Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 27(5): 1299 – 1320 (2023)
www.ejabf.journals.ekb.eg

Assessment of heavy metal distribution, contamination, and ecological risk in mangrove sediments of the Nabq Protectorate, Gulf of Aqaba

Alaa M. Younis[1,2*], Donia H. Elnaggar[2], Lamiaa I. Mohamedein[3], Artem V. Kolesnikov[4]

1 Department of Chemistry, College of Science, Qassim University, Buraidah, 51452, Saudi Arabia
2 Aquatic Environment Department, Faculty of Fish Resources, Suez University, Suez, Egypt
3 National Institute of Oceanography & Fisheries (NIOF), Egypt
[4] Inorganic substances and electrochemical processes department, Mendeleyev University of Chemical Technology of Russia, Moscow, Russia

[*]**Corresponding Author: a.younis@qu.edu.sa**

ARTICLE INFO

Article History:
Received: Sept. 20, 2023
Accepted: Oct. 11, 2023
Online: Oct. 30, 2023

Keywords:
Heavy metals,
mangrove sediments,
ecological hazards,
contamination,
risk assessment,
Gulf of Aqaba.

ABSTRACT

This study investigates the distribution and characteristics of heavy metals (Cu, Fe, Cd, Pb, Zn, and Mn) in the mangrove sediments of the Nabq Protectorate in the Gulf of Aqaba. The concentrations of these metals were analyzed at various sampling sites, and their values were compared to reference standards to assess the level of contamination. The results indicate that the studied sites are generally uncontaminated when compared to crustal averages and upper-crust values. Iron (Fe) exhibited the highest concentration, followed by Mn, Pb, Zinc, Cu, and Cd. The sediments in the research area were found to have relatively low concentrations of heavy metals, except for Cd, at one specific location, suggesting ongoing pollution from human activities. Strong positive correlations were observed between Zn, Cu, Mn, and Fe, while Pb showed a weak positive correlation. Cd had a negative correlation with the other metals, indicating a distinct source. The results of the geo-accumulation index (Igeo) and potential ecological risk index (PERI) suggest mild pollution intensity and low ecological risk in most of the study area. However, continuous monitoring is recommended to ensure the preservation of the ecosystem. The average percentage contributions to potential acute toxicity revealed that Cd had the highest contribution, followed by Pb, Zn, and Cu. Overall, the study concludes that the ecological risk posed by heavy metals in the research area is relatively low based on the ∑TU criterion.

INTRODUCTION

Coastal ecosystems represent a highly valuable resource that is increasingly threatened by human activities. Among these ecosystems, tropical coastal environments encompassing coral reefs, mangrove forests, and seagrass meadows are globally recognized for their exceptional biodiversity (**Ogden and Gladfelter, 1983; Younis, 2019**) and productivity

(**Lewis, 1977; Smith, 1978**). Unfortunately, human actions exert a growing and detrimental influence on these ecosystems. Direct impacts include extracting food and resources, while indirect impacts manifest through pollution and inadvertent damage (**Salm, 1983; Kenchington, 1988; Younis *et al.*, 2022; Taher *et al.*, 2023**).
Mangroves, intertidal wetlands found in tropical and subtropical regions, are renowned for their high productivity and provision of numerous ecological services (**Lin, 2001; Elnaggar e*t al.*, 2022**). Mangroves exhibit unique ecological features that contribute to their remarkable biodiversity and provide highly suitable habitats for various organisms (**Wang *et al.*, 2009**).
However, mangroves, which are among the most threatened tropical ecosystems, face escalating pollution challenges resulting from human activities driven by rapid industrialization and urbanization of coastal areas. Mangroves possess distinct characteristics, including high productivity, organic-rich detritus, fine-grained wetland soil, and anoxic environments, making them susceptible to the accumulation of various contaminants primarily originating from rivers or tidal waves (**Tam, 2006**).
Mangrove habitats possess distinct characteristics, including the presence of fine-grained sediments, a high organic content, and periodic inundation events. These factors contribute to the prevalence of high salinity and low oxygen concentrations within these habitats (**Lewis *et al.*, 2011; Maiti and Chowdhury, 2013**). Furthermore, mangrove habitats are renowned for their intricate ecological dynamics.

According to **Alongi (2009),** active microbial fauna are present in these habitats. The reduction of oxygen levels in the underlying sediments fosters anaerobic metabolism facilitated by fermenting and sulfate-reducing bacteria. These bacteria play a crucial role in decomposing organic matter. The anaerobic reduction process is accompanied by elevated levels of reduced inorganic sulfur, such as pyrite (FeS2) and elemental sulfur. However, iron monosulfide (FeS) and unbound sulfide are present in minimal quantities. Hydrogen sulfide (H2S) is a key component in this context **(Alongi, 2009).** Sulfide ions have a strong affinity for binding with metallic elements, thereby playing a significant role in metal sequestration.

Metal sulfides exhibit limited solubility, which is why sediments in mangrove ecosystems act as repositories for heavy metals, as observed by previous research conducted by **Lewis *et al.* (2011) and Maiti *et al.* (2013).** These sediments possess notable adsorption capacity, as demonstrated by **Giblin *et al.* (1980),** effectively retaining both organic and inorganic pollutants. This characteristic prevents the infiltration of such pollutants into the adjacent marine environment

According to **Maiti and Chowdhury (2013**), ecosystems play a significant role in the natural environment and can also provide valuable services. The remobilization of heavy metals is influenced by the sources of these metals. Empirical research has shown that the removal of mangroves leads to observable changes in the physical environment, including the disturbance of sulfidic sediments, which subsequently liberates

Mangrove habitats are renowned for their capacity to act as physical and biogeochemical barriers that hinder the transport of pollutants. The sediment in mangrove ecosystems plays a vital role as a primary reservoir for heavy metals, owing to its anaerobic and reducing conditions and its elevated levels of sulfide, organic matter, and iron (**Tam, 2006**).

The increasing presence of heavy metal pollutants has emerged as a growing concern in recent decades due to their persistent nature and detrimental effects on water and soil ecosystems (**Weis *et al.*, 2004; Huang *et al.*, 2011; Na *et al.*, 2013; Younis, 2020**). Typically, the release of contaminants into the environment is primarily attributed to untreated or inadequately treated industrial wastewater effluents, vehicle emissions, mining activities, and coal combustion (**Li *et al.*, 2009; Sun *et al.*, 2010; Hanafy *et al.*, 2021; El-Naggar *et al.*, 2021; Younis *et al.*, 2023**). Mangrove ecosystems, commonly found in estuaries or coastal areas, play a significant role in mitigating metal pollution by participating in the dispersion of pollutants within their biogeochemical cycles, facilitating their transfer between land and sea. The presence of mangroves has been observed to enhance metal accumulation in sediments by modifying soil acidity, redox potential, organic content, and salinity (**Zhou *et al.*, 2010; Sekomo *et al.*, 2011**). As a result, this process reduces metal exposure to the surrounding aquatic environment (**Nath *et al.*, 2013**). However, it is important to note that changes in soil physicochemical properties can potentially lead to the liberation and transfer of metals from sediments to water, altering the chemical speciation of metals and posing ecological and human health concerns (**Yu *et al.*, 2010; Li *et al.*, 2014; Younis *et al.*, 2019; Soliman *et al.*, 2020).**

To gain a comprehensive understanding of potential ecological hazards, the systematic and quantitative assessment of heavy metal contamination is crucial (**Soliman *et al.*, 2020**). Various assessment indices commonly employed in environmental research include the geo-accumulation index (Igeo), prospective ecological risk index (RI), risk assessment code (RAC), enrichment factors (EF), and mean probable effect level quotient (m-P-Q). These techniques are frequently used to assess heavy metal contamination in agricultural soils (**Gupta *et al.*, 2008**), urban soils **(Zhu *et al.*, 2013**), mining soils (**Huang *et al.*, 2013**), and lake sediments (**Yohannes *et al.*, 2013**). To advance our knowledge on this issue, it is essential to employ a combination of multiple evaluation approaches to comprehensively assess ecological risk (**Soliman *et al.*, 2020)**.

The objectives of this research are to determine the concentration and distribution of heavy metals in the sediment of the mangrove forest in Nabq Protectorate, Red Sea, and to assess the potential ecological risks associated with heavy metal contamination in the sediment-plant system of the mangrove forest. Additionally, the study aims to explore the influence of environmental factors on the distribution and mobility of heavy metals within the mangrove forest ecosystem.

MATERIALS AND METHODS

Study Area

The Nabq Protected Area's coastline sector in South Sinai, Egypt, was included in the study area (see Figure 1). Situated at coordinates 34.42730°E and 28.09110°N, the Nabq Managed Resource Protected Area is situated on the western shore of the Gulf of Aqaba. A semi-continuous fringing reef and four sizable sections of mangrove vegetation, dominated by *Avicennia marina*, are features of the 47-kilometer coastal region. There is a Bedouin resident community in Nabq, mainly concentrated in Nabq hamlet, which is located in ElGharkana. Fifteen sites were chosen to symbolize the ecosystems that are impacted by human activities.

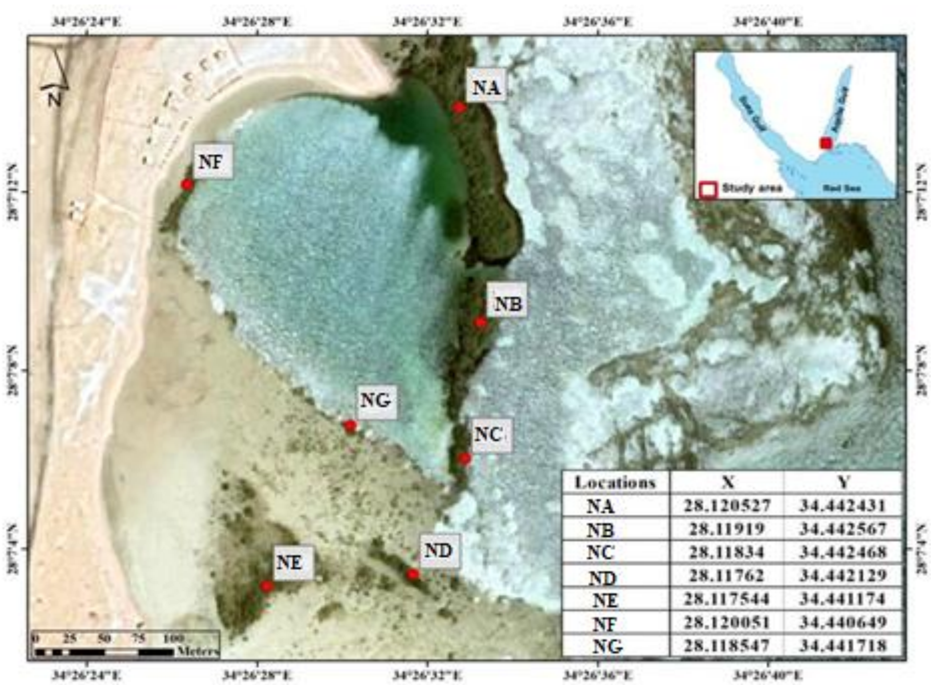

Figure 1: Nabq Protectorate map with sampling location indicated.

The Sinai Peninsula's shoreline, particularly the area close to the Gulf of Aqaba, is included in the Nabq Managed Resource Protected Area. The area has three physiographic zones, and they roughly parallel the shoreline. These zones include four major stands of the mangrove species *Avicennia marina* and the shallow marine zone, defined by bordering reef structures and shallow reef flats. Sand dunes' characteristic flora, gravel, and river sands fill the gently sloping coastal plain. The protected area's western region comprises South Sinai's steep-sided mountains stretching inland toward Mount Sinai and St. Katherine's. There are several Wadis, or riverbeds in this hilly area that flood periodically and then dry out again. Wadi Kid and Wadi Addawy, two bigger valleys, are formed by the convergence of these Wadis. The majority of wadis experience regular or sporadic flooding, which supplies sufficient moisture for the sporadic growth of scant vegetation. The vegetation here facilitates the grazing practices of scattered Bedouin animals, such as goats and camels. Furthermore, a small number of native species rely on this vegetation for grazing.

The Wadi Kid and Wadi Addawy discharge onto expansive alluvial fans that converge onto a coastal plain with a gentle seaward inclination of approximately 1 degree. This coastal plain, which is between 3 and 7 kilometers wide, was mostly developed in the Pleistocene era. Although **Hayward (1984)** previously believed these fan deltas to be inactive, recent developments within the past five years have challenged this assumption, with three documented instances of floods. The plain exhibits scattered and sporadically concentrated bands of salt-tolerant shrubs arranged in a distinct zonation pattern, similar to the successional zonation observed in drier salt marsh vegetation described by **Kassas (1957)**.

The research area experiences two primary sources of human-induced environmental stress. The first is attributed to the Bedouin community, which resides within the protected region. The second source of stress arises from tourists and recreational visitors who frequent the area for leisure purposes.

Sampling Procedures and Analysis

Based on field observations and the study area's water system map, a total of 16 sediment sampling sites were identified within the Nabq protectorate. These sites were distributed across seven sectors, as depicted on the map, each comprising multiple research sites. In sector NA, a single sample was collected from the mangrove sediment, representing station 1. In sector NB, another sample was collected from the mangrove sediments, representing station 2. Sector NC consisted of three samples collected from the mangrove sediments, salt marsh, and intertidal areas, representing stations 3, 4, and 5, respectively. Similarly, sector ND, NE, NF, and NG each had three samples collected from the corresponding habitats, representing stations 6-8, 9-11, 12-13, and 14-16, respectively. To ensure the representativeness of the collected samples, each sampling location was accurately determined using a portable Global Positioning System (GPS) device (Garmin 72, Lenexa, KS, USA).

Upon collection, the sediment samples were air-dried at room temperature and subsequently ground into a fine powder using an agate mortar. The estimation of total heavy metal amounts (Fe, Mn, Zn, Cu, Pb, and Cd) in the sediment samples followed the **UNEP/IAEA criteria (1986).** Approximately 0.5g of the dried sample was fully digested in Teflon containers using a 3:2:1 volumetric ratio of HNO_3, HF, and $HClO_4$. To ensure accuracy, two digestions were performed for each sample. The resulting solution was diluted to a volume of 25 milliliters using distilled de-ionized water. The digested solutions were analyzed thrice using an atomic absorption spectrophotometer (AAS Perkin Elmer analyzer, Model 100). The obtained values were recorded in micrograms per gram of dry weight.

To confirm the reliability and precision of the analysis, reference material (specifically SD-M-2/IM) was used. The analytical results of the quality control samples demonstrated satisfactory performance in identifying heavy metals falling within the permissible range of values. The investigated metals exhibited recovery rates ranging from 90.4% to 97.5%.

RESULTS AND DISCUSSION

Heavy Metal Distribution in Mangrove Sediments

The distribution and characteristics of heavy metals (Cu, Fe, Cd, Pb, Zn, and Mn) in the Mangrove sediments of Nabq protectorate in the Gulf of Aqaba are shown in Figure (2). The figure depicts the distribution and characteristics of heavy metals (Cu, Fe, Cd, Pb, Zn, and Mn) in the mangrove sediments of the Nabq Protectorate in the Gulf of Aqaba. The analysis reveals that at site 7, the copper (Cu) concentration reached its maximum value of 8.86 µg/g, while site 3 recorded the lowest concentration of 1.68 µg/g. The mean concentration was approximately 3.29 ± 1.78 µg/g. Comparing these values to reference standards, the sites in our study area are considered uncontaminated when compared to the mean crust (50 mg/kg) (**Bowen, 1979**), upper crust (25 mg/kg) (**Taylor and Mclennan, 1995**), and crustal average (55 mg/kg) (**Taylor, 1964**).

Iron (Fe) concentrations varied from 19.59 µg/g at site 13 to 224.1 µg/g at site 7. The average concentration was 67.96 ± 48.22 µg/g. The sediments in the research area exhibited lower Fe concentrations compared to the mean crust (**Bowen, 1979**), upper crust (**Taylor and Mclennan, 1995**), and crustal average (**Taylor, 1964**). Thus, it is inferred that the sediments along the Nabq Protectorate are relatively pure.

The concentrations of lead (Pb) exhibited variation, with a mean value of 13.57 ± 2.56 µg/g and a range of 10.6 µg/g at location (14) to 19.8 µg/g at location (7). In comparison to the upper crust (20 mg/kg) (**Taylor and Mclennan, 1995**) and average shale (20 mg/kg) (**Turekian and Wedepohl, 1961**), the surveyed areas are considered unpolluted. However, the mean lead content in the sediment (19 mg/kg) was lower than the lead content at the site (7) (**Salomons and Forstner, 1984**), indicating potential lead contamination in that specific location. One significant contributing factor to the elevated lead concentrations in this area could be the use of lead-contaminated fuel in yachting and marine transportation.

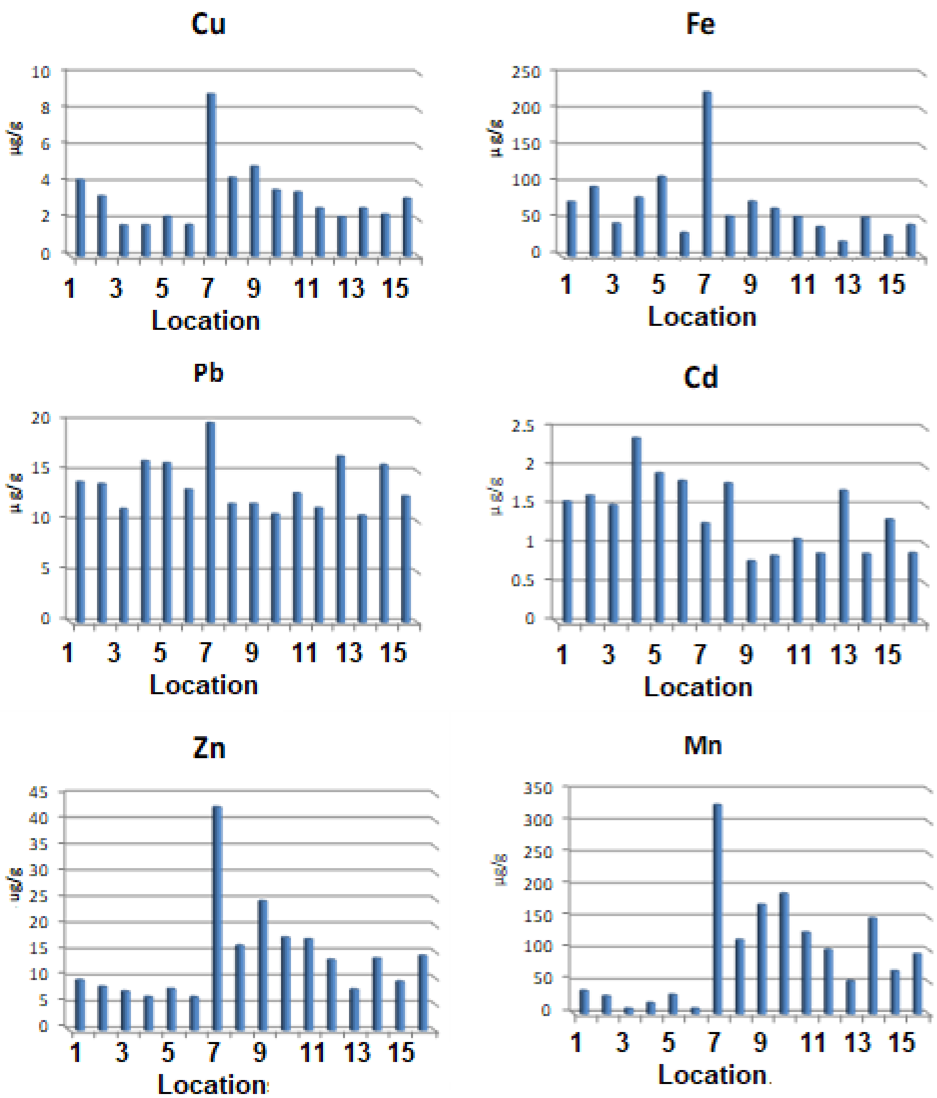

Figure 2. The distribution of heavy metals in the mangrove sediments of the Gulf of Aqaba's Nabq Protectorate.

The investigation revealed that the mean concentration of cadmium (Cd) was 1.38 ± 0.47 µg/g, with the highest concentration observed at the site (4) (2.37 µg/g) and the lowest at position (9) (0.78 µg/g). The presence of high levels of Cd in the sediments can be attributed to the terrigenous origin of the sediments and increased human activities near the position (4). These sediments in the Nabq protectorate at location (4) are considered polluted with Cd when compared to the crustal average (0.2 mg/kg) (**Taylor, 1964**), upper crust (0.098 mg/kg) **(Taylor and Mclennan, 1995**), mean crust (0.11 mg/kg)

(**Bowen, 1979**), average shale (0.3 mg/kg) (**Turekian and Wedepohl, 1961**), and the background concentrations of sediments.

Regarding zinc (Zn) concentration, the highest value of 42.51 µg/g was found at position (7), while the lowest value of 6.33 µg/g was observed at location (4), with a mean concentration of 13.91 ± 9.18 µg/g. Comparison with the crustal average (70 mg/kg) (**Taylor, 1964**), upper crust (71 mg/kg) (**Taylor and Mclennan, 1995**), mean crust (75 mg/kg) (Bowen, 1979), average shale (95 mg/kg) (**Turekian and Wedepohl, 1961**), mean sediment concentration (95 mg/kg) (**Salomons and Forstner, 1984**), and average continental crust (65 mg/kg) (**Hans Wedepohl, 1995**) indicated that the study area was not contaminated with zinc.

The distribution of manganese (Mn) in the study region showed a mean concentration of 94.78 ± 85.06 µg/g, with the highest concentration observed at position (7) (326.5 µg/g) and the lowest at site (3) (8.05 µg/g). In addition to the impact of flooding, which leads to the erosion of manganese from the area's mountains and rocks, the increase in human activity near the study area, especially in close proximity to human settlements, contributes to the elevated levels of manganese at location (7). The proximity of location No. 7 to residential areas within the study site, coupled with its close proximity to the torrent's mouth, presents a unique scientific setting. Notably, the torrent experiences a substantial influx of manganese during the rainy season, stemming from the surrounding geological formations and mountainous terrains.

Table 1. Mean, SD, Minimum, and Maximum of heavy metal concentrations (µg/g) in the study area.

Metals	Mean	± SD	Min	Max	CV	$TEL_{(a)}$	$PEL_{(a)}$
Cu	2.86	1.6	1.68	8.87	0.57	18.7	108.2
Fe	77.61	47.22	19.59	224	0.61	-	-
Pb	14	2.2	11	20	0.15	30.2	112
Cd	1.42	0.39	0.79	2.37	0.27	0.68	4.21
Zn	13.5	7.67	6.34	42.5	0.57	124	271
Mn	76	75	8.1	327	0.98	-	-

(a): **Canadian Council of Ministers of Environment (2002)**

Table 1 in this study presents the grouping of heavy metals in the mangrove sediments of the Nabq-protected area based on their mean values and standard deviations, as follows: Iron (77.61 µg/g ± 47.22) exhibited the highest concentration, followed by Mn (76 µg/g ± 75), Pb (14 µg/g ± 2.2), Zinc (14 µg/g ± 7.7), Cu (2.86 µg/g ± 1.6), and Cd (1.42 µg/g ± 0.39). The distribution ranges of these metals were as follows: Fe (19.59 - 224 µg/g), Mn

(8.1 - 327 µg/g), Pb (11 - 20 µg/g), Zn (6.34 - 42.5 µg/g), Cu (0.87 - 8.87 µg/g), and Cd (0.79 - 2.37 µg/g).

Table 2: Correlation matrix of investigated metals Mangrove deposits in the Nabq Protectorate, Gulf of Aqaba.

	Cu	**Fe**	**Pb**	**Cd**	**Zn**	**Mn**
Cu	1					
Fe	0.45562	1				
Pb	0.32759	0.51139	1			
Cd	-0.3188	0.03714	0.43878	1		
Zn	0.85986	0.50758	0.29993	-0.4382	1	
Mn	0.85027	0.38166	0.10639	-0.5785	0.86984	1

Table 2 displays the strong positive relationships between Zn, Cu, Mn, and Fe, while Pb demonstrates a weak positive correlation. Conversely, there is a negative correlation between Cd and the other metals. This suggests that, unlike cadmium, which has a distinct source, these elements are interconnected and likely originate from the same source.

Based on a comparative analysis with previous studies, the long-lasting presence of heavy metals such as Cd indicates ongoing pollution resulting from human activities. Various potential sources of this pollution have been identified, including mining and smelting operations, fuel processing and combustion activities, wood preservation practices, chemical production and application, as well as the improper disposal and incineration of municipal and industrial waste (**Popovic *et al.*, 2001; Wang and Mulligan, 2006**).

Quality Guidelines for Sediment (SQG)

Environmental contamination by heavy metals is a global concern due to their toxicity, long-lasting nature, and tendency to accumulate in organisms. These heavy metals can enter aquatic ecosystems from both natural and human activities, posing a significant risk **(Chon *et al.*, 2010).** Sediments, which retain historical information about water bodies and the impact of human activities, are more conservative than water and are commonly used as environmental indicators to track and monitor contamination sources. Sediments have the ability to accumulate trace amounts of heavy metals from water, integrating them over time (**de Vallejuelo *et al.*, 2010**).

Hazardous compounds can be absorbed by sediments or released from them, making sediment quality measurements crucial. In the past decade, several sediment quality guidelines (SQGs) have been developed **(MacDonald *et al.*, 2000; McCready and Birch, 2006)** to predict adverse biological effects in polluted sediments and protect aquatic organisms in and around sediments. These guidelines help assess regional variations in sediment contamination, categorize sediment contamination status, plan monitoring programs, analyze historical data, and guide future remedial actions **(MacDonald *et al.*, 2000).**

Sediment quality standards play a vital role in safeguarding aquatic biota from the harmful effects of sediment-bound contaminants **(McCready and Birch, 2006).** These guidelines evaluate the potential harm to aquatic life caused by the chemical condition of sediments, thereby assessing sediment quality. Furthermore, **Díaz-de *et al.* (2011)** prioritize and investigate regions of concern for toxicity.

SQGs are developed using various techniques, including effect-range, effect-level, and apparent effect-threshold methods. The selection of appropriate SQGs is crucial, as the derived values can significantly vary depending on the specific location's methodology, objective, and geological background (**MacDonald *et al.*, 2000**). In this study, the concentrations of Cd, Cu, and Pb in the mangrove sediments from the area of study were found to be lower than the Canadian sediment quality guidelines' (PEL) likely impact level and (TEL) threshold effect level, except for Cd, which exceeded the TEL value. Monitoring the distribution of heavy metals revealed that Cd levels were approaching the TEL limit, potentially impacting the environmental quality of the study area due to the development of recreational activities.

Assessment of pollution indices

Geo–accumulation Index (Igeo)

In the present study, the evaluation of heavy metal contamination in sediments includes the utilization of the geo-accumulation index (Igeo), a fundamental metric. The geo-accumulation index (Igeo), initially developed by Müller in 1969, serves as a means to identify and quantify metal pollution in sediments. The formula for the geo-accumulation index (Igeo) is as follows:

$$Igeo = Log^2 \frac{Cn}{1.5 * B_n}$$

where Bn represents the geochemical background concentration of the specific metal (n), and Cn denotes the observed concentration of the examined metal (n) in the sediment **(Turekian and Wedepohl, 1961).** The adjustment factor of 1.5 is incorporated to account for lithological variations in the background matrix. The baseline concentrations of the metals align with those determined for the enrichment factor. Similar to the metal enrichment factor, the geo-accumulation index (Igeo) serves as a valuable tool for assessing the extent of metal contamination **(Zhang *et al.*, 2009).**

Müller has categorized the geo-accumulation index (Igeo) into seven classes, ranging from Class 0 (Igeo = 0) to Class 6 (Igeo > 5) as shown in Table 3. The geo-accumulation index (Igeo) is associated with a qualitative scale of pollution intensity, with Class 6 indicating a minimum 100-fold increase in enrichment compared to the background values presented in Table 3.

Table 3. Geo–accumulation Index (Igeo) according to **Muller 1969.**

I_{geo} value	I_{geo} class	Pollution level
≤ 0	0	Unpolluted
0 – 1	1	Unpolluted to moderately polluted
1 – 2	2	Moderately polluted
2 – 3	3	Moderately polluted to highly polluted
3 – 4	4	Highly polluted
4 – 5	5	Highly polluted to very highly polluted
> 5	6	Very highly polluted

Table 5 presents the calculated values of the geo-accumulation index (Igeo). The accompanying graph clearly illustrates that the Igeo values for Cu, Pb, Cd, Zn, and Mn at all sampling sites fall within the "1" class, indicating that these metals either do not contribute to pollution or only cause mild pollution. Among the sampling sites, location (7) in Nabq Protectorate exhibited the highest Igeo values for Mn, Cu, and Zn were determined to be 0.97, 0.741, and 0.72, respectively. Although these values suggest some level of metal contamination, they still fall within Class 1 (unpolluted to moderately polluted), indicating a relatively low pollution intensity at these sites.

Table 4. Igeo values of the metals in the mangrove sediments in the Nabq protectorate

Location	Cu	Pb	Cd	Zn	Mn
1	0.350	0.210	0.215	0.164	0.108
2	0.275	0.207	0.225	0.142	0.083
3	0.141	0.170	0.208	0.127	0.024
4	0.142	0.242	0.328	0.109	0.051
5	0.181	0.238	0.265	0.135	0.089
6	0.143	0.199	0.251	0.108	0.025
7	0.742	0.299	0.175	0.727	0.978
8	0.359	0.177	0.247	0.276	0.347
9	0.410	0.177	0.109	0.421	0.511
10	0.302	0.162	0.117	0.302	0.563
11	0.293	0.193	0.016	0.297	0.381
12	0.219	0.171	0.013	0.230	0.300
13	0.179	0.249	0.026	0.133	0.153
14	0.219	0.160	0.013	0.234	0.448
15	0.190	0.236	0.020	0.159	0.001
16	0.264	0.189	0.013	0.243	0.001

Metal pollution index (MPI)

To facilitate the comparison of overall metal content across different locations, the Metal Pollution Index (MPI) serves as a mathematical model that condenses the results of metal concentrations into a single value. The formula used to calculate the MPI is as follows:

MPI = $(Cf1 * Cf2 ******* Cfk)^{(1/k)}$ as stated by **Teodorovic *et al.* (2000).**

Here, Cf1 represents the concentration value of the first metal, Cf2 represents the concentration value of the second metal, and Cfk represents the concentration value of the k metal.

Furthermore, the Pollution Load Index (PLI) for metals, as determined by **Tomlinson *et al.* (1980)** and **Harikumar *et al.* (2009),** is another metric utilized in the assessment. When the PLI value is greater than 1, it indicates the presence of pollution, while a value less than 1 suggests the absence of pollution.

In the context of this study, the evaluation of MPI results reveals that values exceeding one were more prevalent in the sampling locations within the Nabq regions. Locations 1, 7, 8, 9, 10, and 11 exhibit MPI values greater than 1. Figure 3 visually represents these findings, suggesting the current burden of metal contamination based on the study's conclusions.

Except for the specific sites mentioned, which exhibited significant contamination in the mangrove sediment, these data, in accordance with **Hakanson's (1980)** assessment, indicate a low level of pollution. A previous study conducted in the Port Klang area, focusing on surface sediment, revealed that shipyards, marinas, and heavy metals significantly influenced the release and leaching of protective paint from the port vicinity **(Haris and Aris, 2015)**. This finding suggests that these metals are readily absorbed by sediment particles. Additionally, the river's main channel receives sediments from surrounding streams, along with solid waste discharged by the local population (**Patel *et al.*, 2017**).

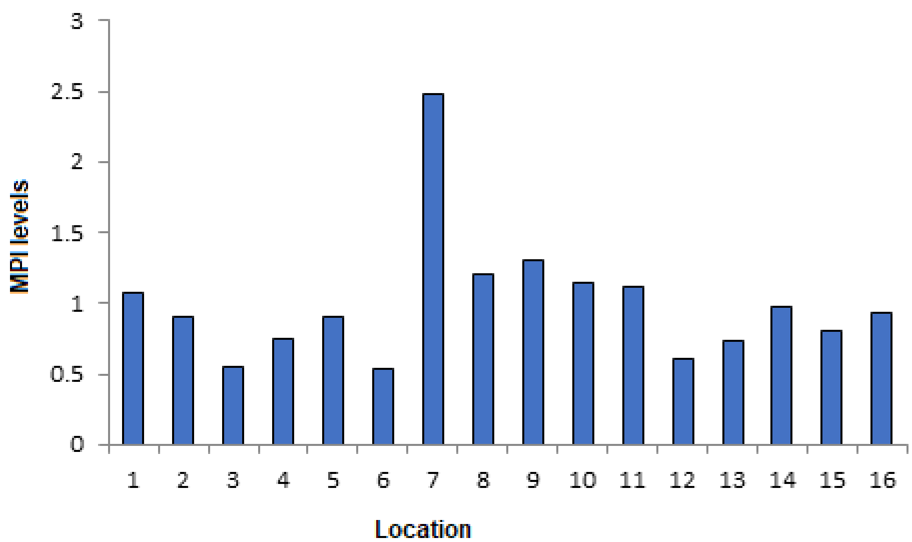

Figure 3. Sediment quality assessment utilizing multi-element indices (MPI: modified pollution index) for the Nabq protectorate.

Potential Ecological Risk Index (PERI)

In order to assess the potential dangers posed by the metals, **Hakanson (1980)** developed the potential ecological risk index (PERI). This risk index aims to evaluate the ecological health risks associated with introducing pollutants that may eventually enter the food chain. The PERI is calculated by considering both the combined effects of the metals and the potential ecological risk coefficient of each individual metal, utilizing the following formula.

$$PERI = \sum_{i=1}^{n} E_r^i$$

To establish background levels of sedimentary metals in the current study, the average shale background concentrations of global sediments **(Turekian and Wedepohl, 1961)** were employed due to the absence of relevant background data specific to the analyzed location.

Hakanson (1980) classified the PERI into four categories: low ecological risk (PERI < 150), moderate ecological risk (150 < PERI < 300), high ecological risk (300 < PERI < 600), and very high ecological risk (PERI ≥ 600). Similarly, the potential ecological risk index for each individual element was categorized as high risk (160 < $\boldsymbol{Ei}$r < 320), extremely high risk ($\boldsymbol{Ei}$r > 320), moderate risk (40 < $\boldsymbol{Ei}$r < 80), low risk ($\boldsymbol{Ei}$r < 40), or considerable danger (80 < $\boldsymbol{Ei}$r < 160).

Figure 4 displays the results of estimating the potential ecological PERI for sediment samples obtained from the research region. Among the locations in the Nabq area, the highest PERI value was 60.63 at location (7), whereas the lowest was 30.48 at location (12).

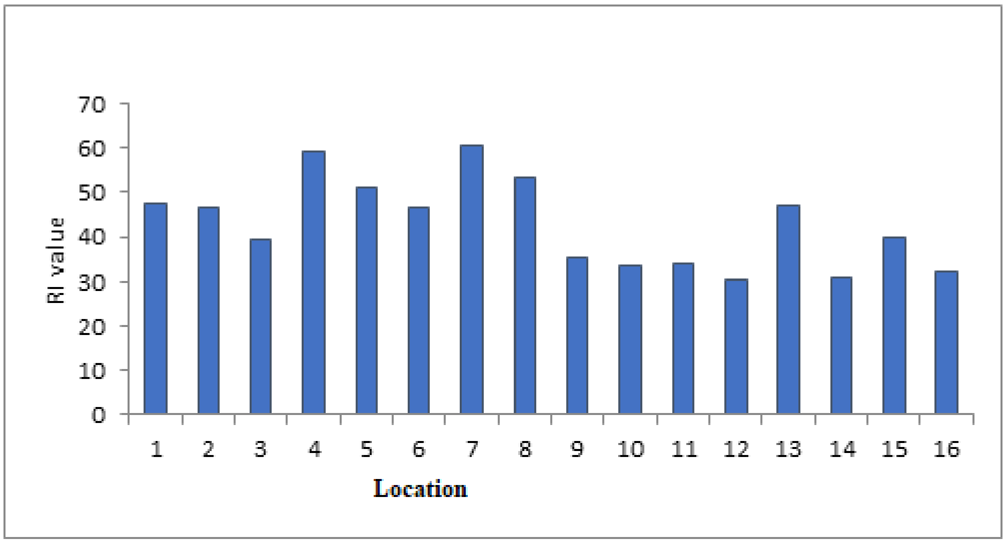

Figure 4. Potential ecological risk index (PERI) of heavy metals in Nabq protectorate sediments.

The elevated PERI value observed at locations (7) in Nabq may be attributed to higher concentrations of heavy metals. The observed results can be attributed to the heightened anthropogenic impact in the vicinity of Site 7, particularly in close proximity to human settlements. This factor significantly contributes to the escalated concentrations of heavy metal pollutants within the study area, setting it apart from other sites under investigation. Nonetheless, **Hakanson (1980)** concluded that according to the PERI results, all sites presented a minimal ecological risk (PERI < 150). Therefore, every test conducted indicated a low ecological risk, as the results were below 150. However, it is highly recommended to maintain continuous monitoring of this site. Such monitoring will provide valuable insights to the relevant authorities, enabling them to concentrate their efforts on safeguarding this ecosystem.

Potential ecological risk factors (Eri)

The total ecological risk associated with the presence of heavy metals at each site was assessed using the potential ecological risk factors (Eri) developed by **Hakanson** in **1980**. The following formulas can be utilized to calculate the ERI:

$$C_f^i = C_i / C_n^i$$

$$E_r^i = T_r^i / C_f^i$$

$$ERI = \sum_{i=1}^{n} E_r^i$$

In these formulas, Cfi represents the contamination factor of individual heavy metal i, Ci represents the tested content of heavy metal i in the sediment sample, and Cni represents the background value of heavy metal i. Eri represents the toxicity coefficient and ecological risk index for a single heavy metal, while Tri denotes the biological sensitivity and toxicity of metal i. The ERI index portrays the ecological risk posed by a combination of multiple heavy metals at a specific location, revealing the vulnerability of biological communities to hazardous compounds **(Hakanson, 1980).**

Figure 5 depicts the potential ecological risk factors (Eri) associated with each heavy metal in the studied sediment area. Across all metals, the $\boldsymbol{Ei}$r values at Nabq sampling locations were below 40. According to **Hakanson (1980)**, these metals posed a moderate ecological risk within the examined area. The exception was Cd at site 4, which exhibited a higher value of 48.96. The average potential ecological risk factor coefficient ($\boldsymbol{Ei}$r) for each metal examined in the research area followed the following order: Cd > Cu > Pb > Zn > Mn.

According to Hakanson's classification system established in 1980, metal concentrations below 95 indicate a metal-free condition within the research region. However, **Liu *et al.* (2014)** discovered significant or moderate ecological concerns related to silt in China's mangrove ecosystems. In contrast, **Li *et al.* (2016)** conducted a separate study and revealed that the ERI values of sediments in the Futian mangrove ecosystems consistently exceeded 600, indicating an extremely high ecological risk.

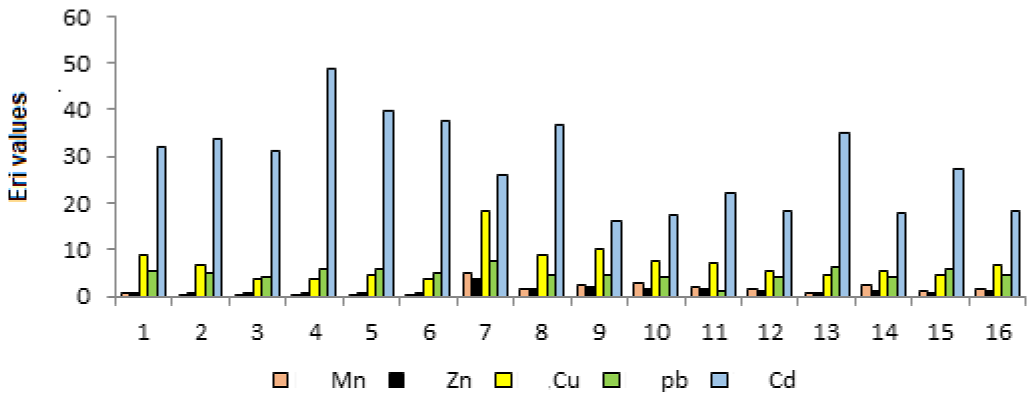

Figure 5. Heavy metals' ecological risk index factor value in Nabq (Eri)

Toxic Unit (TU)

In accordance with **MacDonald *et al.* (1996)**, the sediment Toxicity Unit (TU) was calculated by dividing the observed concentration of heavy metals (HMs) by the probable effect level (PEL). The cumulative TU values represent the potential acute toxicity of HMs in the sediment, providing an estimate of their potential harmful effects.
The total toxic unit (∑ TU) is calculated using the formula proposed by **Pedersen *et al.* (1998)**, where PELn represents the probable effect level value of each heavy metal: $\sum TU = \sum(C_n/PEL_n)$. The values reported by **MacDonald *et al.* (1996)** are as follows: Cd = 4.21 µg/g, Cu = 108.2 µg/g, Zn = 271 µg/g, Pb = 112.18 µg/g, Ni = 42.8 µg/g, and Cr = 160 µg/g.

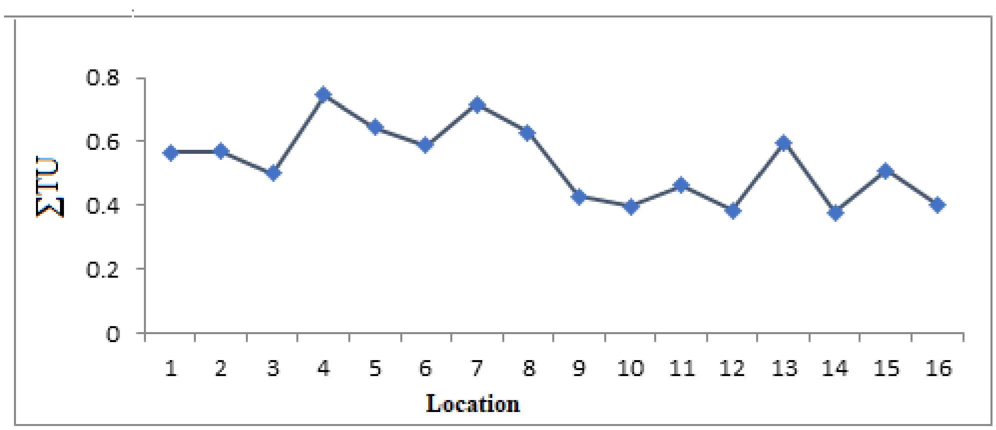

Figure 6. Toxic Unit (∑TU) for metals at various locations along the Nabq protectorate

Based on **Longe *et al.* (1998)** sediment quality criterion, the PEL represents the concentration at which adverse impacts are likely to occur. The ∑TU values for the sediment in the study area ranged from 0.5 to 0.61 (Figure 7), considering the concentrations of Cu, Pb, Cd, and Zn, as illustrated in Figure 6.

Comparing the average percentage contributions of each metal to potential acute toxicity in the Nabq protectorate area (Figure 6), the typical percentages of metal contributions to possible acute toxicity are: Cd (60.8%) > Pb (23.9%) > Zn (10%) > Cu (5.8%).
According to **Pedersen *et al.* (1998),** these findings indicate that no metals in the study area pose a potential hazard to aquatic life, as the TU values at all locations are below 4. Based on the criteria of ∑TU proposed by **Pedersen *et al.* (1998),** heavy metals with a ∑TU value of >4 in the research area indicate a relatively low ecological risk posed by heavy metals.

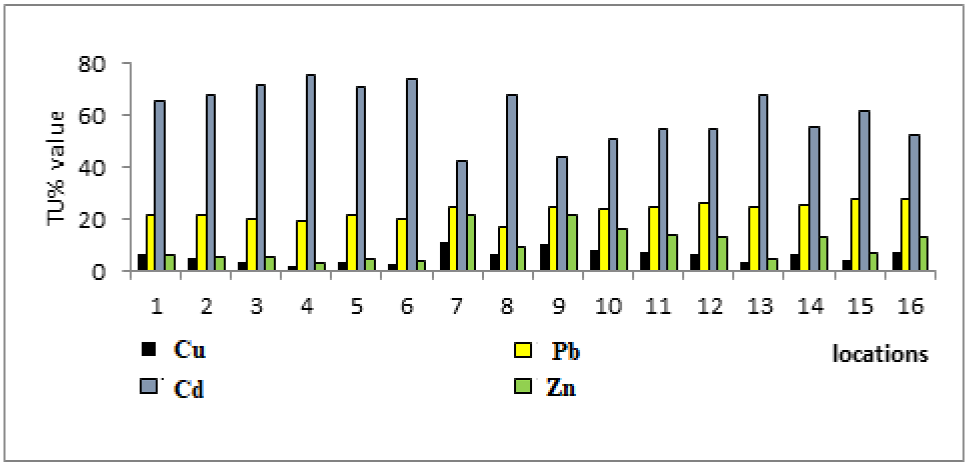

Figure **7.** Toxic Unit (TU %) value for metals at various locations along the Nabq protectorate

CONCLUSION

In conclusion, this study examined the distribution and characteristics of heavy metals (Cu, Fe, Cd, Pb, Zn, and Mn) in mangrove sediments of the Nabq Protectorate in the Gulf of Aqaba. Varying concentrations of these metals were observed across different sampling sites. Overall, the sediments were relatively uncontaminated compared to reference standards and background concentrations. Comparison with reference standards and background concentrations indicated relative purity of the sediments for most heavy metals. However, elevated lead concentrations were detected at site 7, possibly due to the use of lead-contaminated fuel in yachting and marine transportation. Cadmium pollution was observed at site 4, attributed to the terrigenous origin of the sediments and increased human activities in the vicinity. Strong positive correlations among zinc (Zn), copper (Cu), manganese (Mn), and iron (Fe) suggested a common source for these metals, while a negative correlation between cadmium (Cd) and the other metals indicated a distinct source for cadmium pollution.

Based on the geo-accumulation index (Igeo), the study area was classified as unpolluted to moderately polluted for copper (Cu), lead (Pb), cadmium (Cd), zinc (Zn), and manganese (Mn). The potential ecological risk index (PERI) indicated a low ecological risk for all sampling sites except for location 7, which exhibited a higher PERI value due to elevated heavy metal concentrations. The assessment of potential ecological risk factors (Eri) revealed a moderate ecological risk associated with heavy metals, with cadmium (Cd) posing the highest risk.

The mangrove sediments in the Nabq Protectorate of the Gulf of Aqaba showed relatively low levels of heavy metal contamination, except for specific locations with elevated lead (Pb) and cadmium (Cd) concentrations. Continuous monitoring of the area is recommended to ensure the preservation and safeguarding of the ecosystem. These findings contribute to the understanding of heavy metal pollution in mangrove sediments and provide valuable insights for environmental management and conservation efforts in the study area.

REFERENCES

Alongi, D. (2009). The energetics of mangrove forests. Springer Science & Business Media.

Bowen, H. J. M. (1979). Environmental chemistry of the elements, Academic Press.: London, UK: 333.

Chon, H.S.; Ohandja, D.G.; Voulvoulis, N. and Implementation of EU. (2010). Water Framework Directive: source assessment of metallic substances at catchment levels. J. Environ. Monit. 12: 36-47.

de Vallejuelo, S. F.-O.; Arana, G.; de Diego, A.; Madariaga, and Risk, J. M. (2010). Assessment of trace elements in sediments: the case of the estuary of the Nerbioi–Ibaizabal River (Basque Country). J. Hazard. Mater. 181: 565-573.

Díaz-de Alba, M.; Galindo-Riano, M.; Casanueva- Marenco, M.; García-Vargas, M. and Kosore, C. (2011). Assessment of the metal pollution, potential toxicity and speciation of sediment from Algeciras Bay (South of Spain) using chemometric tools. J. Hazard. Mater. 190: 177-187.

Elnaggar, D. H.; Mohamedein, L. I.; and Younis, A. M. (2022). Risk assessment of heavy metals in mangrove trees (Avicennia marina) and associated sea water of Ras Mohammed Protectorate, Red Sea, Egypt. *Egyptian Journal of Aquatic Biology & Fisheries*, *26*(5).

El-Naggar, M.; Hanafy, S.; Younis, A.M.; Ghandour, M.A. and El-Sayed, A.A.Y. (2021). Seasonal and temporal influence on polycyclic aromatic hydrocarbons in the Red Sea coastal water, Egypt. *Sustainability*, *13*(21), p.11906.

Giblin, A. E.; Bourg, A.; Valiela, I. and Teal, J. M. (1980). Uptake and losses of heavy metals in sewage sludge by a New England salt marsh. *American Journal of Botany*, *67*(7): 1059-1068.

Gupta, S.; Nayek, S.; Saha, R. N. and Satpati, S. (2008). Assessment of heavy metal accumulation in macrophyte, agricultural soil, and crop plants adjacent to discharge zone of sponge iron factory. *Environmental geology*, *55*, 731-739.

Hakanson, L. (1980). An ecological risk index for aquatic pollution control. A sedimentological approach. *Water research*, *14*(8), 975-1001.

Hanafy, S.; Younis, A.M.; El-Sayed, A.Y. and Ghandour, M.A. (2021). Spatial, seasonal distribution and ecological risk assessment of Zn, Cr, and Ni in Red Sea surface sediments, Egypt. *Egyptian Journal of Aquatic Biology & Fisheries*, *25*(4).

Hans Wedepohl, K. (1995). The composition of the continental crust. Geochim. Cosmochim. Acta 59: 1217-1232.

Harikumar, P.S.; Nasir U.P. and Mujeebu, R.M.P. (2009). Distribution of heavy metals in the core sediments of a tropical wetland system. Int. J. Environ. Sci. Technol., 6(2): 225-232. http://doi.org/ 10.1007/BF03327626

Haris, H. and Aris, A. Z. (2015). Distribution of metals and quality of intertidal surface sediment near commercial ports and estuaries of urbanized rivers in Port Klang, Malaysia. *Environmental earth sciences*, *73*: 7205-7218.

Hayward, A. B. (1981). Coastal alluvial fans (fan deltas) of the Gulf of Aqaba, Red Sea *Sedimentary Geology*. 43: 241-260.

Huang, H.; Yuan, X.; Zeng, G.; Zhu, H.; Li, H.; Liu, Z. and Bi, W. (2011). Quantitative evaluation of heavy metals' pollution hazards in liquefaction residues of sewage sludge. *Bioresource Technology*, *102*(22): 10346-10351.

Huang, X.; Zhu, Y. and Ji, H. (2013). Distribution, speciation, and risk assessment of selected metals in the gold and iron mine soils of the catchment area of Miyun Reservoir, Beijing, China. *Environmental monitoring and assessment*, *185*: 8525-8545.

Kassas, M. (1957). On the Ecology of the Red Sea coastal land. 1. Ecol. 45: 187-203.

LEWIS, J. B. (1977). Processes of organic production on coral reefs. *Biological Reviews*, *52*(3): 305-347.

Lewis, M.; Pryor, R. and Wilking, L. (2011). Fate and effects of anthropogenic chemicals in mangrove ecosystems: a review. *Environmental pollution*, *159*(10): 2328-2346.

Li, C.; Lu, F. Y.; Zhang, Y.; Liu, T. W. and Hou, W. (2008). Spatial distribution characteristics of heavy metals in street dust in Shenyang city. *Ecol Environ*, *17*(2): 560-564.

Li, L.; Wu, H.; van Gestel, C. A.; Peijnenburg, W. J. and Allen, H. E. (2014). Soil acidification increases metal extractability and bioavailability in old orchard soils of Northeast Jiaodong Peninsula in China. *Environmental Pollution*, *188:* 144-152.

Li, R.; Chai, M. and Qiu, G. Y. (2016). Distribution, fraction, and ecological assessment of heavy metals in sediment-plant system in mangrove forest, South China Sea. *PloS one*, *11*(1), e0147308.

Lin, P. and Wang, W. Q. (2001). Changes in the leaf composition, leaf mass and leaf area during leaf senescence in three species of mangroves. *Ecological Engineering*, *16*(3), 415-424.

Liu, J.; Wu, H.; Feng, J.; Li, Z. and Lin, G. (2014). Heavy metal contamination and ecological risk assessments in the sediments and zoobenthos of selected mangrove ecosystems, South China. *Catena*, *119*: 136-142.

Long, E. R.; Field, L. J. and MacDonald, D. D. (1998). Predicting toxicity in marine sediments with numerical sediment quality guidelines. *Environmental Toxicology and Chemistry: An International Journal*, *17*(4): 714-727.

MacDonald, D. D.; Ingersoll, C. G.; Berger, T. A. (2000). Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. Arch. Environ. Contam. Toxicol. 39: 20-31.

Maiti, S. K. and Chowdhury, A. (2013). Effects of anthropogenic pollution on mangrove biodiversity: a review. Journal of Environmental Protection, 4: 1428-1434.

McCready, S.; Birch, G. F.; and Long, E. R. (2006). Metallic and organic contaminants in sediments of Sydney Harbour, Australia and vicinity — A chemical dataset for evaluating sediment quality guidelines. Environ. Int. 32: 455-465.

Mona, M. H.; El-Naggar, H. A.; El-Gayar, E. E.; Masood, M. F. and Mohamed, E. S. N. (2019). Effect of human activities on biodiversity in nabq protected area, south sinai, Egypt. *The Egyptian Journal of Aquatic Research*, *45*(1): 33-43.

Muller, G. (1969). Index of geoaccumulation in sediments of the Rhine River. Geojournal, 2: 108-118.

Na, G.; Fang, X.; Cai, Y.; Ge, L.; Zong, H.; Yuan, X. and Zhang, Z. (2013). Occurrence, distribution, and bioaccumulation of antibiotics in coastal environment of Dalian, China. *Marine pollution bulletin*, *69*(1-2): 233-237.

Nath, B.; Birch, G. and Chaudhuri, P. (2013). Trace metal biogeochemistry in mangrove ecosystems: a comparative assessment of acidified (by acid sulfate soils) and non-acidified sites. *Science of the Total Environment*, *463*: 667-674.

Ogden, J. C. and Gladfelter, E. H. (Eds.). (1983). *Coral Reefs, Seagrass Beds and Mangroves: Their Interaction in the Coastal Zones of the Caribbean: Report of a Workshop*. Unesco .

Patel, P.; Raju, N. J.; Reddy, B. S. R.; Suresh, U.; Sankar, D. B. and Reddy, T. V. K. (2018). Heavy metal contamination in river water and sediments of the Swarnamukhi River Basin, India: risk assessment and environmental implications. *Environmental geochemistry and health*, *40:* 609-623.

Pedersen, F.; Bjørnestad, E.; Andersen, H. V.; Kjølholt, J. and Poll, C. (1998). Characterization of sediments from Copenhagen Harbour by use of biotests. *Water Science and Technology*, *37*(6-7): 233-240.

Popovic, A.; Djordjevic, D. and Polic, P. (2001). Trace and major element pollution originating from coal ash suspension and transport processes. *Environment International*, *26*(4): 251-255.

Popovic, A.; Djordjevic, D. and Polic, P. (2001). Trace and major element pollution originating from coal ash suspension and transport processes. *Environment International*, *26*(4): 251-255.

Salm R.V. (1983). *Managing Coastal and Marine Protected Areas.* IUCN Commission on National Parks and Protected Areas, IUCN.

Salomons, W.; Förstner, U.; Salomons, W. and Förstner, U. (1984). Sediments and the transport of metals. *Metals in the Hydrocycle,* 63-98.

Sekomo, C. B.; Nkuranga, E.; Rousseau, D. P. and Lens, P. N. (2011). Fate of heavy metals in an urban natural wetland: the Nyabugogo Swamp (Rwanda). *Water, Air, & Soil Pollution, 214:* 321-333.

Soliman, N.; Elkady, E. M. and M Younis, A. (2020). Chemical fractions and ecological risk of metals in sediments of the Bitter Lakes, Egypt. *Egyptian Journal of Aquatic Biology and Fisheries*, *24*(6): 167-196.

Sun, Y.; Zhou, Q.; Xie, X. and Liu, R. (2010). Spatial, sources and risk assessment of heavy metal contamination of urban soils in typical regions of Shenyang, China. *Journal of hazardous materials*, *174*(1-3): 455-462.

Taher, N.Z.; Shabaka; Yosry A. Soliman and Younis, A. M. (2023). Assessment of microplastic pollution in the Gulf of Suez: Abundance and polymeric composition in beach sediments. *Egyptian Journal of Aquatic Biology & Fisheries*, *27*(4).

Tam, N. F. (2006). Pollution studies on mangroves in Hong Kong and Mainland China. In *The environment in Asia Pacific harbours* (pp. 147-163). Dordrecht: Springer Netherlands.

Taylor, S. R. (1964). Abundance of chemical elements in the continental crust: a new table. Geochim. Cosmochim. Acta 1964, 28: 1273-1285.

Taylor, S. R. and McLennan, S. M. (1995)**.** The geochemical evolution of the continental crust. Rev. Geophys. 1995, 33: 241-265.

Teodorovic, I.; Djukic, N.; Maletin, S.; Miljanovic, B. and Jugovac, N. (2000). Metal pollution index: Proposal for freshwater monitoring based on trace metal accumulation in fish. Tiscia, 32: 55– 60.

Tomlinson, D. L.; Wilson, J. G.; Harris, C. R. and Jeffrey, D. W. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer meeresuntersuchungen*, *33:* 566-575.

Turekian, K. K. and Wedepohl, K. H. (1961). Distribution of the elements in some major units of the earth's crust. Geol. Soc. Am. Bull. 72: 175-192.

UNEP/IAEA. (1986). Reference Methods for Marine Pollution Studies, Athens.

Wang, M.; Huang, Z.; Shi, F. and Wang, W. (2009)**.** Are vegetated areas of mangroves attractive to juvenile and small fish? The case of Dongzhaigang Bay, Hainan Island, China. *Estuarine, Coastal and Shelf Science*, *85*(2): 208-216.

Wang, S. and Mulligan, C. N. (2006). Occurrence of arsenic contamination in Canada: sources, behavior and distribution. *Science of the total Environment*, *366*(2-3): 701-721.

Weis, J. S. and Weis, P. (2004). Metal uptake, transport and release by wetland plants: implications for phytoremediation and restoration. *Environment international*, *30*(5): 685-700.

Yohannes, Y. B.; Ikenaka, Y.; Saengtienchai, A.; Watanabe, K. P.; Nakayama, S. M. and Ishizuka, M. (2013). Occurrence, distribution, and ecological risk assessment of DDTs and heavy metals in surface sediments from Lake Awassa—Ethiopian Rift Valley Lake. *Environmental Science and Pollution Research*, *20:* 8663-8671.

Younis, A.; Aly-Eldeen, M. and M Elkady, E. (2019). Effect of different molecular weights of chitosan on the removal efficiencies of heavy metals from contaminated water. Egyptian Journal of Aquatic Biology and Fisheries, 23(4): 149-158.

Younis, A.M. (2019). Environmental Impacts on Egyptian Delta Lakes' Biodiversity: A Case Study on Lake Burullus. In: "Coastal Lakes and Wetlands: Part II:

Climate Change and Biodiversity." Negm, A.M.; Bek, M.A. and Abdel-Fattah, S. (Eds.). Handbook of Environmental Chemistry, 72: 107-128.

Younis, A.M. (2020). Accumulation and rate of degradation of organotin compounds in coastal sediments along the Red Sea, Egypt. *Egyptian Journal of Aquatic Biology and Fisheries*, *24*(5): 413-436.

Y**ounis, A.M.; Hanafy, S.; Elkady, E.M.; Ghandour, M.A.; El-Sayed, A.A.Y. and Alminderej, F.M.** (2023). Polycyclic aromatic hydrocarbons (PAHs) in Egyptian red sea sediments: Seasonal distribution, source Identification, and toxicological risk assessment. *Arabian Journal of Chemistry*, *16*(9): 104999.

Younis, A.M.; Soliman, N.F.; Elkady, E.M. and Mohamedein, L.I. (2022). Distribution and ecological risk evaluation of bioavailable phosphorus in sediments of El Temsah Lake, Suez Canal, Oceanologia, 64(2): 287–298

Yu, R., Hu, G. and Wang, L. (2010). Speciation and ecological risk of heavy metals in intertidal sediments of Quanzhou Bay, China. *Environmental monitoring and assessment*, *163*: 241-252.

Zhang, W.; Feng, H.; Chang, J.; Qu, J.; Xie, H. and Yu, L. (2009). Heavy metal contamination in surface sediments of Yangtze River intertidal zone: An assessment from different indexes. Environ. Pollut. 157: 1533-1543.

Zhou, Y. W.; Zhao, B.; Peng, Y. S. and Chen, G. Z. (2010). Influence of mangrove reforestation on heavy metal accumulation and speciation in intertidal sediments. *Marine Pollution Bulletin*, *60*(8): 1319-1324.

Zhu, X.; Ji, H.; Chen, Y.; Qiao, M. and Tang, L. (2013). Assessment and sources of heavy metals in surface sediments of Miyun Reservoir, Beijing. *Environmental monitoring and assessment*, *185:* 6049-6062.