



Heavy Metal Contamination of the River Nile Environment, Rosetta Branch, Egypt

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Abstract The Rosetta Branch is one of Egypt's most important Nile River branches, providing freshwater to multiple cities. However, its water quality has been deteriorating, with various wastes containing high loads of heavy metals being discharged into its body of water. Seasonally, water and sediment samples and two native aquatic plants (*Ceratophyllum demersum* and *Eichhornia crassipes*) were collected and analyzed from the Rosetta Branch to assess the level of metal contamination (Fe, Mn, Zn, Cu, Pb, Ni, Cd, Cr, and Co) using different metal indices. The levels of some metals in the branch water overstepped those suitable for drinking water and aquatic life. In increasing order, the means of the heavy metal concentrations in branch water ($\mu\text{g/L}$) were Cd (1.8–4.9) < Co (7.18–28.1) $\approx$ Ni (9.0–25.1) < Cr (8.56–27.4) < Cu (14–75) < Pb (9.3–67.9) < Zn (22–133) < Mn (68–220) < Fe (396–1640). All the metal indices measured in the sediment confirmed the Ni and Cd contamination, where Ni and Cd in the sediment surpass the sediment quality guidelines in 80% and 53% of samples, respectively, reflecting frequent adverse effects on aquatic organisms. According

to the bioconcentration factor, *C. demersum* and *E. crassipes* have higher accumulation capacities mainly for Cd than those for other metals considered as major pollutants in the water and sediment of Rosetta Branch, reflecting the role of hydrophytes in the biological treatment of polluted water in aquatic environments.

Keywords Heavy metals · Nile River · Plant · Rosetta Branch · Sediment · Water

1 Introduction

Rivers are important natural resources for irrigation, drinking, and domestic uses, and they help improve the economy and sustainability of nearby towns (Loucks & van Beek, 2017). The Nile River is Egypt's lifeline; hence, its water quality is a vital issue for Egyptians. However, Egypt's surface water quality is deteriorating because of increased anthropogenic activity, such as agricultural runoff and urban and industrial wastes (Al-Afify et al., 2018). The Nile River divides into two main branches (Rosetta and Damietta) 25 km north of Cairo and flows into the Mediterranean Sea (Ali et al., 2014). The Rosetta Branch water is of great vital importance as it serves as a water source for municipal, industrial, agricultural, navigation, and aquaculture purposes (Authman et al., 2009; Eissa et al., 2022).

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In many African countries, significant population growth has been accompanied by steep increases in urbanization and industrial and agricultural land use over the last few decades (Idodo-Umeh & Oronsaye, 2006). This has resulted in the significant rise in contaminant discharge into receiving water bodies, which negatively affects the aquatic ecology. Heavy metals make up most of these contaminants, which eventually end up in bottom sediments (Abou El-Anwar et al., 2021). Pollution discharges, particularly heavy metals and nutrient salts, have severe influences on river health and the appropriateness of Nile River water for industrial, household, and agricultural purposes (Abdel-Satar et al., 2022; Al-Afify & Abdel-Satar, 2020; Othman et al., 2021).

Heavy metals are an intriguing category of elements in terms of aquatic contamination because of their severe effects on the aquatic system equilibrium, long-term persistence, and ability to accumulate in water and sediments, in addition to their bioaccumulation in living organisms (Masresha et al., 2021). Among these metals, Cd and Pb are potentially toxic and have no known role in biological systems, whereas others such as Cu and Zn are essential. Still, when the intake of essential metals by aquatic organisms is extremely high, hazardous effects can occur (Yacoub et al., 2021). High inputs of metals to aquatic systems can cause serious water pollution problems, resulting in potential risks to human health through the food chain (Othman et al., 2021).

Metal contamination in aquatic environments is escalating at alarming levels, and it has now become a major global problem. Metal pollution is typically monitored by assessing the metal levels in the water, sediments, and biotic components such as aquatic plants and fish (Ali et al., 2019). Using solely water analyses to identify metals as inputs in aquatic environments is not regarded as proper (Turkmen et al., 2006). Metal levels in sediments, in addition to the measurement of aqueous metals, play a significant role in water quality assessments (Hadi et al., 2019). Sediments are considered the most important indicators of heavy metals because they tend to absorb dissolved metals and act as potential nonpoint metal sources by releasing them into the water column (Algül & Beyhan, 2020).

Aquatic macrophytes are good biological monitors of heavy metals. They play significant roles in water quality control, oxygen production, nutrient cycling,

and sediment stabilization, and they serve as aquatic life habitat and shelter (Tshithukhe et al., 2021). Metals can accumulate in high levels in aquatic macrophytes from the water or/and sediments, proving the utility of plants as aquatic biomonitors. Furthermore, monitoring the buildup of persistent contaminants in aquatic macrophytes can offer time-integrated data on harmful chemicals in aquatic systems (Harguinteguy et al., 2014). The levels of heavy metals in aquatic macrophytes depend on the plant species, the plant sections, the metal levels in the growth environment, and the macrophytes' selective capacity to absorb different substances (Tshithukhe et al., 2021).

Pollution indices are valuable tools for measuring the level of heavy metal contamination in water, sediment, and aquatic plants. The indices help determine if metal accumulation is due to natural or anthropogenic mechanisms (Kowalska et al., 2018). As a result, determining the levels of heavy metals is critical for analyzing the Nile River environment. The present work was undertaken to (1) monitor the distribution of some essential and toxic metals in the water, sediment, and two aquatic macrophytes (*Ceratophyllum demersum* and *Eichhornia crassipes*) in the Rosetta Branch of the Nile River and (2) to perform ecological risk assessments for heavy metals in the Rosetta Branch using the pollution indices of different metals.

2 Materials and Methods

2.1 Study Area

The Nile River is Egypt's principal source of freshwater, and its flow rate is dependent on the amount of water stored in Nasser Lake to meet the country's annual water needs (Othman et al., 2021). The high dam at Aswan and a series of seven barrages between Aswan and the Mediterranean Sea totally control the Nile River (Al-Afify & Abdel-Satar, 2020). The Nile River is divided into two branches 25 km north of Cairo. The western branch (approximately 242 km long) is known as the Rosetta Branch, whereas the eastern branch is known as the Damietta Branch (about 239 km long). The study region covered around 123 km of the Rosetta Branch, from El-Kanater El-Khyria upstream to Kafr El-Zayat City downstream.

The Rosetta Branch is approximately 225 km long and 150 m wide, with an average depth of 2–2.3 m. Numerous sources of pollution may impact and impair the Rosetta Branch's water quality. El-Rahawy drain (domestic) is the main source of pollution in the branch and has the potential to degrade its water quality (Othman et al., 2021). It dumps around 1.5 million cubic meters of sewage from the Giza Governorate and agricultural wastes into the water branch every day (APRP, 2002). Furthermore, the branch in Kafr El-Zayat, one of Egypt's most important industrial regions, which comprises industrial effluents from sulfur and superphosphate compound manufacturers and soap and pesticide factories (Abd El-Hady, 2014). Also, sewage from various cities and neighboring villages is dispersed along the two banks of the Rosetta Branch, and other tiny agricultural drains dump their wastes straight into the water (Othman et al., 2021). The release of untreated sewage water into aquatic habitats has become a serious concern, resulting in declining water quality and seriously threatening aquatic life (Bastami et al., 2015).

2.2 Sample Collection, Processing, and Analysis

Seasonally, all samples were taken from ten locations in the Rosetta Branch from the mid-stream channel (40 samples for each media). As indicated in Table 1, the selected locations are both directly and indirectly subjected to municipal wastewater,

agricultural drainage, and industrial disposals. Consequently, heavy metals, suspended matter, and organic pollutants damage the Nile system (Othman et al., 2021). Table 2 shows the basic features of the Rosetta Branch water, whereas Fig. 1 shows the sampling sites.

A polyvinyl Van Dorn plastic bottle was used to collect ten subsurface (approximately 30 cm) water samples from the Rosetta Branch's mid-stream channel. The samples were maintained in clean stoppered plastic bottles and preserved using nitric acid (65%) to a pH of less than 2. Lastly, the samples were digested using nitric acid (65%) according to APHA (2005).

Sediment samples were taken from the ten sampling sites in the Rosetta Branch using Eckman sampling equipment from the top 20-cm layer of the

Table 2 Main characteristics of the Rosetta Branch of the Nile River

Variable	Othman et al. (2021)	
	Range	Mean ($\pm$ SD)
Transparency (Cm)	10.00–150.00	67.68 $\pm$ 35.14
Dissolved oxygen (DO) (mg/L)	0.00–12.80	5.16 $\pm$ 3.55
pH	7.27–8.49	7.83 $\pm$ 0.29
Alkalinity (mg/L)	55.00–375.00	191.18 $\pm$ 68.58
Chloride ion (mg/L)	28.99–306.29	103.44 $\pm$ 75.12

Table 1 Description of the sampling sites in the Rosetta Branch using GPS (latitudes and longitudes)

Site no	Site name and description	GPS	
		Longitude	Latitude
1	El-Kanater El-Khyria, bifurcation point about 25 km from Cairo	30° 17' 69.36" N	31° 12' 61.29" E
2	Up stream of El-Rahawy drain, 8 km from El-Kanater El-Khyria	30° 20' 85.96" N	31° 03' 44.30" E
3	El-Rahawy drain (in front of El-Rahawy drain discharge point—domestic and agricultural wastes)	30° 20' 70.75" N	31° 03' 25.42" E
4	Downstream of El-Rahawy drain, 10 km from El-Kanater El-Khyria	30° 20' 41.73" N	31° 02' 48.71" E
5	Tamalay, under Tamalay bridge village (about 68 km from El-Kanater El-Khyria)	30° 50' 84.75" N	30° 83' 38.92" E
6	Sobal drain (in front of Sobal drain discharge point—agriculture wastes—about 70 km from El-Kanater El-Khyria)	30° 53' 52.34" N	30° 85' 19.41" E
7	Downstream of Sobal drain (73 km from El-Kanater El-Khyria)	30° 54' 15.72" N	30° 85' 07.18" E
8	Kom Hamada (100 km from El-Kanater El-Khyria)	30° 71' 48.09" N	30° 76' 17.23" E
9	Kafr El-Zayat (1) (120 km from El-Kanater El-Khyria)	30° 82' 19.11" N	30° 81' 21.56" E
10	Kafr El-Zayat (2) (123 km from El-Kanater El-Khyria (in front the soap and salt and El-Malya companies' factories discharge point—industrial wastes)	30° 82' 81.48" N	30° 80' 17.38" E

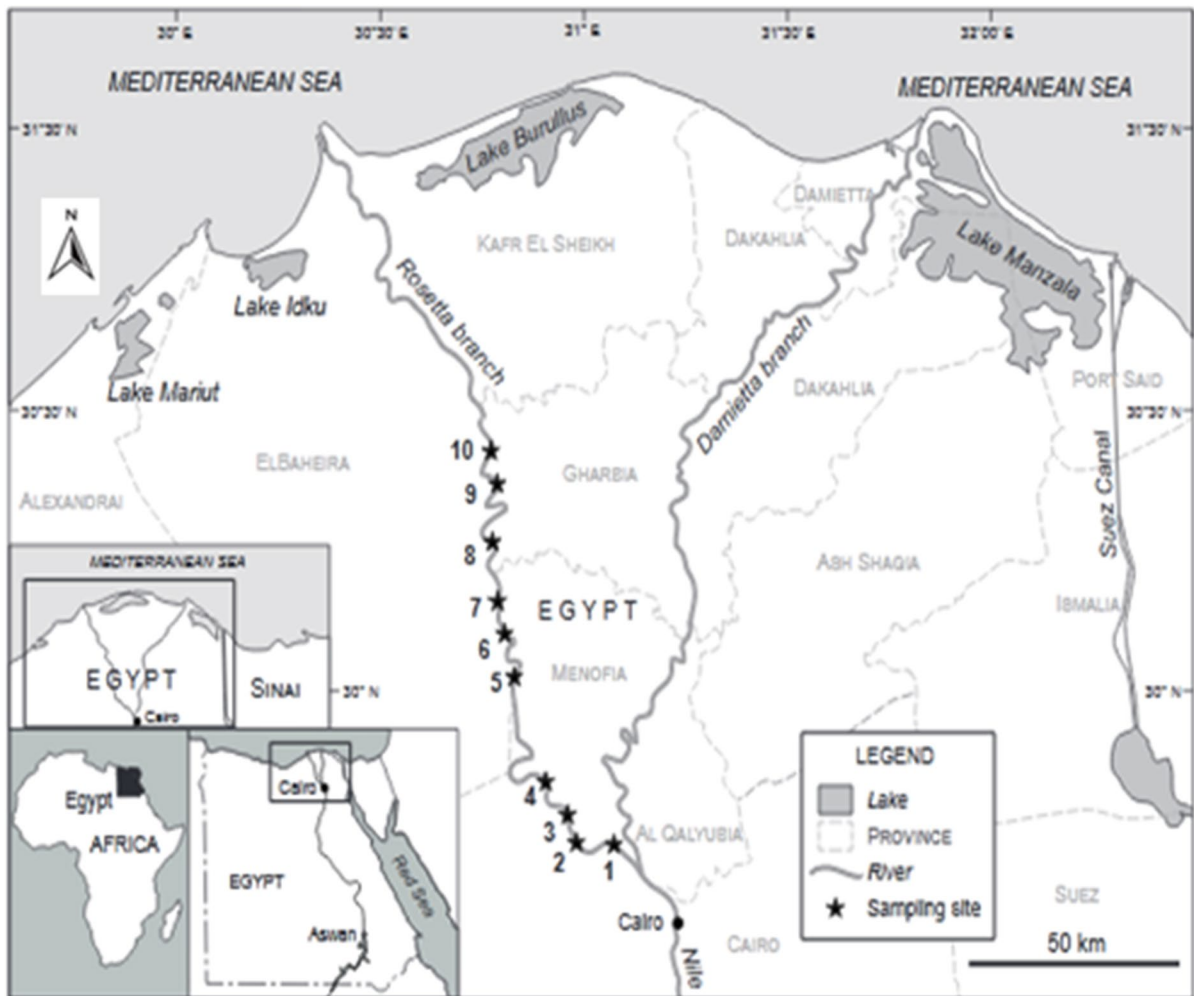


Fig. 1 Map showing the sampling sites in the Rosetta Branch of the Nile River (after Othman et al., 2021)

bottom. Stone fragments were removed by running the air-dried samples through a 2-mm sieve. The sieved sediment was powdered, where 0.5 g of finely ground samples was digested using Kouadia and Trefry's technique (1987).

Also, according to the plant type, representative macrophytes were collected from the ten sampling sites (submerged or floating). A 0.5 m×0.5 m quadrant was used to capture floating macrophytes (*E. crassipes*). Meanwhile, submerged plants (*C. demersum*) were harvested using a volume-controlled grab. The macrophytes were thoroughly rinsed with distilled water three times before drying at 60 °C. The dried macrophyte parts were ground, and 0.5 g was digested using 65% nitric acid, 98% sulfuric acid,

and 35% hydrogen peroxide, following Saison et al. (2004).

The samples (water, sediment, and plants) were analyzed for Mn, Fe, Cu, Zn, Cd, Pb, Ni, Cr, and Co concentrations using inductively coupled plasma mass spectrometry (iCAP TQ ICP-MS; Thermo Scientific, Germany). Triplicate readings were used to control the precision of the metal analyses, where the average values were determined with less than 5% relative standard deviations.

2.3 Water Assessment

The metal content suitability of the Rosetta Branch water for drinking purposes was determined using

the heavy metal pollution index (HPI) proposed by Prasad & Bose (2001) and the contamination index (Cd) proposed by Backman et al. (1997). Also, the Rosetta Branch water was assessed for drinking, irrigation, and aquatic life suitability using the pollution index (PI) proposed by Caerio et al. (2005). The metal guidelines used for the several index measurements were the Egyptian drinking water quality standards (EWQS, 2007) and that of the World Health Organization (WHO, 2017) for drinking water, that of the United State Environmental Protection Agency (USEPA) for aquatic life suitability, and those of WHO/Food and Agriculture Organization (FAO) (2007) for irrigation use. The indices used are described in detail in the supplementary materials (Text S1).

2.4 Sediment Assessment

Several indices were used to evaluate the metal contamination risk in Rosetta Branch sediment. These include the enrichment factor (EF) index (Yahaya et al., 2012); geoaccumulation index (I-geo) (Müller, 1969); potential ecological risk index (ER) (Hakanson, 1980, 1988); modified contamination degree (mCd) (Abraham & Parker, 2008); pollution load index (PLI) (Tomlinson et al., 1980); toxic risk index (TRI) (Gao et al., 2018); and the toxic unit (Pedersen et al., 1998). The metal content guideline used for the several measurement indices was the Freshwater Sediment Screening Benchmarks (EPA, 2006; MacDonald et al., 2000). More details on these indices can be found in the supplementary file (Text S2).

2.5 Macrophyte Assessment

The bioconcentration factor (BCF) was used to assess the plants' ability to absorb and accumulate heavy metals from aqueous media. The detailed calculation of the factor is in the supplementary file (Text S3).

2.6 Statistical Analysis

Pearson correlation coefficients ($p < 0.01$ and 0.05) were used to estimate the correlations between the metal concentrations in the water, sediment, and plant samples. Furthermore, data from the water and sediment samples were examined for significant spatial

and temporal distributions using the analysis of variance test.

3 Results and Discussion

3.1 Heavy Metals in Surface Water

In recent decades, the metal contamination of river water has been viewed as a severe ecological and public health hazard (Lipy et al., 2021). Table 3 shows the range, mean, and standard deviation of the metal concentrations in the Rosetta Branch water during different seasons. In increasing order, the means of the heavy metal concentrations ($\mu\text{g/L}$) were Cd (1.8–4.9) < Co (7.18–28.1) $\approx$ Ni (9.0–25.1) < Cr (8.56–27.4) < Cu (14–75) < Pb (9.3–67.9) < Zn (22–133) < Mn (68–220) < Fe (396–1640). The metal concentrations in the branch water varied significantly by site ($p < 0.05$), with the highest levels of all examined metals observed at sites 3 and 6. This indicates the fluctuation of metals in sewage effluents, industrial wastes, and agricultural drainage water discharged into the branch. The branch water metal contents were compared with the WHO (2017) and EWQS (2007) guidelines for drinking water, chronic levels for aquatic life criteria (USEPA, 1993), and the WHO/FAO (2007) standard for irrigation use. The obtained results show that the levels of Fe, Pb, and Cd in most sites and throughout different seasons were higher than the EWQS (2007) and WHO (2017) threshold limits established for drinking water suitability. The Cr, Cd, and Pb levels in all locations and seasons surpassed USEPA's chronic thresholds for aquatic life, whereas the Fe and Zn concentrations in anthropogenically impacted locations exceeded the standards. Ni is the only metal with concentrations that are still within acceptable limits for aquatic life. As confirmed by Sani et al. (2022), the increase in the metal contents in water may originate from anthropogenic activities, such as urban and agricultural runoff (fertilizers and pesticides).

Finally, except for Mn in station 6 during the spring season, all metals were within the WHO/FAO (2007) irrigation standards. In the branch water, significant correlations between all measured metal pairs ($r = 0.59\text{--}0.95$; $n = 40$, $P < 0.01$) revealed common metal sources and associations.

Table 3 Seasonal distribution of heavy metals ($\mu\text{g/L}$) in water compared with different criteria and HPI values for the Rosetta Branch of the Nile River

Parameters		Autumn	Winter	Spring	Summer	Drinking water		Irrigation WHO/ FAO (2007)	Aquatic life USEPA*
						EWQS (2007)	WHO (2017)		
Fe	Range	397–1175	410–1640	441–1250	396–1290	300	300	5000	1000
	Mean $\pm$ SD	786.0 $\pm$ 2295	855.0 $\pm$ 337.2	825.5 $\pm$ 253.1	804.0 $\pm$ 301.4				
Mn	Range	76.00–220.00	68.00–188.00	71.00–205.00	40.02–220.00	100	400	200	-
	Mean $\pm$ SD	149.5 $\pm$ 46.45	133.00 $\pm$ 40.02	125.00 $\pm$ 41.30	133.00 $\pm$ 46.67				
Zn	Range	22.00–86.00	34.00–115.00	24.00–133.00	21.05–133.00	3000	3000	2000	120
	Mean $\pm$ SD	52.00 $\pm$ 21.05	57.00 $\pm$ 28.64	58.00 $\pm$ 34.71	52.50 $\pm$ 29.60				
Cu	Range	14.00–63.00	18.00–69.00	17.00–72.00	14.00–72.00	2000	2000	200	-
	Mean $\pm$ SD	35.00 $\pm$ 15.23	36.00 $\pm$ 16.97	38.00 $\pm$ 18.53	35.00 $\pm$ 17.01				
Pb	Range	10.40–67.90	9.800–65.70	12.40–63.80	9.30–67.90	10	10	5000	2.5
	Mean $\pm$ SD	57.70 $\pm$ 20.78	55.85 $\pm$ 20.21	56.60 $\pm$ 18.95	56.13 $\pm$ 20.56				
Cd	Range	1.80–4.50	2.30–4.70	1.90–4.90	0.81–4.90	3	3	10	0.72
	Mean $\pm$ SD	3.20 $\pm$ 0.84	3.25 $\pm$ 0.81	3.50 $\pm$ 1.00	3.20 $\pm$ 1.02				
Ni	Range	9.00–19.85	9.30–23.25	10.58–25.10	3.91–25.10	20	70	200	52
	Mean $\pm$ SD	17.54 $\pm$ 3.91	19.03 $\pm$ 4.36	20.23 $\pm$ 4.52	18.12 $\pm$ 5.32				
Cr	Range	8.56–20.15	9.80–24.56	10.25–27.42	3.88–27.42	50	50	100	11
	Mean $\pm$ SD	17.80 $\pm$ 3.88	19.12 $\pm$ 4.026	22.12 $\pm$ 5.36	19.05 $\pm$ 5.80				
Co	Range	7.18–22.15	8.45–26.54	10.57–28.10	5.01–28.10			50	-
	Mean $\pm$ SD	17.81 $\pm$ 5.01	19.39 $\pm$ 6.02	20.73 $\pm$ 6.07	17.96 $\pm$ 6.36				
HPI ¹	Range	66.25–238.25	76.85–238.18	73.12–242.21	71.07–234.38				
	Mean $\pm$ SD	175.10 $\pm$ 59.88	178.25 $\pm$ 56.13	181.15 $\pm$ 58.05	174.71 $\pm$ 58.07				
HPI ²	Range	72.12–250.88	82.88–252.17	79.63–256.65	76.93–247.94				
	Mean $\pm$ SD	185.72 $\pm$ 62.41	189.52 $\pm$ 58.84	192.92 $\pm$ 60.72	185.07 $\pm$ 60.31				

*Chronic level

HPI¹, according to WHO (2017); HPI², according to EWQS (2007)

Table 3 shows the calculated HPI values for the branch locations based on the WHO (2017) and EWQS (2007) criteria. Except for sites 1 and 2, the HPI at all branch sites surveyed at different seasons exceeded the critical HPI of 100 suggested by Prasad & Bose (2001) for drinking water, indicating that the branch water is seriously contaminated with metals, according to the EWQS (2007) and WHO (2017). Except for upstream unpolluted areas (sites 1 and 2), the entire examined branch length had moderate ($1 \leq \text{Cd} \leq 3$) or high ($\text{Cd} \geq 3$) metallic levels of pollution. The branch water is highly polluted by heavy metals at the anthropogenically impacted sites (3 and 6), as shown in Fig. 2. The main explanations for the regional variations in the metal levels are the amount of agricultural drainage water, sewage effluents,

and industrial wastes released into the branch water through the El-Rahawy and Sobal drains, as documented by Abdel-Satar et al. (2017a) and Al-Afify & Abdel-Satar (2020) for Nile water. Extreme care must be applied at the anthropogenic input points, where the metals can bioaccumulate in aquatic organisms, to keep the heavy metal influx under control.

The PI is based on the evaluation of individual metals in the branch water. For various uses, the detected metals showed varying degrees of pollution in the branch water. According to WHO/FAO (2007), the PI value for irrigation usage showed no degree of pollution at various places for all seasons. According to the assessment of the measured metal concentrations for drinking purposes (EWQS, 2007), the branch water suffers from

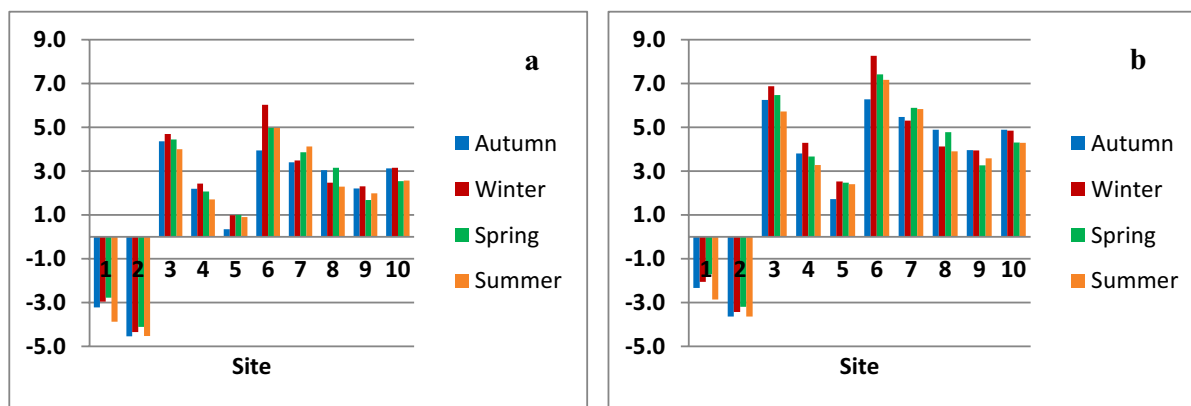


Fig. 2 Contamination index values (Cd) on Rosetta Branch water of the Nile River according to **a)** WHO and **b)** EWQS criteria

various contamination grades, with the PI for Zn and Cu being significantly less than 1, indicating no adverse effect. Cd had only a slight impact on the branch water at site 3 (the discharge point of the El-Rahawy drain). Finally, except for sites 1 and 2, the branch water is contaminated to varying degrees by Fe, Mn, and Pb in the following ascending order: Mn > Fe > Pb (Fig. 3).

The PI data for the aquatic life assessment show that Fe had only a minor impact on the branch water at site 6 (Sobal Drain discharge point), whereas Cr had a slight pollution impact on all sites except 1 and 2. Pb pollution was moderate to high in the branch water, but Cd pollution was low to moderate (Fig. 3).

Table 4 compares heavy metal concentrations in the Nile River's water at Rosetta Branch to those in

Fig. 3 Pollution index for **(a)** drinking and **(b)** aquatic life suitability

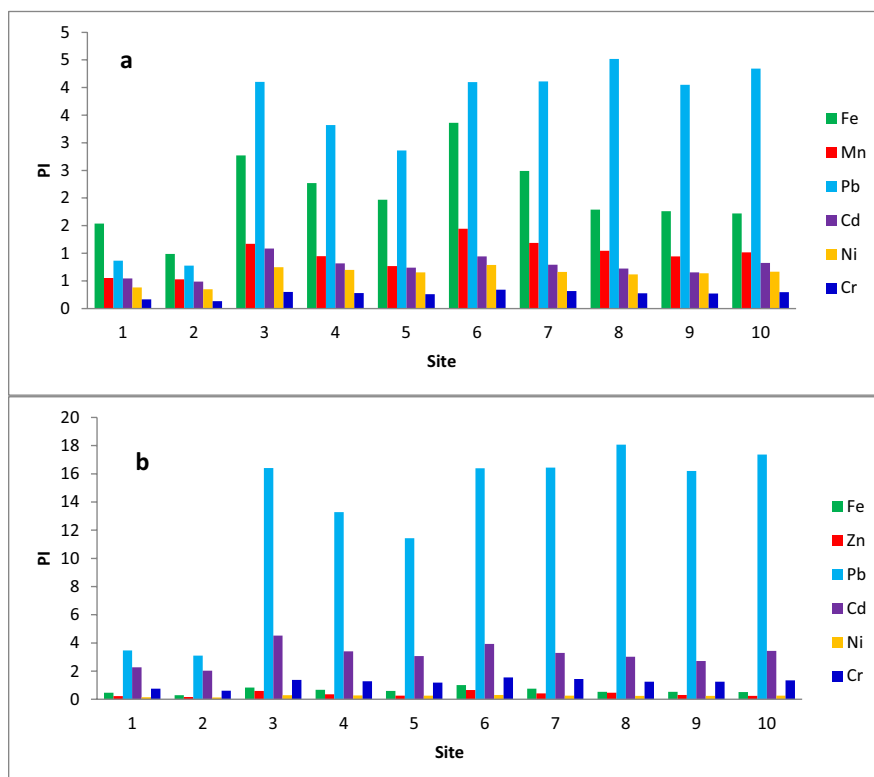


Table 4 Heavy metal levels in water ($\mu\text{g/L}$) of several global rivers compared to current results

River	Country	Fe	Mn	Zn	Cu	Pb	Cd	Ni	Cr	Co	Reference
Xinbian River	China			3.2	0.88	0.1	0.03		0.14		Yu et al., 2022
Major River	Argentina	172	22	22	3.1	1.7	ND	1.6		ND	Avigliano & Schenone, 2015
Pearl River	China			17–61	3–5	0.06–1.09	0.05–0.75	1.42–4.53	0.36–1.1	0.08–0.32	Jiao et al., 2018
Halda River	Bangladesh	311–494	175–1185	399–941		700–2600	< 1–8		< 11–14	< 5–170	Dey et al., 2021
Ganga River	India	80	26	60	10	120	5	140		ND	Aktar et al., 2010
Yixi River	China			134	16	25	1	105			Lu et al., 2018
Pasig River	Philippines				ND–63	ND–628	ND–51	ND–249			Paronda et al., 2019
Nile River	Egypt	396–1640	40–220	21.1–133	14–72	9.3–67.9	0.81–2.3	3.9–25.1	3.9–27.4	5.0–28.1	Present results

ND, not detected

other global rivers, where the Rosetta Branch water has ordinary heavy metal levels, with the exception of areas in front of pollution sources. The pollution of the River Nile system by agricultural, domestic, and industrial pollutants has generally grown in recent decades due to population growth (Abdelmageed et al., 2022).

3.2 Heavy Metals in Surface Sediment

The metal levels in sediment from several sites on the Nile River's Rosetta Branch are shown in Table 5. The heavy metal concentrations in the Rosetta Branch sediment are substantially greater than those in the water, as indicated in Tables 3 and 5, indicating metal enrichment in the Nile sediment.

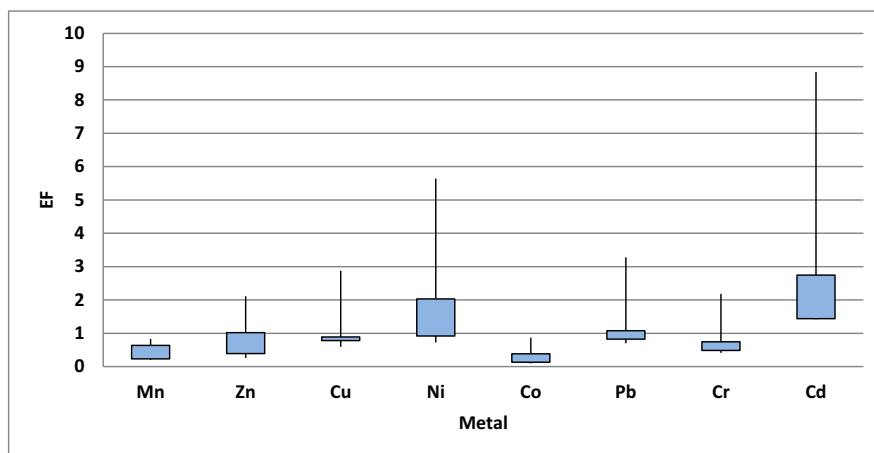
In descending order, the average amounts of heavy metals in the sediments were $\text{Fe} > \text{Mn} > \text{Zn} > \text{Pb} \approx \text{Ni} > \text{Cr} \approx \text{Cu} > \text{Co} > \text{Cd}$. When compared with those in the upstream sites, the metal levels increased in the branch sediment at sites 3, 6, and 10 at different seasons and exceeded the freshwater sediment EPA benchmarks. These indicate that the sediments receive a heavy load of domestic, agricultural, and industrial waste from various sources, including the discharge points of the El-Rahawy and Sobal drains. The Pearson correlation analysis revealed the association between the heavy metal pairs Mn/Zn , Mn/Co , Mn/Cr , Mn/Cd , Zn/Ni , Zn/Co , Zn/Cd , Cu/Pb , Ni/Co , Ni/Cr , Ni/Cd , Co/Cr , Co/Cd , Pb/Cr , and Cr/Cd ($r = 0.30\text{--}0.87$, $n = 40$, $p < 0.05$), suggesting similar sources of metal inputs (human or natural) in the Nile sediment. No significant variations in metal levels across the sampling seasons were noted, except for Cu. Furthermore, except for Cu and Pb, the metals in the branch sediment had significant spatial distributions.

The assessment of the EF index values for the Rosetta Branch established that Ni and Cd have generally higher enrichment than those of the other metals (Fig. 4). The EF values for Cu, Pb, Ni, and Cd indicate moderate enrichment at about 3%, 5%, 18%, and 33% of the samples, respectively. The EF range of 0.5–1.5 indicated that a metal was entirely derived from natural processes or crustal minerals, whereas EF values greater than 1.5 indicated that metal sources were largely anthropogenic (Abdel-Satar et al., 2017b). An analysis of the spatial distribution of EF revealed high contamination of sediments in

Table 5 Heavy metal distributions ($\mu\text{g/g}$) compared with EPA (2006), contamination factor (C_f), and PLI values for the Nile sediments of the Rosetta Branch

Metals		Autumn	Winter	Spring	Summer	EPA (2006)	MacDonald et al. (2000)		C_f
							TEL	PEL	
Fe	Range	7999–49,233	6118–50,814	10,417–50,212	8598–38,675	20,000			0.31–2.54
	Mean $\pm$ SD	28,825 $\pm$ 11,953	26,117 $\pm$ 12,875	33,188 $\pm$ 12,814	30,904 $\pm$ 8679				1.49 $\pm$ 0.58
Mn	Range	162.6–365.8	165.8–764.8	126.6–396.6	142.6–385.7	400			0.28–1.66
	Mean $\pm$ SD	264.8 $\pm$ 79.6	323.6 $\pm$ 180.8	269.0 $\pm$ 96.0	270.0 $\pm$ 89.4				0.61 $\pm$ 0.25
Zn	Range	55.47–154.63	60.74–157.85	55.53–160.87	49.85–166.56	121	123	315	0.41–1.38
	Mean $\pm$ SD	121.17 $\pm$ 33.71	122.86 $\pm$ 35.37	121.86 $\pm$ 39.55	123.00 $\pm$ 38.06				1.01 $\pm$ 0.29
Cu	Range	30.45–36.58	29.55–44.78	31.25–37.59	37.63–49.52	31.6	35.7	197	0.94–1.57
	Mean $\pm$ SD	33.33 $\pm$ 1.97	36.78 $\pm$ 4.62	34.97 $\pm$ 1.79	41.53 $\pm$ 3.58				1.16 $\pm$ 0.14
Pb	Range	34.10–53.56	41.85–53.87	41.45–54.58	40.47–58.45	35.8	35	91.3	0.95–1.63
	Mean $\pm$ SD	44.02 $\pm$ 6.03	47.91 $\pm$ 3.32	47.80 $\pm$ 4.30	47.61 $\pm$ 5.78				1.31 $\pm$ 0.14
Cd	Range	2.15–4.56	2.14–4.54	2.45–4.78	2.16–4.52	0.99	0.956	3.53	2.16–4.83
	Mean $\pm$ SD	3.64 $\pm$ 0.73	3.50 $\pm$ 0.85	3.64 $\pm$ 0.66	3.49 $\pm$ 0.77				3.60 $\pm$ 0.74
Ni	Range	31.69–54.47	27.41–61.12	28.78–62.74	28.40–53.56	22.7	18	36	1.21–2.76
	Mean $\pm$ SD	45.86 $\pm$ 7.42	46.84 $\pm$ 12.42	49.00 $\pm$ 12.06	44.19 $\pm$ 9.22				2.05 $\pm$ 0.45
Cr	Range	25.68–48.59	28.35–52.45	29.85–53.68	29.52–45.68	43.4	37.3	90	0.59–1.24
	Mean $\pm$ SD	36.39 $\pm$ 8.28	39.41 $\pm$ 8.47	42.50 $\pm$ 7.14	36.33 $\pm$ 6.09				0.89 $\pm$ 0.18
Co	Range	8.10–25.62	8.15–27.42	8.32–29.85	8.65–23.52	50			0.16–0.60
	Mean $\pm$ SD	19.36 $\pm$ 6.31	20.32 $\pm$ 6.44	21.67 $\pm$ 6.90	18.80 $\pm$ 5.51				0.40 $\pm$ 0.12
PLI	Range	0.80–1.32	0.78–1.50	0.89–1.39	0.84–1.33				
	Mean $\pm$ SD	1.09 $\pm$ 0.18	1.13 $\pm$ 0.24	1.16 $\pm$ 0.19	1.13 $\pm$ 0.19				

SD, standard deviation

Fig. 4 EF values for different metals in Rosetta Branch sediment

the downstream stretch of the Rosetta Branch, where significant spatial differences in the EF values were recorded, reflecting the effect of downstream point pollution sources.

The analysis of the average of the I-geo values confirmed the Ni and Cd pollution intensity in the samples, where the Rosetta Branch was practically unpolluted to moderately polluted in all seasons concerning

Ni and Fe for most sites, especially the downstream stretch. Concerning Cd, the investigated sites were moderately polluted except the upstream sites 1 and 2, which were unpolluted. The results of the I-geo values showed that the sediment of the branch was practically unpolluted by Mn, Zn, Cu, Co, Cr, and Pb (Fig. 5).

Furthermore, as demonstrated in Fig. 6, the metal pollution in the Rosetta Branch sediment determined using the mCd and ER indices is characterized by a different spatial distribution. The presence of point and area pollution sources resulted in higher index values in the samples (sites 3, 6, and 7), and the metal contamination in the upstream sites 1 and 2 along the branch was the lowest. The mCd and ER values in all seasons for sites 3, 6, and 7 were classified as moderate-grade risk ($mCd > 1.5$; $ER > 150$). The average contribution of Cd to ER was about 80% in

the branch sediment, whereas the Ni contribution was 8%, followed by a 5% Pb contribution.

Another index used to assess the contamination levels in the Rosetta Branch sediments is the PLI. The resulting PLI values are presented in Table 5 and range from 0.78 to 1.50. At all sites except sites 1, 2, and 5, the PLI index values in all seasons were greater than 1, indicating contaminated sites because of the appreciable input of metals from anthropogenic sources. Except for Cd, the contamination factor (Cf) values for all the analyzed metals revealed moderate levels of contamination ($1 \leq Cf < 3$) in various sites and seasons (Table 5), but the Cf values for Cd showed slightly high levels of contamination ($Cf > 3$) for sites 3, 6, and 7.

The sediment quality guidelines (SQGs) give a simple and comparable technique for quantifying the level of metal pollution and its potential damage to

Fig. 5 The average I-geo values for different sites in the Rosetta Branch sediment

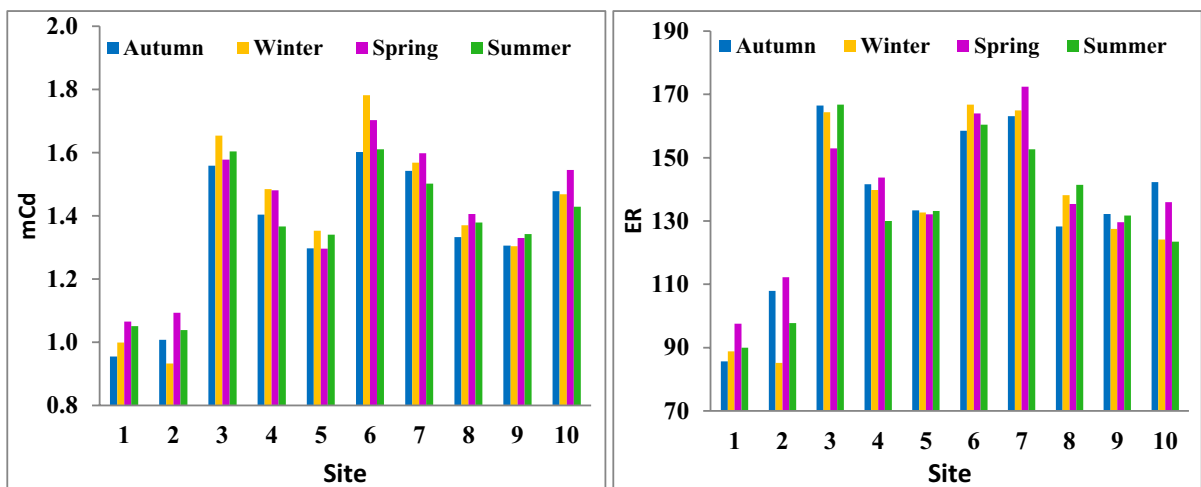
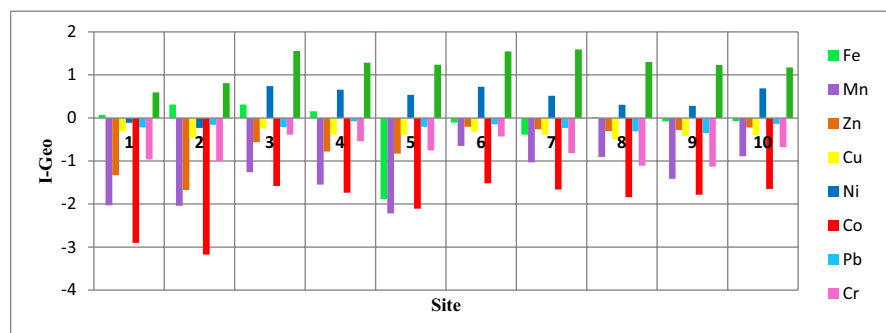


Fig. 6 mCd and ER values for different sites in the Rosetta Branch sediment

aquatic ecosystems (Zhao et al., 2021). SQGs established for freshwater ecosystems were utilized to estimate the contamination level and potential risk of metals in sediments (MacDonald et al., 2000) using the probable effects level (PEL) and threshold effects level (TEL) (Table 5). Most sediment samples showed high levels of Zn, Cu, Pb, and Cr exceeding the TEL in 55%, 53%, 98%, and 58% of the samples, respectively, reflecting occasional adverse effects on aquatic biota inhabiting the Nile. Meanwhile, Ni and Cd in the branch sediment surpassed the PEL in 80% and 53% of the samples, respectively, indicating frequent adverse effects on aquatic organisms. Because of the significant influences of domestic wastes, industrial

emissions, agricultural applications of pesticides and fertilizers, and atmospheric deposition, many sources continuously degrade the sediments (Ali et al., 2022). The overall degree of ER for the metals in the branch sediments (Σ TU and TRI) revealed that the samples posed low to moderate overall ecological risks, with no seasonal differences and high regional variations (Figs. 7 and 8). The Σ TU value for the metals was greater than 4 in sites 3 and 6 (point sources of pollution) and downstream of these sites (4 and 7), reflecting a significant toxic effect on aquatic biota (Gao et al., 2018). Similar observations were noted for the TRI values, where the anthropogenically influenced areas (sites 3, 4, 6, and 7) recorded values greater

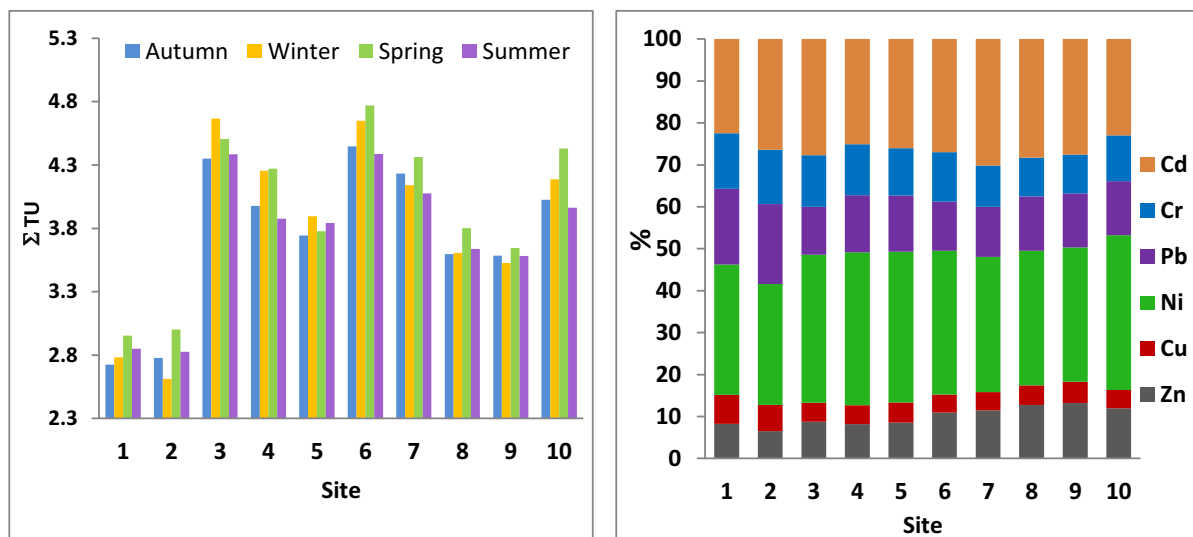
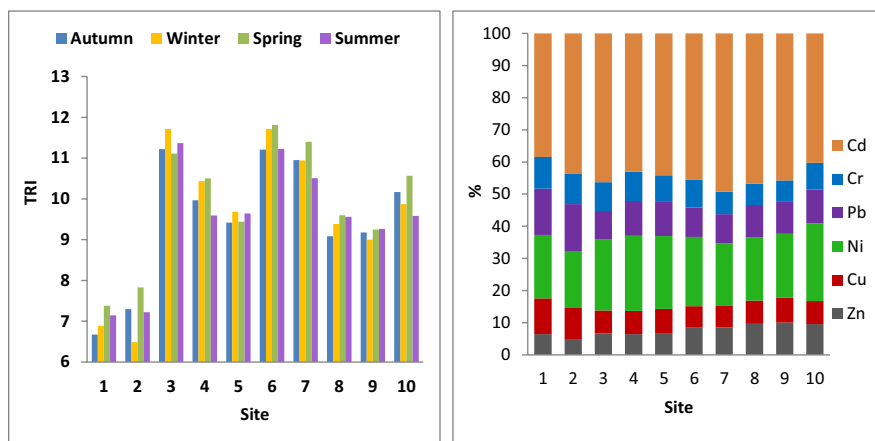


Fig. 7 Σ TU values and the average contribution percent of metals to Σ TU in the Rosetta Branch sediment

Fig. 8 TRI values and the average contribution percent of metals to TRI in the Rosetta Branch sediment



than 10, indicating a moderate level of pollution. Cd contributed about 26% and 44% to the toxic risk indices (Σ TU and TRI), respectively, whereas Ni contributed approximately 34% and 21%, and Pb contributed 14% and 11%, respectively.

3.3 Heavy Metals in Macrophytes

Bulk mineral salts can be absorbed by aquatic plants from sediments via the root system, from the water column via the leaves, or both (Abdel-Satar & Geneid, 2009). Figure 9 shows the metal levels in two macrophytes from the Rosetta Branch. Although there are limitations when comparing concentrations in different species owing to their differences in exposure and absorption ability, the average distribution of the most analyzed elements in the two plants showed similar trends: $\text{Fe} > \text{Mn} > \text{Zn} > \text{Cu} > \text{Co} > \text{Pb} > \text{Ni} > \text{Cr} > \text{Cd}$, where Fe, Mn, Ni, Cr, and Co were dominant in *C. demersum*. Significant seasonal variations were recorded for Mn, Cd, and Co in *E. crassipes* and for Fe, Zn, Cd, and Co in *C. demersum*. Also, significant spatial distributions were observed for all studied metals in the two plants, except for Cd in *E. crassipes* and Pb in *C. demersum*, where the upstream sites 1 and 2 showed the lowest accumulation levels of most metals in the two macrophytes. At the same anthropogenically impacted sites, high levels of heavy metal accumulation in *E. crassipes* and *C. demersum* were observed, with the highest metal levels seen in the surface water and sediment, where the macrophytes are considered the biological filters that significantly impact metal mobility in aquatic ecosystems. Consequently, they may be able to accumulate metals at

levels greater than their contents in a given environment (Harguinteguy et al., 2014).

The levels of the examined metals were much higher in *E. crassipes* and *C. demersum* than those in the branch water. The BCF is the ratio of heavy metal levels in the plant to the same metal content in water. It is used to reflect the heavy metal capacity of plants compared with that of the surrounding water (Al-Afify & Abdel-Satar, 2020). The higher the EF, the better the plant's ability to absorb metals (Sun & Zheng, 2018). The metal BCF values were ranked in the following order for the two studied plants (Fig. 10): $\text{Cd} > \text{Mn} > \text{Zn} > \text{Fe} > \text{Co} > \text{Cu} \approx \text{Ni} > \text{Pb} > \text{Cr}$, where Cd bioaccumulation was several times higher than those of other metals. Cd, which was considered the major pollutant in the water and sediment of the Rosetta Branch, was able to accumulate in the tissues of *E. crassipes* and *C. demersum* in self-purification processes. Therefore, these species could be considered as heavy metal bioindicators of Nile pollution.

4 Conclusion

On the basis of the current findings and analysis, we can derive the following conclusions:

- Heavy metals accumulated at varying degrees in all components (water, sediments, and plants) at sites 3, 4, 6, and 7 near the discharge points of the El-Rahawy and Sabal drains.
- The levels of some metals in the branch water overstepped the aquatic life suitability guidelines in front of and downstream the pollution source.

Fig. 9 Average distribution of metals in *E. crassipes* and *C. demersum* on Rosetta Branch of the Nile River

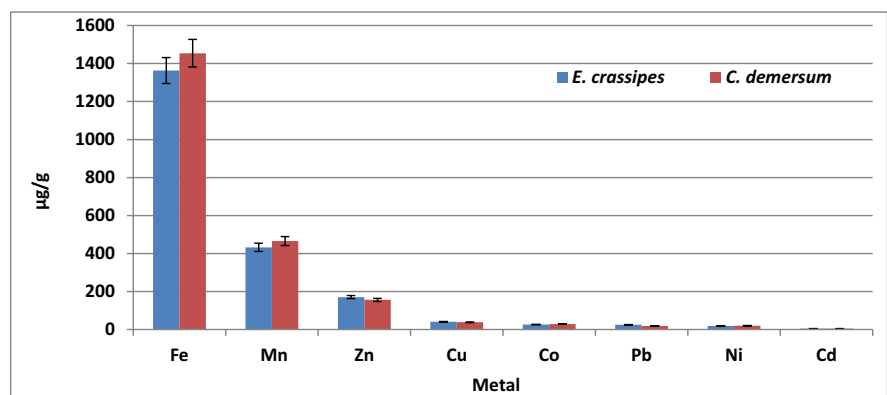
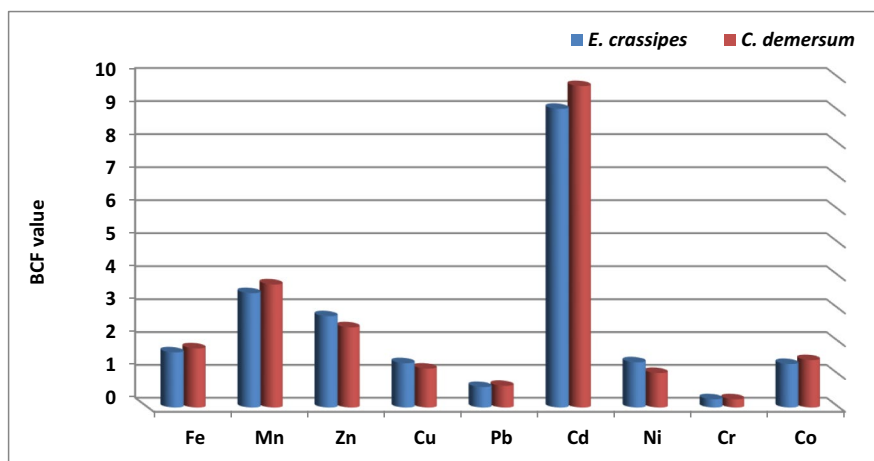


Fig. 10 Average BCF in *E. crassipes* and *C. demersum* on Rosetta Branch of the Nile River



Also, the HPI, Cd, and PI metal indices confirmed that the levels of some metals, especially Cd and Pb, in the branch water exceeded the drinking water criteria.

- The metal levels were the highest in the branch sediments at sites 3, 6, and 10 at different seasons and exceeded the freshwater sediment EPA benchmarks. Ni and Cd in the branch sediments surpassed the PEL of SQG in 80% and 53% of samples, respectively, reflecting frequent adverse effects on aquatic organisms.
- The calculated EF and I-geo indices for the metals in the Rosetta Branch established that Ni and Cd have generally higher enrichment than those of the other metals.
- The mCd and ER values in all seasons for sites 3, 6, and 7 were the highest and classified as moderate-grade risk (mCd > 1.5; ER > 150), where the average contribution of Cd to ER was about 80%, followed by Ni (8%) and Pb (5%).
- The Σ TU and TRI values at the anthropogenically influenced areas (sites 3, 4, 6, and 7) recorded values greater than 4 and 10, respectively. These indicate a moderate level of pollution. Ni and Cd contributed the most to the toxic risk indices (Σ TU and TRI).
- The aquatic plants *E. crassipes* and *C. demersum* were found to have a high potential to accumulate heavy metals in their tissues, particularly in the anthropogenically impacted areas of the branch.
- Cd, which was considered the major pollutant in the water and sediments of the Rosetta Branch, was able to accumulate in the tissues of *E. cras-*

sipes and *C. demersum* in self-purification processes according to the BCF values. Consequently, these species could be considered as heavy metal bioindicators of Nile pollution.

Author Contribution Afify DG Al-Afify: conceptualization, collection of samples, heavy metals analysis, data curation, and writing the original draft. Amaal M Abdel-Satar: chemical data curation, writing, review, and final editing for the manuscript.

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Data Availability The data can be available on request.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors declare no competing interests.

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