




Research



Assessment of pollution and metal toxicity in the bed sediment of El-Rayan Lakes, Fayoum, Egypt

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Abstract

Sediments are vital components of aquatic ecosystems, which trap and store various essential elements as well as harmful polluting substances. This is why sediment quality assessment is of great importance in measuring the quality, or pollution, of water bodies. In this study, the levels, ecological risk, and toxicity indices of 17 heavy metals (HMs) were evaluated in the sediments of the two lakes: Upper Wadi El-Rayan Lake (UWRL) and Lower Wadi El-Rayan Lake (LWRL). Both are important wetlands in Egypt used as agricultural drainage water reservoirs for Fayoum province. As revealed by the texture of the sediments, the sand represented the major sediment portion of the UWRL, while the mud was dominant in the LWRL. According to ecological risk assessment, the sediments of the two lakes suffer different degrees of metal pollution, mainly Cd, Pb, and Ni. Based on sediment quality guidelines, toxicity indices indicated different potential toxic effects of the studied HMs on benthic-dwelling organisms, but Ni and Ba had the highest potential biological risk. Results also revealed that the area facing the El-Wadi Drain is the most polluted due to its proximity to the water drainage entrance. However, LWRL is generally more polluted than UWRL. This is related to the shrinkage of water volume and lake area; it causes an increase in the concentration of metals in water, and thus an increase in the sedimentation rate of these metals into the bottom.

Article Highlights

1. This study focuses on evaluating the effects of some heavy metals in the sediments of Wadi El-Rayan lakes: Upper Wadi El-Rayan Lake and Lower Wadi El-Rayan Lake and their accumulation risks.
2. The lowest levels of heavy metals were for the toxic metals: As, Cd, and Hg, while Pb appeared in significant values.
3. Ecological indices revealed that the two lakes suffer from different pollution levels, where Cd, Pb, and Ni are the most polluting elements.
4. The area facing the El-Wadi Drain is the most polluted. But in general, the sediment of the Lower Wadi El-Rayan Lake is more polluted than the Upper Wadi El-Rayan Lake.
5. According to sediment quality guidelines, Ni and Cr have the most potentially adverse effect on sediment biota in El-Rayan lakes.

Keywords Heavy metals · Pollution indices · Toxicity indices · Ecological risk assessment · El-Rayan Lakes · Sediment

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Abbreviations

HMs	Heavy metals
WRD	Wadi El-Rayan Depression
WRLs	Wadi El-Rayan Lakes
UWRL	Upper Wadi El-Rayan Lake
LWRL	Lower Wadi El-Rayan Lake
Igeo	Geoaccumulation Index
EF	Enrichment Factor
CF	Contamination Factor
PLI	Pollution Load Index
E_{irr}	Potential ecological risk factor
RI	Risk Index

1 Introduction

The Wadi El-Rayan Depression (WRD) is located in the Western Desert of Egypt, about 125 km southwest of Cairo and 42 km southwest of Fayoum city. The total area of Wadi El-Rayan desert is 1759 km² [1]. At sea level, the WRD occupies an area of about 352 km² between latitudes 28°45'N and 29°2.0'N and longitudes 30°15'E and 30°35'E [2]. In 1973, the WRD was used as an agricultural drainage water reservoir. About 200 × 10⁶ m³/year of drainage water comes from surrounding cultivated areas which are annually transported through the El-Wadi Drain to the Wadi El-Rayan Lakes (WRLs) [3]. The WRLs are two artificial lakes, namely the Upper Lake (UWRL) and the Lower Lake (LWRL). The UWRL covers an area of 50.36 km² at an elevation of 10 m below sea level (b.s.l.). It is filled with water and bordered by highly dense vegetation. The excess water of UWRL runs to the LWRL through a shallow connecting canal of 5 km in length [4]. The LWRL reached its maximum area of 55.98 km² in 2000 at an elevation of 32 m b.s.l. Due to using water for agriculture, reclamation, and aquaculture farms, the water inflow to the LWRL has been reduced. Therefore, the water area of LWRL is continuously shrinking. The WRLs are recognized as a wetland area under the Ramsar Convention [5]. They are also stated as a protected area by Prime Ministerial Decree No. 943/1989 [6]. The WRLs play a critical role in the life cycles of a remarkable diversity of species, including 38 wild plant species, 68 zooplankton species, 214 phytoplankton species, 25 macrobenthic species, and 34 fish species [7]. According to [4], the range of water temperature of WRLs (i.e., 17.8–32.40 °C) is suitable for fish. Meanwhile, the water pH values on the alkaline side ranged between (8.33–9.17) and (8.7–9.06) in the UWRL and LWRL, respectively. The water of the two lakes is well-oxygenated all year round, varying between (7.29–12.58 mg/l) and (5.22–11.75 mg/l) in the UWRL and LWRL, respectively. In general, many authors have studied the water quality, water pollution, physicochemical properties, and biological aspects of

WRLs [4, 6–11]. However, there is a severe lack of research focusing on the sediments of these lakes and their levels of heavy metals (HMs), but only [12] studied the fractionation, distribution, and potential pollution of four HMs—i.e., Fe, Mn, Zn, and Cu—in three sites at each lake of them. In addition, [13] studied the distribution of carbonate content in the sediments of the UWRL, while [14] studied the sedimentological characteristics of the two lakes.

For the geology of WRD, the Fayoum Depression (FD) is located in the Egyptian Western Desert, covering 6068 km². The FD is a marine sedimentary basin that witnessed alternating geological periods of deposition and erosion 70 million years ago since the Late Cretaceous Age [15]. The current depression was formed 1.8 million years ago, most probably due to wind erosion agents in the desert environment. Wadi El-Rayan is one of the three sub-basins that compose the large circular FD. The WRD was formed in carbonate rocks during the Middle Eocene. Meanwhile, both WRD and FD are geologically separated by a ridge of 15 km long and 10 km wide, consisting of fissured Eocene limestone with a surficial gravelly layer [16]. The WRD consists of three main parts geomorphological units. They are the 'depression edges' bounded by high lands without vegetation and absence of drainage; the 'depression floor' divided topographically into three depressions; and the Holocene sand dunes typically longitudinal parallel dunes with 20 to 30 m height with direction of North–North West [17].

The Middle Eocene sedimentary successions consist of two main formations, namely the Qaret Gehannam Formation and the Wadi El-Rayan Formation. The Qaret Gehannam Formation is about 50 m in thickness and consists of nummulitic limestone as well as shale, gypsum, and marlstone intercalated with limestone. The Wadi El-Rayan Formation, which lies in the southern portion of the Depression, is mainly composed of extremely hard limestone with alternating nummulitic limestone intercalated with reefal limestone at its base, and occasional argillaceous sandstone [16].

Lakes and wetlands are significantly invaluable resources for humans and living organisms [18]. Wetlands are highly sensitive to environmental changes, and they have high importance in the productive networks of the world biosphere. Monitoring the feature changes in wetlands helps identify both natural and artificial phenomena producing them and also gives perfect predictions of future changes. In addition, it is essential for planning procedures to be applied to the WRLs ecosystem as part of the efforts by decision makers to conserve such precious resources [19].

Contamination of aquatic systems by potentially toxic substances such as HMs is of great concern because they cause unwanted effects. HMs can reach the tissues of

living organisms in many ways and thus enter the food chain. They can come from either geogenic sources or anthropogenic activities. However, most environmental contaminations by HMs originate from anthropogenic activities, including industrial activities (e.g., coal combustion processes, chemical plants, mining, power plants, metallurgical industry, etc.), traffic contamination, weathering of buildings, washing agricultural land, agricultural wastewater, fertilizers, pesticides, disposal of solid wastes, sewage, and vehicle exhausts [20–22]. Sediments not only represent a final store, but also serve as an important secondary source of HMs in the aquatic environment. HMs can enter again into the water column because of changes in environmental conditions such as redox potential and pH. Sediments also play an important role in the transportation and deposition of HMs [23–25]. During environmental studies, assessing both the availability and concentration of metals is necessary to assess potential risks to human health from sediment pollution. There are many articles and studies on the distribution, pollution status, risk assessment, and sources of HMs in aquatic ecosystems sediments [26, 27]. Many models and equations have been used to assess HM contamination levels. Among them are the Pollution Index (PI), Geoaccumulation Index (I_{geo}), Contamination Factor (CF), Nemerow Integrated Pollution Index (NIPI), and Pollution Load Index (PLI) [28]. The application of such methods can assess the contamination degree of a single and integrated effect of HMs.

Hence, the present study examines the status of the WRL sediment as part of their ecosystem used in irrigation, aquacultures, and fisheries activity. By investigating sediment samples from ten sites covering the WRLs, including all activity types, this study aims to (1) determine the total concentrations of 17 HMs: Al, As, Ba, B, Cd, Co, Cr, Cu, Fe, Hg, Li, Mn, Ni, Pb, Se, Sr, and Zn, as important contaminants in the WRL sediments; (2) use assessment models and indices to determine HMs sources; and (3) evaluate the environmental risks posed by HMs in both individual and total manners.

As shown in the sections of the present study, sediment samples were investigated to assess pollution and metal toxicity in the WRL sediment. *Section Two* overviews the methodologies, including the sampling locations and a description of analysis methods such as sediment texture, organic matter content, water content, pH, and EC. The levels of As, Ba, B, Cd, Cr, Co, Cu, Se, Sr, Li, Na, K, Ca, Mg, Hg, Fe, Pb, Mn, Ni, and Zn were also determined, in addition to the assessment of the pollution effect by using several indices such as I_{geo}, EF, CF, PLI, potential E_{irr}, RI, ERM-q, mERM-q, PEC-q, and mPEC-q. *Section Three* shows the type and fractions of the lake sediment, which indicates the levels of metal abundance. It also discusses the major metals with the most potential adverse effects on aquatic organisms,

and the most locations suffering from high degrees of pollution. *Section Four* gives the conclusion of the study.

2 Methodology

2.1 Study area

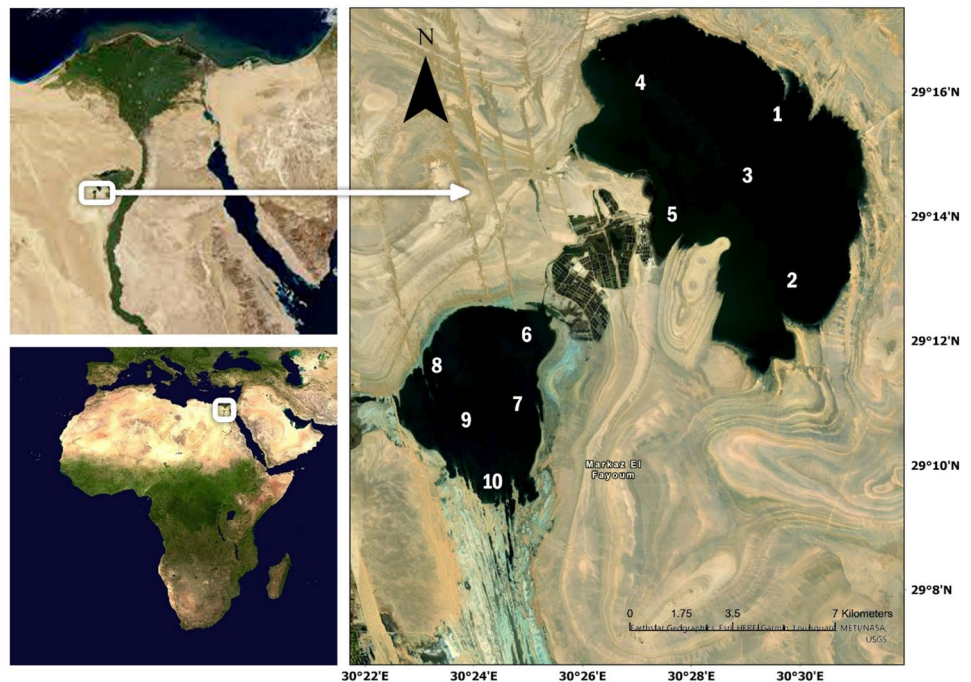
In 1973, water flowed to the WRD to convey 31% of drainage water of Fayoum province through about a 17 km channel (i.e., 9 km open and 8 km tunnel), and thus the first northern lake: UWRL was formed. After filling the UWRL in 1980, the water flowed to a lower level through a 5-km channel and some waterfalls to form the second southern lake: LWRL. In 2000, the two lakes: UWRL and LWRL reached maximum areas of 50.35 km² and 55.98 km², respectively. However, a dramatic shrinking in the surface area and water volume then occurred, particularly in LWRL, due to the reduction of discharged water into LWRL accompanied by high evaporation rates in such a hyper-arid district. Since then, the area of the LWRL has been gradually shrinking as follows: 55.98 km² in 2000, 48.6 km² in 2007, 34.09 km² in 2013 [4], 28.1 km² in 2015, and 19.5 km² in 2020 [8]. To this date, the LWRL continues shrinking. In addition to such reductions in both the LWRL area and water volume, there have been significant changes in the environmental status of the lake. For example, the salinity has increased from about 2.5‰ (on average) in 1985 to more than 32‰ in 2022 [29]. Meanwhile, the salinity in the UWRL has been almost constant (1.6–2.0‰).

2.2 Sampling sites

Shallow sediment samples were collected during the winter of 2022 from five sampling points for each lake; i.e., the UWRL (R1–R5) and the LWRL (R6–R10). Table 1 and Fig. 1 show the locations of sampling points. Triplicate surface sediment samples were collected from each sampling

Table 1 Coordination of sampling sites in El-Rayan Lakes

Site	Code	Lat N	Long E
1	R1	29°15'23.4"	30°30'43.5"
2	R2	29°13'09.9"	30°30'07.4"
3	R3	29°14'37.18"	30°29'10.95"
4	R4	29°16'15.8"	30°26'55.7"
5	R5	29°13'59.45"	30°27'39.44"
6	R6	29°12'7.56"	30°25'5.54"
7	R7	29°11'22.08"	30°24'40.72"
8	R8	29°11'49.76"	30°23'30.84"
9	R9	29°10'41.13"	30°23'56.48"
10	R10	29°9'36.54"	30°24'25.34"

Fig. 1 Map of sampling sites

point by using Ekman Dredge sampler. Each sample was immediately packed in an airtight polythene bag and stored at $-20\text{ }^{\circ}\text{C}$ before analysis.

2.3 Analytical methods

2.3.1 Grain size analysis and sediment textural classes

Half of each sample was put in a 1000 mL beaker, and boiled for 60 min after adding H_2O_2 (6%). The sample was then washed with distilled water several times by using the decantation method [30]. After adding HCl (10%) and anhydrous SnCl_2 crystals, the sample was heated for 15 min, then rinsed. Finally, the samples were washed with distilled water and stirred until no flocculation was observed. Part of these sediments was dried in an oven at $85\text{ }^{\circ}\text{C}$. Representative portions of the samples were taken out and the granule size was measured by a Fritsch laser size analyzer: ANALYSETTE 22 Nanotec with a dry dispersion unit ranging from 2 to 100 nm.

2.3.2 Organic matter and water content

The water content percentage was determined by drying a certain weight of the sample at $105\text{ }^{\circ}\text{C}$ until a constant weight was achieved, whereby the water content equals the weight difference before and after drying [31]. According to [32], the Loss on ignition (LOI) method

was used to determine the organic matter in the sediment by calculating the difference between the sample weight after drying at $105\text{ }^{\circ}\text{C}$ and after burning at $550\text{ }^{\circ}\text{C}$.

2.3.3 The pH and electrical conductivity

According to [33] and [34], the values of pH and electrical conductivity of the sediment samples were determined by using the Thermo Orion Star (A329 multi-parameter) in 1:1 and 1:5 sediment suspensions, respectively.

2.3.4 Heavy metals (HMs)

For heavy metal analysis, sediment samples were dried, finely ground, and homogenized. They were then digested by using the microwave digestion system: Multiwave PRO, Anton Paar (Graz, Austria) according to the method described by [35]. The digested samples were diluted to a known volume with deionized water. The concentrations of Al, As, Ba, B, Cd, Cr, Co, Cu, Se, Sr, Li, Na, K, Ca, Mg, Hg, Fe, Pb, Mn, Ni, and Zn were determined by Inductively Coupled Plasma Optical Emission Spectroscopy: iCAP 6500 Duo (Thermo Scientific, England). The obtained results were expressed in $\mu\text{g/g}$ dry weight. The recoveries of standard reference metals varied from 84.7 to 108.6%, which lies within the acceptable recovery percentage range of 80–120% [36].

2.4 Sediment indices

Different indicators have been recently utilized to estimate heavy metal pollution and risk in sediments. In this study, the examined indices include the Geoaccumulation Index (I_{geo}), Enrichment Factor (EF), Contamination Factor (CF), Pollution Load Index (PLI), potential ecological risk factor: (E_{ir}), and Risk Index (RI). Table 2 shows the calculation, terminology, and categories of the different indices.

2.5 Sediment quality guidelines and toxicity indices

For further evaluation and indication of the biological toxicity of sediments on benthic-dwelling organisms, other tools that consider the individual and combined effect of toxic metals were used. Hence, ERM-q, mERM-q, PEC-q, and mPEC-q were used to evaluate the toxicity levels of WRL sediments on benthic organisms, as shown in Table 3.

2.6 Data analysis

The results of metal concentrations were statistically analyzed by using the Minitab statistical software. The Anderson–Darling Normality Test was used to test the normality of the investigated metals in the two lakes, where most metals passed the normality test ($p > 0.05$). Except for B, Cu, Li, Mn, and Se, they were not normally distributed and homogeneous ($p < 0.05$). Thus, an unpaired sample t -test was used for the normally distributed metals and the Mann–Whitney U Test (Rank Sum) for the not-normally distributed metals to detect, whether there is a significant difference in the distribution of metals between the two lakes. To identify relationships between the concentrations of different heavy metals, the Pearson correlation analyses were used.

Table 2 Sediment pollution indices used

Pollution index	Equation	Evaluation criteria	References
I_{geo}	$I_{geo} = \log_2(C_i/1.5 \times C_b)$	$I_{geo} \leq 0$ (uncontaminated), $0 \leq I_{geo} \leq 1$ (uncontaminated to moderately contaminated), $1 \leq I_{geo} \leq 2$ (moderately contaminated), $2 \leq I_{geo} \leq 3$ (moderately to heavily contaminated), $3 \leq I_{geo} \leq 4$ (heavily contaminated), $4 \leq I_{geo} \leq 5$ (heavily to extremely contaminated), $I_{geo} \geq 5$ (extremely contaminated)	[37, 38]
EF	$EF = (C_i/Fe)_{\text{sample}} / (C_i/Fe)_{\text{background}}$	$EF < 2$ (Depletion to mineral), $2 < EF < 5$ (Moderate enrichment), $5 < EF < 20$ (Significant enrichment), $20 < EF < 40$ (Very highly enriched), $EF > 40$ (Extremely enriched)	[39]
CF	$CF = C_i/C_b$	$CF < 1$ (low contamination), $1 < CF < 3$ (moderate contamination), $3 < CF < 6$ (considerable contamination), $CF > 6$ (high contamination)	[40, 41]
PLI	$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n) / n$	$PLI < 1$ (uncontaminated), $PLI > 1$ (contaminated)	[42]
E_{ir}	$E_{ir} = T_{ir} \times CF$	< 40 , Low risk, 40–80, Moderate risk, 80–160, considerable risk; 160–320, high risk, > 360 , Very high risk	[40]
RI	$RI = \sum E_{ir}$	< 150 , Low risk, 150–300 Moderate risk, 300–600, High risk; > 600 Very high risk	[40]

where C_i : the concentration of element i ; C_b : the background concentration of element i ; C/Fe : the ratio of element concentration to Fe concentration; and T_{ir} : the toxic response factor of the element. The T_{ir} values for Al, As, Ba, B, Cd, Co, Cr, Cu, Fe, Pb, Li, Mn, Hg, Ni, Se, Sr, and Zn are 1, 10, 1, 1, 30, 5, 2, 5, 1, 5, 1, 1, 1, 1, 1, 1, 1, and 1, respectively [43]

Table 3 Toxicity indices of sediment

Toxicity index	Equation	Evaluation criteria	References
ERM-q	$ERM-q = [C_i/ERM]$	Low priority site (≤ 0.1), medium–low priority site (0.1–0.5), high-medium priority site (0.5–1.5), and high priority site, (> 1.5) with a 9%, 21%, 49% and 76% probability of being toxic	[44]
mERM-q	$mERM-q = (\sum C_i/ERM) / n$		
PEC-q	$mPEC-q = C_i/PEC$	Low (< 0.1), moderate ($0.1 < mPEC-Q < 1$), considerable ($1 < mPEC-Q < 5$) and very high ($mPEC-Q > 5$) with $< 14\%$, 15–29%, 33–58% and 75–81% risk, respectively	[45]
mPEC-q	$mPEC-q = (\sum C_i/PEC) / n$		

Where C_i : concentration of element i ; ERM : effect range median; $ERMq$: ERM quotient; $mERMq$: mean ERM quotient; PEC : probable effect concentration; $PECq$: PEC quotient; $mPECq$: mean PEC quotient; n : number of metals analyzed

3 Results and discussion

3.1 Sediment properties and levels of HMs

The study of grain size analysis is crucial in understanding environmental sediment forms. The generation of sediments by weathering as well as their erosion reshape the terrain, and the deposition of transported sediments creates and develops a different set of terrain. Moreover, the nature of sediment deposits gives insight into the ecological processes associated with their transport and deposition as well as the distribution of pollutants and the quantity and quality of fauna and flora [46]. As revealed in the results, sand is the predominant fraction in the UWRL with an average of 70.84%, while the mud fraction was the most prevalent in the LWRL with an average of 47.24%, as shown in Table 4.

The rate of mud deposition increased in the middle of lakes, where the increase in depth and the low energy of water were recorded as 64.4% at Site 3 in the UWDL and 65% at Site 9 in the LWRL. In general, mud (i.e., silt and clay) was deposited from water (i.e., river deposit) that was transported by water drains. However, no gravel fraction was detected neither at Site 3 in the UWRL nor at Sites 8 and 9 in the LWRL. It is noteworthy that the WRL bottom sediments varied between muddy sand, sandy mud, gravel sandy mud, and muddy gravel sand. They came from different sources—both allochthonous produced by erosion of the bottom bed and autochthonous transported by different transport agents: drains and wind. These results agreed with those obtained by [13, 14, 25, 47].

Figure 2 shows the organic matter percentage in the WRL sediments. The highest organic matter content: 6.45% and 13.6% were recorded at Site 2 in the UWRL and Site 8 in the LWRL, respectively. The average content of organic matter showed a noticeable increase in the

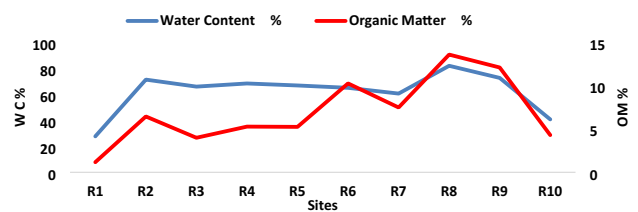


Fig. 2 Horizontal distributions (%) of water content and organic matter in sediments of El-Rayan Lakes

LWRL (9.55%, on average) compared to the UWRL (4.42%, on average). This can be related to the differences in evaporation rates as well as fish farm activities eastward of the LWRL compared with the UWRL. In addition, the western region is considered a tourist area and is also affected by animal grazing operations in both the western and southern regions of the LWRL. Water content is one of the most significant indicator properties used to clarify sediment behavior in aquatic ecosystems. The investigated sediment samples clarify that water content agreed with both organic matter and mud distributions, where it increased at Sites 2 and 8 and decreased at Sites 1 and 10 in the UWRL and LWRL, respectively as shown in Fig. 2.

The pH values of sediment samples ranged between 6.36–7.03 and 6.53–7.0 in the UWRL and LWRL, respectively. The lowest pH value was at Site 5 of the UWRL. As stated in [48], the decay of organic matter releases acids into sediments and leads to a decrease in pH values. Therefore, the decrease in pH value in Site 5 can be attributed to the decay and fermentation of deposited organic matter and the release of gases and acids that decrease pH value and reduce the content of the organic matter after the decomposition process by microbial activity. According to the results, pH was positively correlated with Cr, Co, Se, Ba ($p < 0.05$) and B, As, Pb ($p < 0.01$), which can also correlate

Table 4 Sediment fractions, water content, organic matter, and organic carbon in El-Rayan Lakes

Stations	Gravel%	Sand %	Mud%	Silt%	Clay%	Sediments type	
Upper lake	R1	18.6	80.2	1.1	0.8	0.3	Gravelly Sand
	R2	1.1	89.5	9.4	7.9	1.5	Sand
	R3	0	35.6	64.4	41.8	22.6	Sandy Mud
	R4	20	74.6	5.4	4.64	0.72	Gravelly Sand
	R5	1.2	74.3	24.5	23.6	0.9	Muddy Sand
Average	8.18	70.84	20.96	15.748	5.204		
Lower lake	R6	9.1	55.1	35.8	29.8	6.1	Gravelly Muddy sand
	R7	6.2	43.2	51.6	38.9	12.8	Gravelly sandy Mud
	R8	0	39.4	60.6	44	16.6	Sandy Mud
	R9	0	35	65	43.3	21.7	Sandy Mud
	R10	20	56.8	23.2	17.1	6.2	Gravelly Muddy sand
Average	7.06	45.9	47.24	34.62	12.68		

with the increase of most HMs content in Site 1 which recorded the highest pH value. EC varied from 0.742 to 1.562 mS/cm in the UWRL and from 8.25 to 10.66 mS/cm in the LWRL. It positively correlated with Na, Ca, ($p < 0.01$), and K ($p < 0.05$), but negatively correlated with Mn, Fe, and Hg ($p < 0.01$). There was a significant difference between the recorded levels of major metal content in two lakes—i.e., 9.78–12.06; 19.72–34.0; 2.13–5.99; 0.87–1.35 mg/g and 17.85–30.36, 22.22–74.05, 4.22–5.04, and 1.12–1.48 mg/g for Na, Ca, Mg, and K in the UWRL and LWRL, respectively. The increase in the levels of major elements in the LWRL sediments is mainly due to the increase in its water salinity. The concentrations of Al, As, Ba, B, Cd, Co, Cr, Cu, Fe, Pb, Li, Mn, Hg, Ni, Se, Sr, and Zn in the UWRL and LWRL are represented in Table 5. Site 1 recorded the highest metal levels with concentrations of 7575, 6.091, 144.240, 68.210, 2.555, 16.436, 146.040, 39.953, 11,828, 35.407, 17.703, 577.575, 0.023, 91.475, 1.332, 302.605, and 179.393 $\mu\text{g/g}$ for Al, As, Ba, B, Cd, Co, Cr, Cu, Fe, Pb, Li, Mn, Hg, Ni, Se, Sr, and Zn, respectively in the UWRL. Meanwhile, in the LWRL, Site 6 contained the highest concentrations of As (6.823 $\mu\text{g/g}$), Cr (144.46 $\mu\text{g/g}$), Fe (9032 $\mu\text{g/g}$), Hg (0.019 $\mu\text{g/g}$), and Se (0.194 $\mu\text{g/g}$); and Site 8 recorded the highest concentrations of Al (7474 $\mu\text{g/g}$), Co (18.611 $\mu\text{g/g}$), Cu (59.782 $\mu\text{g/g}$), Zn (253.2 $\mu\text{g/g}$), and Sr (256.22 $\mu\text{g/g}$).

According to statistical data, it was clear that there was a significant difference ($p < 0.001$) in the investigated HMs between the two lakes. Based on the average HMs concentrations, the pattern content of the sediment of the two lakes was similar and in the order of $\text{Fe} > \text{Al} > \text{Mn} > \text{Sr} > \text{Cr} >$

$\text{Zn} > \text{Ba} > \text{Ni} > \text{B} > \text{Cu} > \text{Pb} > \text{Li} > \text{Co} > \text{As} > \text{Cd} > \text{Se} > \text{Hg}$ in the UWRL. However, the Zn concentration was higher than Cr in the LWRL. Site 1—which is close to the discharge point of the El-Wadi Drain—recorded the maximum content of As, Ba, B, Cd, Cr, Fe, Pb, Hg, Mn, Sr, Se, and Zn. In addition, the organic matter was positively correlated with several metals such as Li, Na, Ca, K, and Zn ($r = 0.57\text{--}0.77$, $p < 0.01$). This can be attributed to the precipitation of metals as bound to organic matter.

Notably, the lowest levels of HMs were for the toxic metals: As, Cd, and Hg, but Pb appeared in significant values. However, the average Cd concentration, for example, in the two lakes was five times higher than its background value. The increased content of Cd and Pb is primarily related to phosphate fertilizers [49–51] that enter the lakes through the El-Wadi Drain. As highlighted in [52], the high levels of Cd in Edku Lake can be attributed to a large amount of organic matter, domestic discharge, and clay sediments enriched with Mn and their oxide and hydroxide associations. Correlation between all pairs of studied metals ($r = 0.57\text{--}0.94$, $p < 0.01$), particularly with Fe and Mn, indicates the role of Fe–Mn oxides in the precipitation of metals in addition to the common source of most metals.

Several studies have recorded the relationship between the precipitation of HMs—such as Fe and Mn—and the muddy nature of the sediment [53]. However, the results in this study were opposite to such a conclusion, where Fe ($r = -0.55$, $p < 0.05$) and Mn ($r = -0.65$, $p < 0.01$) appeared negatively correlated with mud content. This can be attributed to the positive correlation

Table 5 Heavy metal levels ($\mu\text{g/g}$) in sediments of El-Rayyan Lakes, average shale, and earth crust

Metal Conc. ($\mu\text{g/g}$)	UWRL			LWRL			Average Shale	Earth Crust
	Min	Max	Avg	Min	Max	Avg		
Al	4300	7580	5965	1360	7474	5720	80,000	82,300
As	1.79	6.09	3.0762	1.73	6.823	3.75	13	1.8
Ba	58.49	144.24	98.61	37.15	136.403	102.98	580	425
B	37.78	68.21	46.36	12.55	49.796	43.76	100	10
Cd	0.82	2.56	1.50	0.71	1.871	1.39	0.3	0.15
Co	7.72	16.44	11.08	4.07	18.611	12.36	19	25
Cr	93.50	146.04	122.34	22.21	144.463	117.56	90	102
Cu	19.13	39.95	29.69	8.20	59.782	29.78	45	60
Fe	7800	11,830	9480	1510	9032	8030	47,200	56,300
Pb	15.75	35.41	24.50	7.82	29.824	21.89	20	14
Li	9.75	17.70	14.08	3.00	50.183	23.64	66	20
Mn	370.66	577.58	464.63	89.36	329.827	387.96	850	950
Hg	0.02	0.02	0.02	0.00	0.019	0.02	0.4	0.085
Ni	78.54	91.48	83.13	4.91	98.636	79.29	68	84
Se	0.14	1.33	0.43	0.12	0.194	0.38	0.6	0.05
Sr	104.93	302.61	169.12	86.92	256.22	172.80	300	370
Zn	66.80	179.39	116.59	43.02	253.202	132.92	95	70

Table 6 Levels of HMs (mg/Kg, dry weight) in the sediment of El-Rayan Lakes in comparison to other Egyptian Lakes

Metal Lake	Fe	Mn	Cd	Cu	Pb	Zn	Ref
UWRL	9780.4	464.9	1.50	29.69	83.13	24.50	The present Study
LWRL	6870.8	321.2	1.26	34.30	87.26	20.11	
UWRL	2109	707		57		172.6	[12]
LWRL	2251	391		47		198.6	
Qarun Lake	3264	416.33		101.77		121	[12]
Manzala lake	14,130	800	1.8	110	60	20	[55]
Edku Lake	25,460	1200	2.79	41.56		31.7	[56]
Mariout Lake	19,340	585	0.7	91	40	59	[57]
Burullus Lake	17,550	948	0.2	30	40	30	[58]

between sediment salinity (EC) and mud content ($r = 0.58$, $p < 0.01$). Therefore, the increase in salinity and major ions such as Na reduces HM precipitation due to their competition with HMs for particulate binding sites [54]. Such findings can be confirmed by the negative correlation of sediment salinity (EC) with Fe ($r = -0.75$, $p < 0.01$) and Mn ($r = 0.87$, $p < 0.01$) as well as the positive correlation between EC and Na ($r = 0.88$, $p < 0.01$).

Table 6 shows that the concentrations of Fe, Mn, Cu, and Pb in El-Rayan Lakes were lower than their corresponding values in the Delta Lakes, namely Manzala, Edku, Mariout, and Burullus Lakes, respectively as obtained by [55–58]. This can be related to the enormous amounts of sewage discharged to these lakes compared with El-Rayan lakes. However, the present results of Mn and Cu were lower than the findings of the previous studies by [12] on El-Rayan Lakes. However, Fe was much higher in this study as shown in Table 6. On the other hand, the concentration of cadmium in El-Rayan Lakes was lower than its level in Manzala and Edku Lakes. In addition, the zinc content was lower than its content in Edku and Mariout Lakes, but close to the result obtained in previous studies by [12] for El-Rayan and Qarun Lakes.

Figure 3 represents the spatial distribution of different metals in the sediments of El-Rayan Lakes by using ArcMap (ArcGIS, 10.5), where data interpolation was achieved by applying the Inverse Distance Weighted (IDW) method. The geological distribution similarity of most metals was observed in both lakes. However, the highest concentrations were in the eastern of the UWRL which lies opposite the El-Wadi Drain and gradually decreased with distance toward the channel connecting the two lakes. In the LWRL, most metals such as Al, Cu, Ni, Sr, and Zn were concentrated in the western north area. Mn and Se showed lower levels in the LWRL than the UWRL. On the other hand, As, Ba, Co, Sr, and Zn showed higher values in the LWRL.

3.2 Ecological risk assessment

The I_{geo} index is used to assess the contamination degree of sediment by heavy metals in different water bodies. The results of I_{geo} values indicated that all sites in El-Rayan Lakes were unpolluted with Al, As, Ba, B, Co, Cr, Cu, Fe, Pb, Li, Mn, Hg, Co, Cu, Fe, Li, Mn, Hg, Ni, Se, and Sr. However, Site 1 appeared slightly to moderately polluted with Pb and Se. On the other side, all sites of the lakes were slightly to moderately polluted by Cd, except Site 1 which was highly polluted. In the same context, Cr appeared slightly to moderately contaminated at Site 1 in the UWRL and Sites 8–10 in the LWRL. Zn exhibited slight pollution at Site 1 and Sites 7–10 in the LWRL as shown in Fig. 4.

The Contamination Factor (CF), also known as Anthropogenic Factor (AF), reflects the possible pollution of sediment due to different human activities in terms of the relation between the present levels of contaminants and their background levels. The CF results indicate that El-Rayan Lakes are exposed to low contamination with Al, As, Ba, B, Co, Cu, Fe, Li, Mn, Hg, Se, and Sr, where the CF values were < 1 at 100% of the samples, except Cu at Site 7 and Se and Sr at Site 1, as shown in Table 7. Meanwhile, Cd showed different degrees of contamination, where the CF of Cd recorded moderate pollution at Sites 3, 5, 7, and 10; considerable pollution at Sites 2, 4, 6, and 8; and high pollution at Site 9. Cr, Ni, and Zn exhibited moderate contamination at all sites of the two lakes, except Site 2 which is low contaminated with Zn. The CF values of Pb varied between low and moderate contamination in the two lakes.

The EF tool is used to distinguish between natural and anthropogenic activities as sources of metals and assess the enrichment of heavy metals [28, 59–62]. The higher EF values increase the pollution degree. When EF value < 2 , the sediment is less affected by human activities, while higher EF values suggest anthropogenic sources. The EF values of Al, Ba, and Hg were < 2 at all sites of the two lakes;

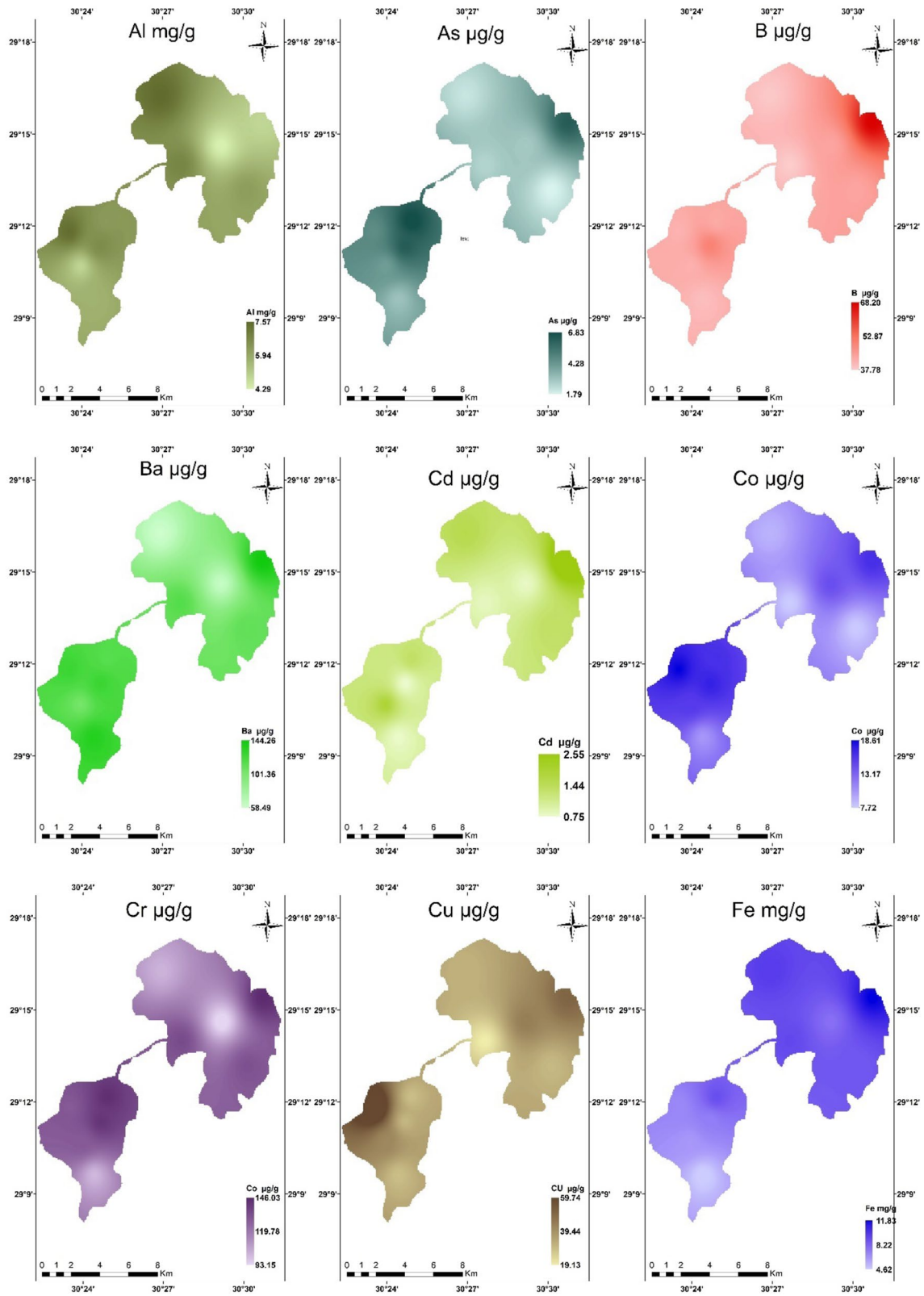


Fig. 3 ArC map distribution of investigated metals in sediments of El-Rayan Lakes

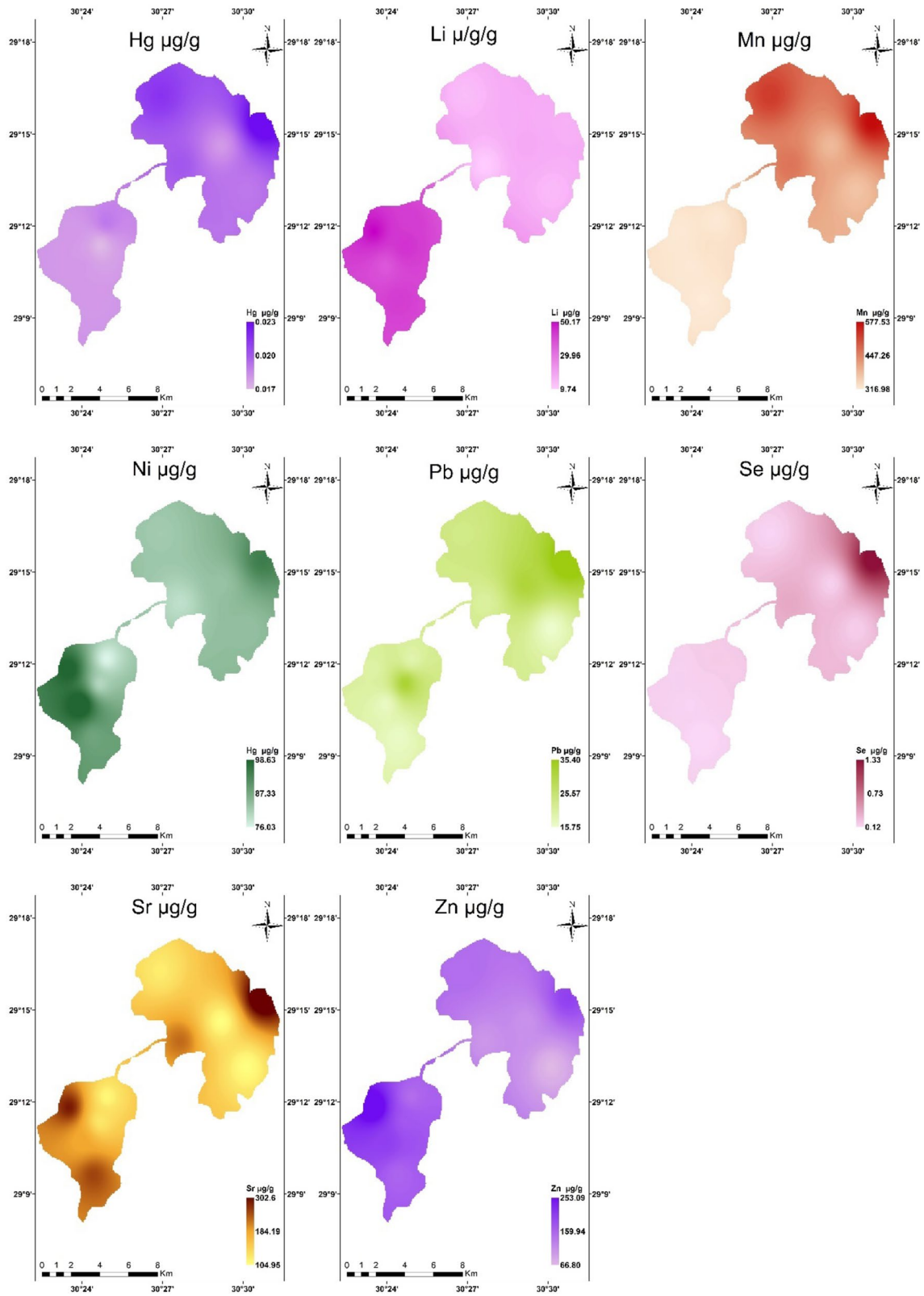


Fig. 3 (continued)

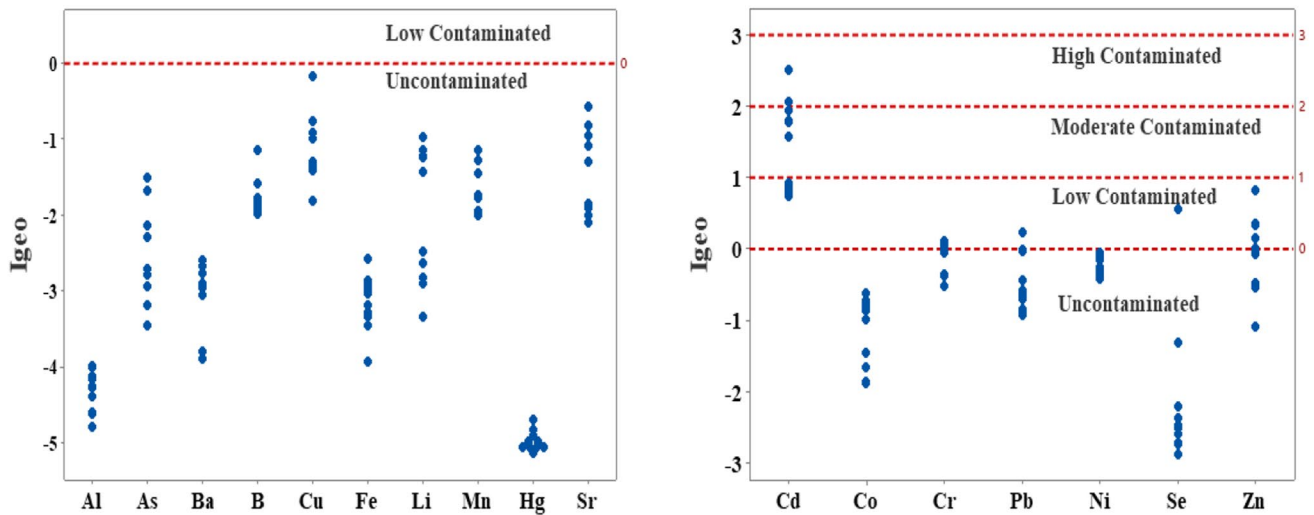


Fig. 4 Individual plot of Igeo values of sediments of El-Rayyan Lakes during winter 2022

Table 7 The CF index of sediments in El-Rayyan Lakes

Metal	Rayan Lake I			Rayan Lake II		
	Min	Max	Avg	Min	Max	Avg
Al	0.054	0.095	0.075 ± 0.017	0.062	0.093	0.078 ± 0.012
As	0.137	0.469	0.237 ± 0.133	0.23	0.525	0.375 ± 0.121
Ba	0.101	0.249	0.17 ± 0.064	0.18	0.235	0.21 ± 0.021
B	0.378	0.682	0.464 ± 0.126	0.398	0.498	0.432 ± 0.039
Cd	2.733	8.517	5.013 ± 2.382	2.503	6.237	4.193 ± 1.624
Co	0.407	0.865	0.583 ± 0.214	0.547	0.98	0.824 ± 0.165
Cr	1.039	1.623	1.359 ± 0.247	1.147	1.605	1.445 ± 0.183
Cu	0.425	0.888	0.66 ± 0.182	0.566	1.328	0.762 ± 0.326
Fe	0.167	0.251	0.202 ± 0.031	0.099	0.193	0.147 ± 0.034
Pb	0.787	1.77	1.225 ± 0.391	0.813	1.491	1.005 ± 0.279
Li	0.148	0.268	0.213 ± 0.045	0.557	0.76	0.655 ± 0.073
Mn	0.39	0.608	0.489 ± 0.094	0.334	0.347	0.338 ± 0.005
Hg	0.045	0.058	0.051 ± 0.005	0.043	0.048	0.045 ± 0.002
Ni	1.155	1.345	1.223 ± 0.072	1.118	1.451	1.283 ± 0.146
Se	0.225	2.22	0.72 ± 0.852	0.203	0.323	0.254 ± 0.046
Sr	0.35	1.009	0.564 ± 0.29	0.374	0.854	0.607 ± 0.212
Zn	0.703	1.888	1.227 ± 0.453	1.432	2.665	1.836 ± 0.497

i.e., they are less affected by human activities (i.e., natural sources). However, only Site 10 was moderately enriched with Ba as shown in Fig. 5.

On the other hand, Mn showed a moderate enrichment suggestive of moderate pollution at all sites of the two lakes. Among the investigated metals, Cd showed higher EF values in the two lakes, indicating a strong pollution signal due to anthropogenic activities. The results also showed significant enrichment of Cr and Ni, suggesting a significant pollution signal at all sites of the lakes, with Pb and Zn at most sites. However, As showed EF values < 2 at all sites of the UWRL, where it is depleted to mineral (i.e.,

a natural source), but showed moderate contamination (2 < EF < 5) at all sites of the LWRL. Co and Cu showed moderate contamination in the UWRL, varying between moderate to significant contamination in the LWRL. Se showed moderate contamination at Sites 5 and 10, and significant enrichment at Site 1. On the other hand, Sr has significant enrichment at Sites 8 and 10, and moderate contamination at Sites 1, 3, 5, 7, and 9.

Although wastewater through the El-Wadi Drain is the water source for both lakes, there was a noticeable increase in the pollution degree with many metals in Site 1 in the UWRL and most sites in the LWRL. This increase at

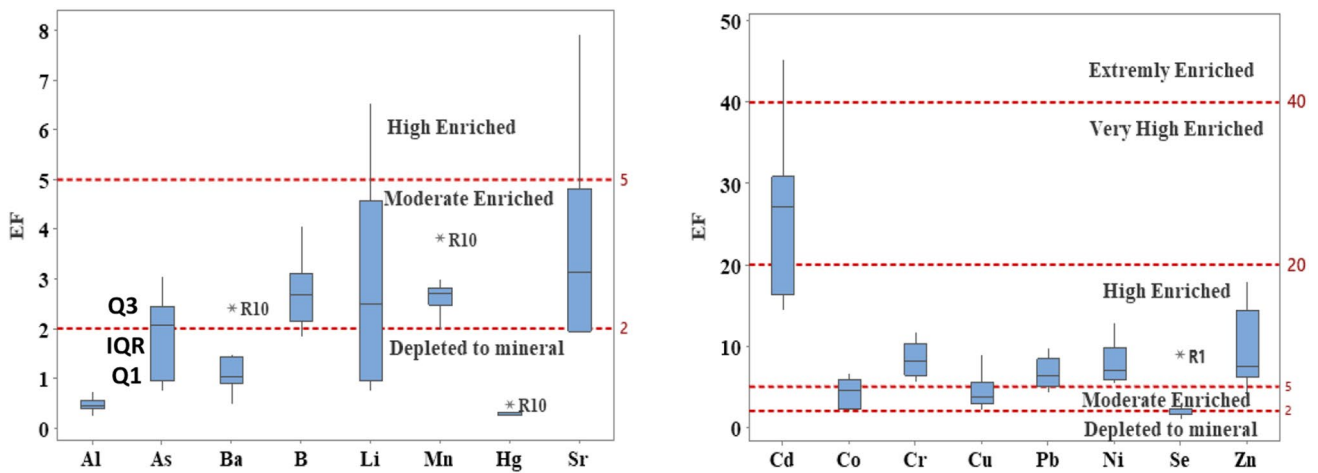
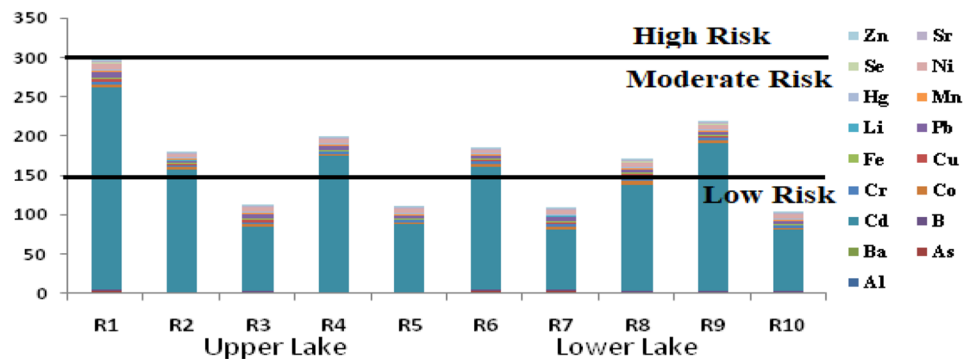


Fig. 5 Boxplot of EF values in sediments of El-Rayan Lakes, * represent outlier values. Q1: represent 1st Quartile and Q3: 3rd Quartile and IQR: Inter quartile Range

Fig. 6 Values of E_{ir} (for metals) and RI (for sites) of studied metals in sediments of El-Rayan Lakes



Site 1 can be due to the huge amounts of wastewater runoff into the lake at this location. However, the noticeable increase in the LWRL can be attributed to the shrinkage of the lake area and water volume, leading to the concentration of metals in water and thus an increase in the metal sedimentation rate to bottom sediments.

Based on the combined effects of metals, the Pollution Load Index (PLI) is a good method to evaluate and compare the contamination level at various zones and sites [59]. PLI is an integrated index that indicates the increase of metal concentration in sediment compared to the background content with time. In addition, it provides a generalized grasp of the status of environmental components [60]. The values of PLI (< 1) at different sites indicate the unpolluted situation of the sediments in El-Rayan lakes through the studied heavy metals. PLI values ranged between 0.38–0.67 and 0.42–0.54 in the UWRL and LWRL, respectively. The highest value was recorded at Site 1—the closest site to the inlet of the deranged water. However, the PLI values of the lakes area recorded 0.44 and 0.48 for the UWRL and LWRL, respectively.

The potential ecological risk factor (E_{ir}) and the Risk Index (RI) were applied to assess the ecological sensitivity of heavy metal pollution in sediments, according to the toxicity of heavy metals and environmental responses [40]. E_{ir} expresses the potential environmental risk of a given pollutant, while RI expresses the possible ecological risk index for any given basin or lake due to the potential risk of collective different pollutants [40, 60]. According to E_{ir} results, all studied metals do not have any dangerous effects. Only Cd exhibited different ecological risks, varying from low to high risk levels with E_{ir} values ranging between 75.1 at Site 7 and 255.5 at Site 1 as shown in Fig. 6. The present results agree with the results of Edku Lake obtained by [63], where high potential risk was evaluated due to Cd levels as a result of receiving different agricultural and industrial wastes.

In general, the E_{ir} values of heavy metals in the sediments of El-Rayan Lakes can be ranked as $Cd > Pb > Ni > Cu > Co > Cr > As > Hg > Zn > Se > Sr > Mn > B > Li > Fe > Ba > Al$ and $Cd > Ni > Pb > Cu > Co > As > Cr > Zn > Hg > Li > Sr > B > Mn > Se > Ba > Fe > Al$ in the UWRL and LWRL,

respectively as shown in Fig. 5. In the same context, RI variables between low and moderate ecological risk in the two lakes recorded values in the range of 111.5–297.3 (180.05, on average) and 104.61–218.61 (158.18, on average) in the UWRL and LWRL, respectively. As stated in [64], extremely high values of the ecological index can give an adverse effect on the benthic organism, particularly the micro-invertebrate species and other organisms such as the egg and larval stages of fish, which spend all or part of their life cycle associated either within or on the bottom sediment. The bioavailability and toxicity of the metals in the sediment samples do not only depend on the metal concentration, but also on their available chemical forms [65].

3.3 Sediment quality guidelines and toxicity indices

Several sediment quality guidelines (SQGs) have been approved and developed by many scientific organizations and agencies. Among these guidelines are the Sediment Quality Standards (SQS), Sediment Quality Objectives (SQO), and Sediment Quality Criteria (SQC) for both marine and freshwater ecosystems. They are widely used in numerous applications such as ecological risk assessments [66]. Many scientists as well as scientific societies and authorities have used the SQGs to determine pollutants in aquatic ecosystems and rank areas of concern on a regional or national basis as shown in Table 8. Using SQGs along with other tools such as sediment toxicity tests is known as an effective and useful approach for evaluating the quality of marine and freshwater sediments. There

are two classes of SQGs for each pollutant; the first is the threshold effect levels (TELs) below which no adverse effects are expected to occur, while the second is the probable effect levels (PELs) above which adverse effects are expected to occur.

The Effects Range Low (ERL) and the Threshold Effect Concentration (TEC) are set in the first class, whereas the Effect Range Median (ERM) and the Probable Effect Concentration (PEC) follow the second class. According to the SQG values, 90%, 10%, 100%, and 70% of the selected sites in El-Rayan lakes exceeded the ERL of Cr, Pb, Ni, and Zn, respectively. Moreover, 100%, 60%, 100%, 40%, 100%, 10%, and 70% of the sites exceeded the TEC of Ba, Cd, Cr, Cu, Ni, Se, and Zn, respectively. On the other side, Ni exceeded its ERM and PEC values at all sites. In addition, Ba values were above its PEC value at 10% of the sites, while Cr exceeded its ERM and PEC in 100% and 10% of the sites, respectively. These findings indicate that the metal contents in the sediment of El-Rayan Lakes have different degrees of adverse effects on the sediment biota. In addition, Ni and Cr have the most potentially adverse effect on sediment-dwelling organisms in El-Rayan Lakes.

Many SQG indices have been suggested to determine the toxic effects of polluted sediments on benthic-dwelling organisms. The mERM-q are powerful methods to assess the potential biological risk of multiple pollutants in the sediment of a site or an area on living organisms, while ERM-q is used to assess any potential toxic effects of an individual pollutant. Regarding the present study, the investigated metals had different priority risks. However, As and Hg showed low potential risks, where $ERM-q \leq 0.1$,

Table 8 SQGs of the sediment of El-Rayan Lakes

SQGs	Al	As	Ba	B	Cd	Co	Cr	Cu	Fe	
Threshold effect level	(ERL)*	NA	33	NA	NA	5	–	80	70	NA
	% samples > ERL	NA	0	NA	NA	0	Co	90	0	NA
	(TEC)*	NA	9.79	20	NA	0.99	NA	43.4	31.6	20,000
	% samples > TEC	NA	0	100	NA	60	NA	100	40	0
Probable effect level	(ERM)*	NA	85	NA	NA	9	–	145	390	NA
	% samples > ERM	NA	0	NA	NA	0	NA	10	0	NA
	(PEC)*	58,030	33	60	NA	4.98	NA	111	149	40,000
	% samples > PEC	0	0	10	NA	0	NA	70	0	0
SQGs										
Threshold effect level	Pb	Li	Mn	Hg	Ni	Se	Sr	Zn		
	ERL	35	NA	NA	0.15	30	NA	NA	120	
	% samples > ERL	10	NA	NA	0	100	NA	NA	70	
	TEC	35.8	NA	1673	0.18	22.7	1	NA	121	
Probable effect level	% samples > TEC	0	NA	0	0	100	10%	NA	70	
	ERM	110	NA	NA	1.3	50	NA	NA	270	
	% samples > ERM	0	NA	NA	0	100	NA	NA	0	
	PEC	128	NA	1081	1.06	48.6	4	NA	459	
% samples > PEC	0	NA	0	0	100	0	NA	0		

*According to [67]

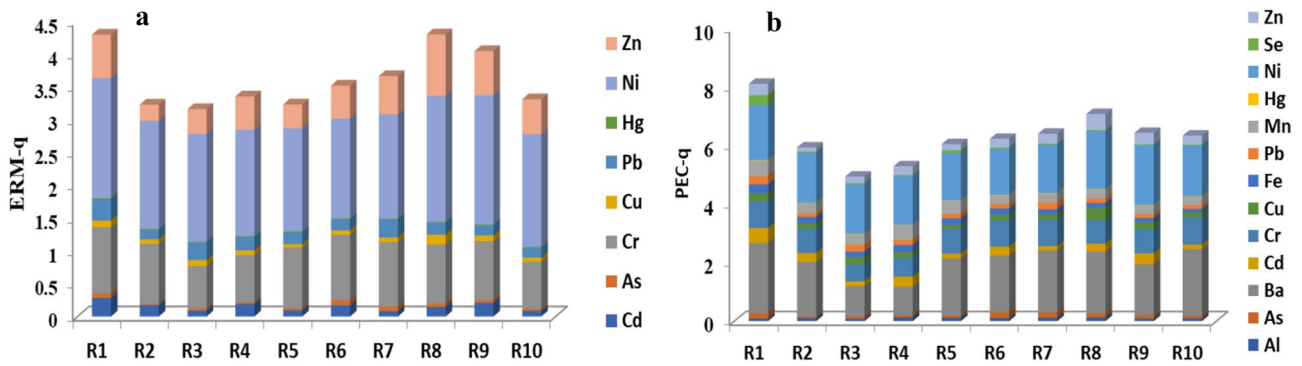


Fig. 7 Values of **a** mERM and **b** mPEC for the studied metals in the different sites of El-Rayan lakes sediments

with a 9% probability of being toxic; and Cd, Cu, and Pb had a moderate to low risk, where $0.1 < \text{ERM-q} < 0.5$, with a 21% probability of being toxic, in 60%, 20% and 100% of samples. Cr showed high to medium risk, where $0.5 < \text{ERM-q} < 1.5$, with a 49% probability of being toxic in 100% of samples. Ni recorded a high probability risk where $\text{ERM-q} > 1.5$, with 76% being toxic in all samples. The results indicate that the sequence of ERM-q is $\text{Ni} > \text{Cr} > \text{Zn} > \text{Pb} > \text{Cd} > \text{Cu} > \text{As} > \text{Hg}$ in both lakes as shown in Fig. 7. However, there was no available data for Al, Ba, B, Co, Fe, Li, Mn, Se, and Sr. The obtained mERM-q results showed that all sites of the two lakes were at moderate to low risk, which shows the potential adverse effect of sediments of El-Rayan Lakes on the benthic-dwelling organisms with a higher risk in the LWRL than the UWRL as shown in Fig. 8.

In a similar trend, the data of PEC-q showed a low potential risk of Hg, where $\text{PEC-q} \leq 0.1$, with a 14% probability of being toxic at all sites of the two lakes. Meanwhile, Cd, Cu, Cr, Fe, Pb, Mn, and Zn showed moderate risks, where $0.1 < \text{PEC-q} < 1$, with a 15–29% probability of

being toxic at 100% of the sites. Ni and Ba also showed considerable potential risks at all studied sites of the two lakes with a 33–58% probability of being toxic, where $1 < \text{PEC-q} < 5$. Only Ba exhibited a moderate risk at Site 4 in the UWRL as shown in Fig. 7. Based on the average value, the descending order of PEC-q of the different metals was $\text{Ba} > \text{Ni} > \text{Cr} > \text{Mn} > \text{Zn} > \text{Cd} > \text{Zn} > \text{Fe} > \text{Cu} > \text{Pb} > \text{Se} > \text{Al} > \text{As} > \text{Hg}$ and $\text{Ba} > \text{Ni} > \text{Cr} > \text{Zn} > \text{Mn} > \text{Cd} > \text{Cu} > \text{Fe} > \text{Pb} > \text{As} > \text{Al} > \text{Se} > \text{Hg}$ in the UWRL and LWRL, respectively as shown in Fig. 7. There were no available data for B, Co, and Sr. Based on the mPEC-q values, all sites of El-Rayan Lakes suffer from moderate pollution and have a potential moderate risk as shown in Fig. 8. Site 1—which is close to the discharge point of wastes—recorded relatively high mERM-q and mPEC-q values. Moreover, the mean value of mERM-q (0.47) and mPEC-q (0.50) in the LWRL was more than the UWRL—where mERM-q = 0.43 and mPEC-q = 0.47. This indicates the relative increase in pollution of the LWRL, confirming the findings of EF data in the present study as shown in Fig. 8.

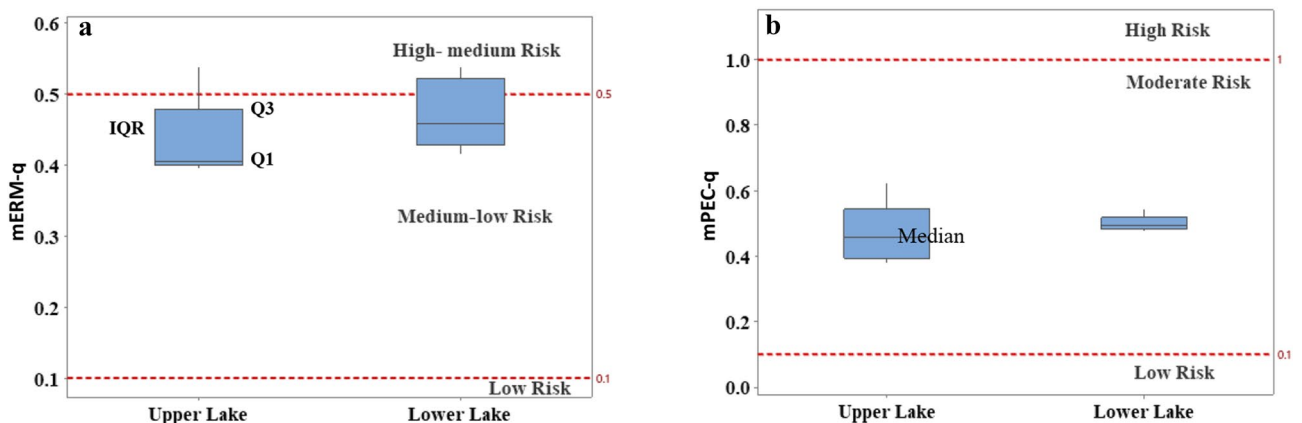


Fig. 8 Box Plot of **a** mERM-q and **b** mPEC-q values for the sediments of El-Rayan lakes, where Q1: 1st Quartile, Q3: 3rd Quartile, and IQR: Inter Quartile Range

4 Conclusion

The Wadi El-Rayan Depression (WRD) was chosen as a reservoir of wastewater excess for Fayoum province, where the water flowed into the first lake, UWRL, in 1976 and the second lake, LWRL, in 1980. Both WRLs were stated as protected areas and wetland areas under the Ramsar Convention. The two lakes reached their maximum area and volume in 2000. However, over time, the area of the second lake has been shrinking to this date. Hence, this monitoring study aimed to evaluate the sediment status of WRLs as part of their ecosystem used in irrigation, aquaculture, and fisheries activity. The study focused on evaluating the level of some heavy metals in the sediments of WRLs and the extent of pollution and risk as a result of the accumulation of these toxic elements. The sand and mud represented the predominant fraction of the lake sediment with averages of 70.84% and 45.9% in the UWRL and 20.96% and 47.24% in the LWRL, respectively. The organic matter content varied between 1.17–6.45 and 4.3–13.6% in the UWRL and LWRL, respectively. Regarding the HMs contents, the lowest levels of HMs were for the toxic metals: As, Cd, and Hg. Meanwhile, Pb appeared in significant values. According to the single and integrated ecological indices, the sediment of the two lakes suffers from different ranks of metal contamination, where Cd, Pb, and Ni are the most polluting elements. Moreover, Site 1—which is opposite the discharge point of the El-Wadi Drain—in the UWRL is the most contaminated area. However, the LWRL sediment is generally more contaminated than the UWRL. The data of SGQs show that Ni and Cr have the most potentially adverse effect on sediment biota in El-Rayan Lakes. On the other side, the toxicity indices declared that all sites of the two lakes were at moderate to low risk, which shows the potential adverse effect of sediments of El-Rayan Lakes on benthic-dwelling organisms.

Author's contribution All authors contributed to the study's conception and design. AIK, MEG, SME-S, SGS, and HIF performed material preparation, data collection, and analysis. AIK, MEG, SME-S, SGS, and HIF wrote the first draft of the manuscript. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability All data generated or analyzed during this study are included in this published article.

Code availability Non applicable.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Ethical approval Not applicable.

Consent to participate All authors voluntarily agree to participate in this research study.

Consent to publish All authors voluntarily approved the publication of this research study.

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