63.81	896	25.11	2.79	23.66	1083
	Average	203	86.34	362	80.61	740	43.26	1.40	22.98	1304
	% to MBI	15.57		27.76		56.75				
El-Manial	Winter	238	97.06	139	93.53	963	32.61	6.96	25.03	1340
	Summer	196	58.16	893	67.41	1754	4.68	26.74	24.91	2843
	Average	217	77.61	516	80.47	1359	18.64	16.85	24.97	2092
	% to MBI	10.37	75.79	24.67	71.88	64.96	29.88	7.47	22.75	

Lim, *Limnodrilus* spp.; Chi., l. Chironomid larvae; Cor., *Corbicula* sp.; Cle., *Cleopatra bulmoides*; Mel., *Melanoides tuberculata*

According to sediment texture variables, species *Cocconeis placentula*, *Navicula plathii*, and *Nitzschia dissipata* were associated with gravel, while *Cyclotella operculata*, *Gomphonema parvulum* and *Nitzschia frustulum* were associated with sand and finally *Achnanthes minutissima* was associated with mud (Fig. 5). All variables (excluding Zn, gravel, and sand) were negatively correlated with species axis 1 at El-Manial shores sediment (Fig. 5). Despite the fact that the weighted correlation matrix for all variables was low, these variables accounted for 68.4% of the variance in the weighted averages of diatom assemblage as calculated from obtained eigenvalues, as a cumulative effect of variables. *Achnanthes minutissima*, *Navicula diluviana*, *Nitzschia amphibia* var. *rostrata*, and *Rhopalodia gibba* were closed to Zn, whereas *Amphora ovalis*, *Amphora venta*, and *Epithemia sorex* were closed to the carbonate point. Despite metal concentrations exceeding international guidelines, numerous species of diatoms were recorded, demonstrating that diatoms may adapt to and survive in heavy metal-contaminated habitats (Ubando et al. 2021; Walha et al. 2021) by biosorption or bioaccumulation of metals (Pistocchi et al. 2019).

In all sampling sites, the nonparametric multiplicative regression (NPMR) was used to fit and compare several heavy metal indices (mCd, ER, TRI, ΣTU, and PLI) to the diatom community diversity index. Non-significant associations were found in the NPMR regression of diatom diversity index with heavy metal indices scores ($R^2=0.3$, P value = 0.5, 0.6, 0.8, 0.3, and 0.3 for mCd, ER, TRI, ΣTU,

and PLI, respectively) (Fig. 6). This lack of significance with diatom diversity could be explained by the fact that most species are more sensitive to some stressors (such as sediment texture) than metals, where diversity was substantially connected with sand and mud sediment ($r=-0.5$ and 0.5 , respectively, with P value 0.05). Metal pollution had little influence on diatom diversity at the research sites, but the changes in assemblage composition, distribution, and species dominance were influenced markedly by heavy metals (Hirst et al. 2002), particularly at the dominance level by a slight shift of subdominant from centric diatom genera to more tolerant species, such as *Fragilaria construens*. Therefore, the examining of diatom status is considered a successful tool for biomonitoring of metals contaminated habitat because of its preference and tolerance to diverse sediment factors (Malinowska-Gniewosz et al. 2018).

3.5 Macrobenthic invertebrates (MBI)

Thirty-four species of benthic invertebrates were identified in the collected samples from the investigated islands shores during winter and summer; of these 9 arthropods, 6 annelids, and 19 molluscs, Table 6. Mollusca were the dominant group by three taxa (*Corbicula* sp., *Cleopatra bulmoides*, and *Melanoides tuberculata*) at all studied islands, except for El-Warraq Island; Annelida was the dominant group (Fig. 7). The highest number of species (17 species) was observed at El-Keratten and El-Manial islands followed by El-Warraq and El-Zamalek islands which registered 14 species for

Fig. 8 Ordination diagram showing the result of CCA analysis for MBI in the four studied islands (*Lim*, *Limnodrilus* spp.; *Chi*., *Chironomid* larvae; *Cor*., *Corbicula* sp.; *Cle*., *Cleopatra bulmoides*; and *Mel*., *Melanoides tuberculata*)

each. The annelid *Limnodrilus* spp. were the most dominant annelid genera in the four islands (75.79% to total annelid count), they were recorded in most of the studied sites. Saad et al. (2015), Abdel-Gawad and Mola (2014) and Mola and Abdel-Gawad (2014) mentioned Annelida was the dominant group of total macrobenthos in Nasser Lake and its khors. El-Warraq Island inhabited the richest number of MBI compared with other islands especially during the winter season, Table 7. The arthropod assemblage was composed mainly of chironomids (71.88% to total arthropods count) that could be related to sediment conditions. The dominance of chironomids indicates their broad range habitat preference and their ability to adapt to seasonal changes. The abundance of macroinvertebrates taxa during the winter and summer seasons have been linked to their diverse habitat preferences and capacity to adjust to seasonal changes (Oppong et al. 2021). CCA was carried out to verify the impact of metals and sediment variables on the most dominant macroinvertebrate taxa

(five taxa) for the studied islands (Fig. 8). The recorded taxa appeared different actions from island to other according to their substrate texture of sediment, metals concentration, OM, and carbonate percent.

El-Keratten Island was the second richest island in bottom fauna, especially during winter, Table 7. K4 occupied the highest PD due to the high number of annelida and mollusca, while the poorest site was K5. CCA analysis indicated that organic matter, carbonate, and Zn were the most effective factors on MBI. The CCA biplot diagram has shown that *Limnodrilus* was closed to carbonate, while the chironomus larvae was close to organic matter. *Melanoides* were correlated positively with Ni, Zn, Co, and Cr, while it correlated negatively with organic matter and mud (Fig. 8). El-Warraq Island had a population density of 5396 and 2011 organisms/m² during winter and summer, respectively. W1 occupied the highest PD during the two seasons due to the richness of Annelida during winter and Mollusca during

summer. Arthropoda reached its maximum number in W5, W6, and W1. Arthropoda had weak representation, especially during summer, as recorded by Abdel Gawad et al. (2014) and Abdel Gawad and Mola (2014). CCA indicated that, the most important mineral affecting the distribution of MBI at El-Warraq Island were Cr, Al, Ni, Co, and Mn in addition to soil texture and carbonate. The CCA biplot diagram has shown that *Limnodrilus* has a positive correlation with carbonate, *Cleoptra* was positively correlated with sand, and finally *Corbicula* was positively correlated with gravel texture (Fig. 8). In El-Zamalek Island, the average population density was 1524 and 1083 organisms /m² in winter and summer, respectively (Table 7). The highest PD was recorded at Z3 due to the increase in Arthropoda and Mollusca number, while the poorest site was Z1 (114 organisms /m²). The CCA biplot diagram had shown that the *Corbicula* correlated negatively with Cu, Cd, and OM, while *Melanoides* correlated positively with Zn, Al, and mud (Fig. 8). El-Manial Island was the poorest island in bottom fauna during winter, where the average population density was reached 1340 organisms/m², Table 6. M4 encountered the highest PD with the high number of Mollusca, while the lowest was observed in M1. CCA revealed the most correlated variables positively with species axis 1 were Al, Fe, Mn, and sand (Fig. 8).

4 Conclusion

The present study attained its primary goal by reporting the baseline data on heavy metal distribution and assessment on the shores of four Nile islands in Great Cairo. In addition, the impact of sediment variables on the distribution of benthic diatoms and macroinvertebrates on islands shores was investigated. According to sediment quality guidelines, Ni and Cd had their accumulation more than TEL; hence they were occasionally associated with adverse biological effects. While Zn, Cu, and Cr levels surpassed the TEL in some sampling sites along different islands shores. The agricultural and domestic wastes can be a significant source of metals inputs into the Nile shores. According to average PLI values for metals, El-Keratten shores have pollution stress during the winter and summer seasons, while El-Warraq and El-Zamalek shores showed pollution levels in the summer season and no pollution was indicated in the winter. Finally, El-Manial shores did not show any pollution level during the two seasons. Metal pollution had little effect on diatom diversity at the Nile shores; however, metals had a significant impact on diatom assemblage composition, distribution, and species dominance. Some diatom taxa showed high adaption and tolerance with high levels of metals, as well as significant uniform relationships were recorded with sediment texture, mostly sand, and mud. Therefore, evaluating

diatom status is regarded as a successful approach for bio-monitoring of metals contaminated habitats. Different sediment characteristics affected the dominating taxa and groups of macrobenthic invertebrates on different islands sediment, with the levels and types of such variables varying from one species to another.

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Availability of data and materials The data can be available on request.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest.

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