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Anthropogenic Heavy Metal Pollution in Nuweibaa, Gulf of Aqaba, Egypt: A Threat to Marine Environment and Water Quality

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ABSTRACT

The contamination of heavy metals (Fe, Zn, Pb, Cu, Mn, Ni, Cd, and Co) in collected water and sediment samples from Nuweibaa, Red Sea, proper was studied to evaluate their distribution. The concentration of studied metals in water decreased in the following order: Fe (16.49)> Zn (8.92)> Cu (1.11)> Pb (0.95)> Ni (0.84)> Co (0.34)> Mn (0.22)> Cd (0.19) µg/l, while in sediments the order follows: Fe (11765.31)> Mn (265.73)> Zn (87.90)> Ni (40.47)> Pb (45.39)> Co (29.14)> Cd (3.62)> Cu (7.93) µg/L. The results showed that metal concentrations in sediment exceeded the permissible limits in the earth's crust. However, in seawater, the metal concentrations are within the allowable limits. The sediment's carbonate (CaCO3) concentration varies between 9.13 - 75.8 %. The partition coefficient values revealed that sediment is the final fate of the heavy metals. Igeo results showed very high to substantial contamination for Cd (5.84) and Ni (2.78), respectively, while other metals ranged between (0 - 1), suggesting uncontaminated to mild contamination. The enrichment factor (EF) in sediments for Cd, Ni, and Co suggested they originated anthropogenic (EF> 2.0), whereas, for Fe, Mn, Zn, Pb, and Cu, they may be natural. Finally, CPI results revealed a higher metal concentration in sediments. This study concluded that strict laws should be applied to protect this area from pollution due to various human activities and to use sources in Nuweibaa.

INTRODUCTION

Egypt's beaches along the Red Sea coast have suffered due to the country's rapid industrial and commercial Development in recent years. Nuweibaa is a coastal town in the eastern part of the Sinai Peninsula, Egypt, located on the coast of the Gulf of Aqaba. (**Moufaddal and Rifaat 2006**). Because it is essential for transferring, complexing, and depositing elements, coastal sediment is a significant sink for heavy metals in the marine environment. Additionally, it is thought that coastal sediments are an indirect source and means of transportation for heavy metals found in the water (**Gopal *et al.*, 2021**). Augmenting human-made activities in the area caused elevated metal levels in sediments, posing a threat to ecosystems and human health. This study aims to determine metal concentrations and contamination levels in Nuweibaa's coastal sediments and how human activities affect water quality and sediments. This will be done using quantitative methods, pollution indices, similar geo-accumulation indices, and enrichment factors (**MacDonald *et al*., 2000 and Feng *et al*., 2011**). The findings will provide crucial information on the magnitude of metal contamination in Nuweibaa and contribute to developing effective pollution control strategies. Overall, the investigations aimed to build on the limited research (**Soliman *et al*., 2010; Hamed *et al*., 2012; Elgendy *et al*., 2018a, 2018b; Dar *et al*., 2021; El-Menhawey *et al*., 2021 and Nasr *et al*., 2021**) on contamination of metal in the Red Sea and provide a reference for future environmental monitoring and management.

MATERIALS AND METHODS

The Gulf of Aqaba is located at Lat. 28° N long. 24° 23' E, and at Lat. 29° 33' N, long 35° 0' E, is 180-kilometer-long, 20-kilometer-wide, and 800-meter-deep. Many towns with various human activities are situated along the Gulf of Aqaba; among these regions is Nuweibaa (on the western side of the Gulf of Aqaba), which is affected by various human activities and strategic industries, resulting in the influence of the marine environment in front of the city. The investigated area is influenced by anthropogenic activities such as tourism and ship transformation in Nuweibaa port, wherein several car ferries run daily in Jordan **(Mohamedein *et al*., 2023)** (Figure 1).

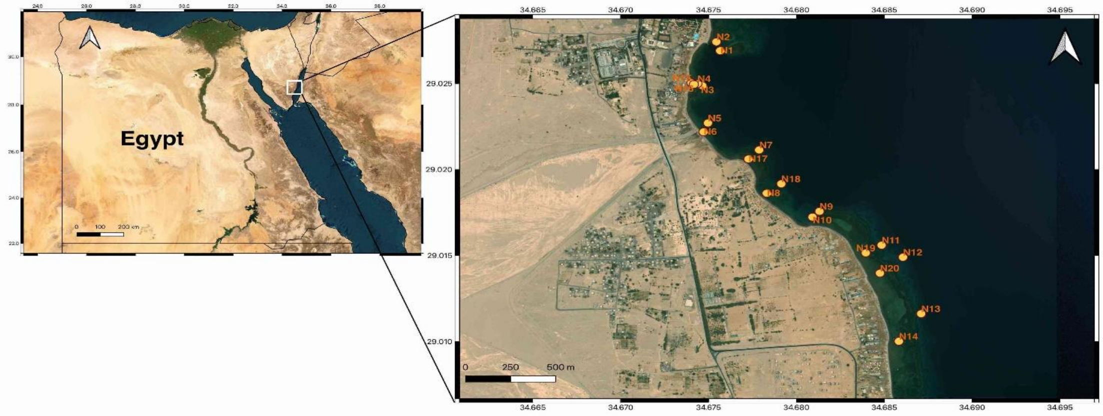


Figure 1: Map of study area and sample locations in the studied area.

<u>Sampling</u>

Twenty surface water and sediment samples (WatSs & SedSs) were collected from twenty locations during the winter and summer of 2019 in clean polypropylene containers using Niskin's Bottle (2L) and Van Veen-grab-sampler. Water Samples were transported in an ice box and subsequently kept at 4°C in a solution of HNO_3 (1%) **(Kiffney & Clements, 1993 and Pandiyan *et al*., 2020)** . Transported in plastic bags, the sediment samples were air-dried at room temperature and kept until examination. The hydro lab (Model YSI 58) was used to evaluate physical and chemical features at various places throughout the day, using standard protocols (**APHA**, **2005**) and classic white enamel. DO (dissolved oxygen) was determined using the Winkler-modified technique.

Heavy metal concentrations in seawater and sediment samples

Heavy metals (Fe, Zn, Pb, Cu, Mn, Ni, Cd, and Co) in seawater and sediments were measured using an atomic absorption spectrometer (AAS model GPC A932 Ver 1.1) (ABDC & MIBK extraction). The results were expressed as (µg/l) in water and µg/g for sediments. Metal quantities in water samples measured according to (**APHA 2005**) and SedSs were analyzed by digesting 0.5 grams with an acid combination. Heavy metal concentrations were determined by digestion of 0.5 g of each sample (bulk, $\varnothing_3$, $\varnothing_4$ and $<\varnothing_4$) with 10 ml of $HNO_3/HClO_4$ acid mixture (**Chester *et al.*, 1994**).

To ensure accuracy, the chemicals used were of the greatest purity and analytical grade, and each batch of samples had reagent blanks. Distilled water was de-ionized with aqueous solutions, and all glassware and plastic were soaked in 10% HNO_3 overnight before being cleaned with filtered water. The samples were compared to acid blanks, and the heavy metal readings were within acceptable limits, with a metal recovery rate ranging from 90.4 to 97.5%. The heavy metal standard is a metal nitrate solution, with detection limits ranging from 1 to 100 ppm using efficient atomic spectroscopy methods. All detection limits are based on a 98% confidence level (3 standard deviation). Precision was confirmed to be good, ranging from 7.4 to 17.6% for various metals.

Analysis of Grain Size

The sediment grain size was determined using sieving techniques following the Wentworth scale and classified particles into different size fractions, and statistical parameters such as mean size, kurtosis, skewness, and sorting were obtained by implementing GRADISTAT **(Folk & Ward, 1957 and Folk, 1974**).

Geochemical analyses

About 10 g of each bulk sample was powdered using agate mortar to less than 80 mesh for the geochemical analyses. Then, the CO_3^{--} in the samples was measured using the reaction with glacial acetic acid. **(Basaham and El-Sayed, 1998; Dar *et al.*, 2016**).

The carbonate percentage was calculated according to the following equation:

$$CO_3\text{--}\% = \frac{wt.of\ sample - wt.Of\ residue}{wt.of\ sample}\ 100 \qquad (1)$$

Total organic matter content measured by burning 1 gram of each bulk sample to ash at 550 ºC for 2 hours. **Walter & Dean (1974); Flannery *et al*. (1982) and Brenner & Binford (1988),** all used sequential weight loss to determine the organic matter content of the sediments. One way to determine the total organic matter content is by using the following equation:

$$TOM\% = \frac{wt.of\ sample - wt.Of\ ash}{wt.of\ sample}\ 100 \qquad (2)$$

Pollution indices

Geo-accumulation Index (I_{geo})

It is a way to quantify how much metal has accumulated in sediments from bodies of water **(Förstner *et al*., 1990)**. **Sutherland, 2000** introduced a revised geo-accumulation index (Igeo) and put it to use:

$$I_{geo} = \frac{C_n}{1.5 * BE_n} \qquad (3)$$

Cn is the metal concentration, while BEn is the metal estimation based on past research in the area and its environs. Since lithogenic factors may cause baseline (BEn) data fluctuations, we include a 1.5 in the calculation (**Salomons & Förstner, 1984**).

Förstner (1993) provided the following descriptive categorization for the geo-accumulation index.

Sediment I_{geo} Contamination	**Index, I_{geo}**
> 5	Very strong
> 4-5	Strong to very strong
> 3-4	Strong
> 2-3	Moderate to strong
>1- 2	Moderate
>0-1	Uncontaminated to moderate
>0	Practically uncontaminated

Geochemical normalization

Any normalization procedure must account for grain size and provenance, two of the most critical factors influencing heavy metal sedimentary variability (**Loring, 1990**). **Horowitz (1991**) states that the geochemical normalization in a simple ratio in bed sediment follows equation (4):

$$\text{Geochemical normalization} = \frac{\text{Concentration of heavy element}}{\text{concentration conservative}} \qquad \textbf{(4)}$$

There was an assumption that iron (Fe) flowed uniformly from the sediment sources from the eroding or deriving of sediment particles till their long-term deposition (**Sutherland, 2000**). It has a long history of usage as a standardizing metal and was the sole measured primary metal, therefore it was considered a conservative metal in this investigation (**White & Tittlebaum, 1985).**

The equation (5) was adapted to enrichment ratio (ERn) form for a given metal n following the work of (**Lee *et al*., 1994 and 1997**) and is defined as:

$$\mathbf{ER_n} = \frac{\frac{\mathrm{C_n Sample}}{\mathrm{C_{Fe} Sample}}}{\frac{\mathrm{BE_n Background}}{\mathrm{BE_{Fe} Background}}} \qquad (5)$$

Where C_n is as before; CF_e is the Fe concentration in the bulk samples and each category of the studied sizes; BE_n Background is the average content of the metal n of the previous studies in the locality, and BE_{Fe} Background is the average content of Fe in the earlier studies.

Sutherland (2000) proposed five categories system in this rank:

1. ER < 2 Depletion to minimal enrichment.
2. ER, 2 – 5 Moderate enrichments.
3. ER 5 – 20 Significant enrichments.
4. ER 20 – 40 Very highly enrichment.
5. ER> 140 Extremely enrichments.

Estimation of Combined Enrichment Index (CEI)

The combined enrichment index (CEI) was used to evaluate heavy metal enrichment rates and modified from the combined pollution index (CPI) equation. The assessment processes of the heavy metal's enrichment according to CEI include two steps, as discussed by (**Jian Min *et al.*, 2007**) in CPI evaluation.

First step: determining the contamination (enrichment) coefficient of heavy metals according to equation (6):

$$C_f^i = \frac{C^i}{C_n^i} \qquad (6)$$

Second step: calculating the CEI by the formula**:**

$$CEI = \sum_{i=1}^{m} C_f^i \,/\, m \qquad (7)$$

Cf_i is the contamination (enrichment) coefficient of heavy metals, C^i is the concentration of heavy metal in sediment, C_n^i is the background value, *and m* is the number of heavy metals. Consequently, the degree of enrichment (CEI) was classified as follows;

- CPI <1.5 Nil to very low degree of enrichment
- 1.5 ≤ CPI<2 Low degree of enrichment
- 2 ≤ CPI<4 Moderate degree of enrichment
- 4 ≤ CPI<8 High degree of enrichment
- 8 ≤ CPI<16 Very high degree of enrichment
- 16≤ CPI<32 Extremely high degree of enrichment

CPI≥32 Ultra high degree of enrichment

Modeling:

Modelling represents contaminant movement between sediment and water using equilibrium partitioning. The sediment-water partition coefficient (K_d) is estimated as:

$$K_d = C_s / C_w$$

Cs are sediment pollutants concentration (µg/g), and Cw is water pollutants concentration (µg/L). Metal flux (J) is calculated as J = K_d* (C_w- C_{eq}). J was the Flux, K_d was the sediment-water partition coefficient, C_w was the metal concentrations in WatSs, and C_{eq} was the equilibrium metal concentrations in SedSs (C_{eq}= K_d*C_w). Negative Flux implies migration from SedSs to WatSs, and positive Flux implies migration from water to sediment.

Statistical analyses

Multivariate analyses (correlation and Principal component analysis PCA) were performed using Graph Pad Prism 9.

RESULTS AND DISCUSSION

1.1. Physico-chemical parameter

Physico-chemical parameters, which may indicate the possible impact on water quality, are among the most significant variables (Fig. 2). Moreover, a decline in water quality may deteriorate marine habitats. In the present study, the water temperature ranged from 21.7 to 27.3 ℃, with a mean of 23.1 ℃. The highest temperature was recorded in N15, while the lowest was in N7. However, the average temperature was within the permissible limit of **WHO (2006).** In general, the solubility of DO may be enhanced by a temperature drop **(Yang *et al*., 2018**). The DO ranged between 7.3 at N16 and 12.8 mg/L at N11, with a mean value more significant than the range indicated by **WHO (2006**).

Hydrogen ion concentration pH is an additional environmental parameter influencing aquatic organisms' survival, growth, metabolism, and physiology (**Lawson & Lawson, 2011**). pH values ranged between 8.3 at N15 and 8.6 at N1, which matched the **WHO (2006**). Changes in pH can affect the toxicity of certain substances in water (**Boyd *et al*., 2016**). The possible results are due to the influence of land-based sources and human activities that affect biodegradable organic matter levels (**Zaghloul *et al*., 2023**)

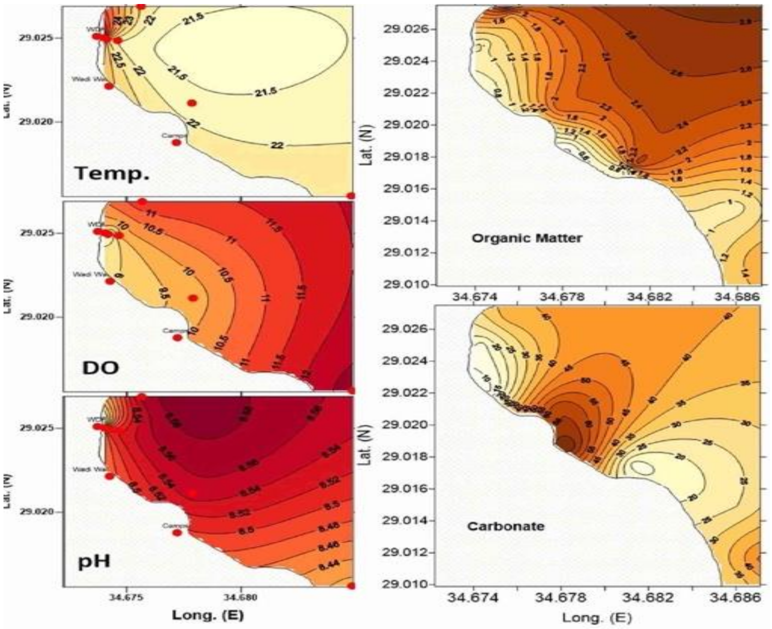


Figure 2: Contour map showing the distribution of Organic matter content (%) and carbonate content (%) in water samples along the study area.

1.2. Heavy metals in seawater and Sediments:

Metal in WatSs decreased as Fe (16.49)> Zn (8.92)> Cu (1.11)> Pb (0.95)> Ni (0.84)> Co (0.34)> Mn (0.22)> Cd (0.19) µg/L (Fig. 3), with the highest levels at N16. The highest absolute levels for all metals were recorded at N16, except for Cu, Ni, and Pb, which increased at N15 and N5, respectively. N1 has the lowest values for all investigated metals, except Cu, Zn, and Pb, reported at N7 and N15, respectively. The distribution of all metals differed considerably among the sites studied ($P < 0.05$). According to these findings, the heavy metal levels were primarily linked to direct intake from multiple sources. Evidence of human impact has been documented (**Al-Taani *et al*., 2014**).

The mean concentration of heavy metals in seawater and sediment was higher than values illustrated in the Egyptian law 4/94 and US EPA, and this may be which may be attributed to the high effect of shipping activity in this area and the predominant Gulf of Aqaba current, which were both responsible for the distribution of heavy metals **(Al-Taani *et al*., 2014)** despite these results being within the permissible limits for that agreement with that of (**Hamed *et al*., 2017**), who stated that the environmental impacts of seawater desalination plants are related to energy use and ecosystem effects of brine discharge.

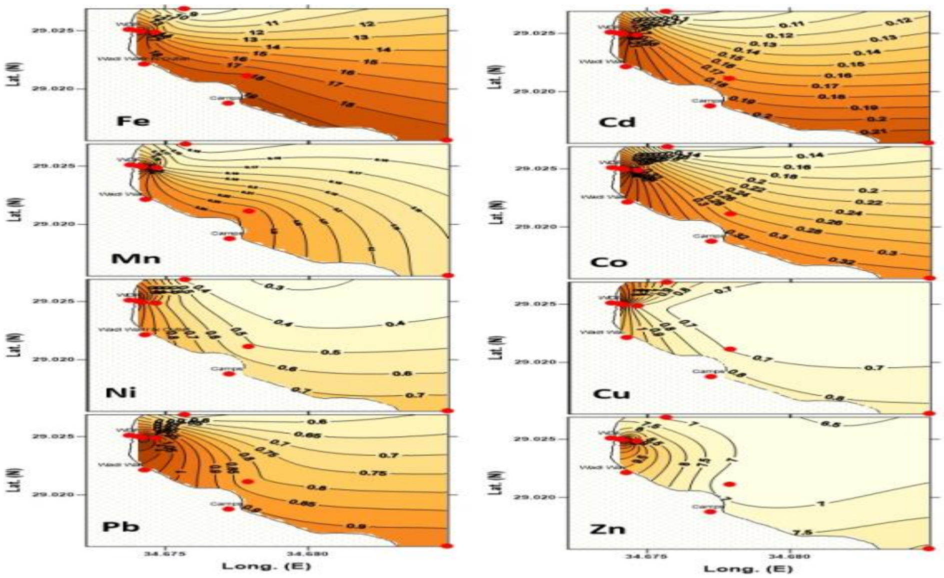


Figure 3: Contour map showing heavy metal distribution in water samples along the study area.

On the other hand, Marine sediments are well-known for preserving geochemical and mineral content. The mean values of heavy metals are 11765.31, 265.73, 87.90, 40.47, 45.39, 29.14, 3.62, and 7.93 µg/g for Fe, Mn, Zn, Ni, Pb, Co, Cd, and Cu, respectively (Fig 4). Sample N15 had the highest Mn, Ni, Pb, Cu, and Zn concentrations (670.2, 164, 62.03, 15.02, 70.12 µg/g, respectively), whereas Sample N7 had the highest Fe content (34530 µg/g) and Sample of N9 had the highest Co level (44.88 µg/g). The highest Cd concentration was recorded at N2 (Fig 4).

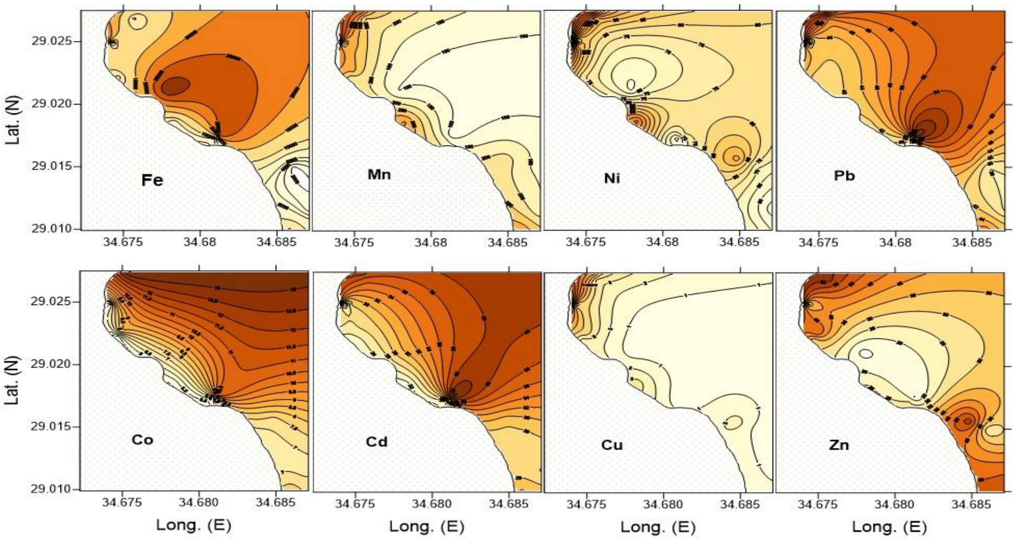


Figure 4: Contour map of heavy metal distribution in sediment samples along the study area.

Inputs from desalination plants, increased sewage and wastewater discharges from harbors, disposal of antifouling paints, and the release of zinc, copper, and cupric oxide from these paints are some of the anthropogenic factors that contribute to desalination rejection. Other factors include tourism, shipping, and desalination. The results showed that the highest concentration of all metals tested was less than the limits defined in table 1 (**El-Sawy *et al.*, 2023**) when compared to the **CCME, 2007** seawater standard, the **WHO, 2011** seawater standard, and the criterion maximum concentration (MCC).

Table (1): Min., Max. and Average values of metals in water samples of the study area compared with different standard values.

		Fe	Mn	Ni	Pb	Cd	Cu	Zn
Maximum		**22.4**	**0.3**	**1.6**	**1.3**	**0.3**	**2.1**	**14.8**
Minimum		**8.0**	**0.1**	**0.4**	**0.1**	**0.1**	**0.7**	**6.5**
Average		**17.7**	**0.2**	**0.8**	**0.9**	**0.2**	**0.9**	**8.5**
CCME, 2007		**300**	**50**	**25**	**7**	**1**	**4**	**50**
MAC, WHO, 2011		**100**	**50**	**70**	**10**	**3**	**2000**	**3000**
MCL		**---**	**---**	**---**	**15**	**5**	**1300**	**---**
CMC, (acute)	**USEPA, 2021a, b**	**---**	**20**	**420**	**82**	**1.8**	**---**	**120**
CCC (Chronic)		**---**	**---**	**52**	**3.2**	**0.72**	**---**	**120**

1.3. Grain Size analysis:

Grain size analysis shows that sand fractions comprised 96.34% of SedSs, whereas mud fractions comprised just 3.66% (Table 2). Supersaturated fluids, such as saltwater, precipitate CO_3 minerals, including aragonite, calcite, and dolomite. CO_3 may be produced by biological precipitation, deposition of complete skeletons (like Foraminifera) or pieces (like barnacle plates), and cementation and lithification to create limestone (**Smith, 1998**). The CO_3 in sediment ranges from 9.13% to 75.8%, and OM% in the SedSs ranged from 0.41% to 3.26% (table 2). The distribution of OM% and CO_3 decreased at increasing temperature (°C) and decreasing pH, resulting from the direct discharge of WDP and may result from various human activities represented in the shipping in the port and tourism activity.

1.4. Geo-accumulation index (I_{geo}) and Contamination factor (CF):

The background value obtained from element abundances in sedimentary strata is based on the base concentrations published by **Turekian and Wedepohl (1961).** Copper and Zinc have relatively low contamination factors. Both nickel and cobalt showed a moderate level of contamination. Meanwhile, lead and cadmium CF values above 3 indicate a high contamination factor, as displayed in Table (3).

The Igeo results, based on Müller, 1979 and Förstner, 1993 classifications, showed that metal pollution in the sediments varied from uncontaminated (0) to substantially polluted contaminated (5.84). Cd and Ni were extremely severely contaminated (5.84 and 2.78, respectively). Co, Fe, Pb, Zn, Mn, and Cu were uncontaminated to moderate contamination (Igeo > 0-1).

Table 2: Organic matter, carbonate, mechanical analysis, and heavy metals concentrations in sediment.

St.	Fe µg/g	Mn µg/g	Ni µg/g	Pb µg/g	Cd µg/g	Co µg/g	Cu µg/g	Zn µg/g	Sand %	Mud %	Mz	Organic Matter %	Carbonate %
N1	6737.0	247.0	96.7	47.8	12.8	36.9	3.5	62.0	94.0	6.0	2.1	1.6	38.6
N2	14030.0	436.0	131.7	60.5	13.5	40.9	7.3	61.1	93.4	6.6	2.1	2.9	36.8
N3	12200.0	354.8	94.4	44.3	8.7	28.0	5.0	37.6	96.8	3.2	2.7	1.0	16.1
N4	2585.0	179.2	56.4	30.7	7.5	18.7	3.1	24.0	94.6	5.4	2.4	0.7	11.4
N5	11830.0	309.0	79.2	41.8	8.5	25.4	4.7	50.3	75.5	24.5	3.5	0.8	11.7
N6	6598.0	227.5	76.9	41.3	5.0	22.0	2.7	32.7	96.9	3.1	2.7	0.7	9.1
N7	34530.0	97.3	59.1	44.1	7.7	29.4	0.6	13.4	99.9	0.1	2.5	2.2	63.8
N8	6309.0	355.8	112.2	41.7	5.2	21.3	3.5	24.7	97.5	2.5	1.9	0.4	75.1
N9	28810.0	77.0	74.5	61.7	11.0	44.9	0.3	14.3	99.9	0.1	2.1	2.5	13.0
N10	6380.0	161.5	56.6	40.2	5.8	23.5	0.5	24.8	99.7	0.3	1.7	0.9	19.1
N11	8276.0	225.5	97.5	46.5	7.3	28.6	2.4	58.3	100.0	0.0	0.6	1.1	20.9
N12	1602.0	157.9	70.8	38.0	7.4	28.1	0.6	25.8	99.8	0.2	1.0	0.9	25.0
N13	2303.0	154.7	52.1	37.7	6.7	25.9	0.6	49.7	99.9	0.1	2.5	1.6	46.2
N14	10210.0	338.1	67.2	47.0	7.8	30.2	1.9	51.7	99.9	0.1	2.5	1.3	30.2
N15	31220.0	670.2	164.0	62.0	6.8	41.2	15.0	70.1	98.9	1.1	2.1	0.9	17.6
N16	4625.0	260.2	117.2	40.9	5.2	21.2	6.3	47.1	94.7	5.3	2.4	1.2	10.4
N17	24908.4	172.2	71.7	42.7	6.6	26.0	1.5	18.4	98.5	1.5	2.5	0.8	11.6
N18	16006.6	238.4	91.7	45.2	6.9	26.9	3.4	19.8	98.5	1.5	2.0	0.9	14.5
N19	8453.9	220.7	88.4	46.1	7.1	28.6	2.0	50.0	100.0	0.1	1.0	0.8	63.3
N20	4425.4	219.8	78.4	41.9	6.8	27.0	1.6	44.4	100.0	0.1	1.2	1.3	42.8

Table 3: Contamination factor, Geo-accumulation index (Igeo) and pollution load index (PLI) of heavy metals in surface sediments

	(Contamination factor CF)						Igeo Geochemical index						PLI
St.	**Ni**	**Pb**	**Cd**	**Co**	**Cu**	**Zn**	**Ni**	**Pb**	**Cd**	**Co**	**Cu**	**Zn**	
N1	1.76	2.81	128.10	2.17	0.09	0.93	0.23	0.91	6.42	0.53	-4.06	-0.70	2.20
N2	2.39	3.56	135.10	2.41	0.19	0.91	0.67	1.25	6.49	0.68	-3.01	-0.72	2.79
N3	1.72	2.60	87.05	1.65	0.13	0.56	0.19	0.80	5.86	0.14	-3.54	-1.42	1.90
N4	1.03	1.81	75.03	1.10	0.08	0.36	-0.55	0.27	5.64	-0.45	-4.24	-2.06	1.28
N5	1.44	2.46	85.04	1.49	0.12	0.75	-0.06	0.71	5.83	-0.01	-3.65	-1.00	1.85
N6	1.40	2.43	50.49	1.30	0.07	0.49	-0.10	0.70	5.07	-0.21	-4.46	-1.62	1.40
N7	1.07	2.60	76.87	1.73	0.01	0.20	-0.48	0.79	5.68	0.21	-6.66	-2.91	1.02
N8	2.04	2.45	51.98	1.25	0.09	0.37	0.44	0.71	5.11	-0.26	-4.07	-2.02	1.48
N9	1.35	3.63	109.90	2.64	0.01	0.21	-0.15	1.28	6.20	0.82	-7.51	-2.81	1.17
N10	1.03	2.37	57.77	1.38	0.01	0.37	-0.54	0.66	5.27	-0.12	-6.92	-2.02	0.98
N11	1.77	2.74	72.85	1.68	0.06	0.87	0.24	0.87	5.60	0.16	-4.63	-0.79	1.77
N12	1.29	2.23	74.49	1.65	0.01	0.39	-0.22	0.57	5.63	0.14	-6.65	-1.96	1.13
N13	0.95	2.22	66.69	1.52	0.02	0.74	-0.66	0.56	5.47	0.02	-6.50	-1.02	1.17
N14	1.22	2.76	77.88	1.78	0.05	0.77	-0.30	0.88	5.70	0.25	-4.94	-0.96	1.61
N15	2.98	3.65	68.10	2.42	0.39	1.05	0.99	1.28	5.50	0.69	-1.96	-0.52	3.00
N16	2.13	2.41	51.59	1.25	0.16	0.70	0.51	0.68	5.10	-0.26	-3.22	-1.09	1.83
N17	1.30	2.51	66.15	1.53	0.04	0.27	-0.20	0.74	5.46	0.03	-5.28	-2.45	1.23
N18	1.67	2.66	68.58	1.58	0.09	0.30	0.15	0.83	5.51	0.08	-4.10	-2.34	1.52
N19	1.61	2.71	71.43	1.68	0.05	0.75	0.10	0.86	5.57	0.16	-4.88	-1.01	1.65
N20	1.43	2.46	68.25	1.59	0.04	0.66	-0.07	0.71	5.51	0.08	-5.22	-1.18	1.47
max	**2.98**	**3.65**	**135.10**	**2.64**	**0.39**	**1.05**	**0.99**	**1.28**	**6.49**	**0.82**	**-1.96**	**-0.52**	**3.00**
min	**0.95**	**1.81**	**50.49**	**1.10**	**0.01**	**0.20**	**-0.66**	**0.27**	**5.07**	**-0.45**	**-7.51**	**-2.91**	**0.98**
average	**1.58**	**2.65**	**77.17**	**1.69**	**0.09**	**0.58**	**0.01**	**0.80**	**5.63**	**0.13**	**-4.77**	**-1.53**	**1.62**

1.5. Sediment enrichment factor (EF) of heavy metals in sediment

EF identified Cd, Ni and Co from human-made sources (EF>2), while other metals were natural. Cd was enriched (EF=7.75) **(Sutherland, 2000)**. Table 4 presents the Ecological Risk Index (ERI) values for heavy metals in sediment samples. Nickel (Ni), Lead (Pb), Cadmium (Cd), Copper (Cu), and Zinc (Zn) exhibit variable ERI values across the sampling stations. Lead and Cadmium show the highest ERI values, indicating a potentially high ecological risk. Copper and Zinc have lower ERI values, suggesting a relatively lower environmental risk. Stations N1 and N9 stand out with high ecological risk for all heavy metals, emphasizing the need to address pollution from these metals to minimize adverse effects on the local ecosystem.

Table 4: Ecological risk index (ERI) for several heavy metals in sediment.

	Ecological Risk Index (ERI)					**C_{deg}**
St.	**Ni**	**Pb**	**Cd**	**Cu**	**Zn**	
N1	8.79	14.05	3843.00	0.45	0.93	135.85
N2	11.97	17.80	4053.00	0.93	0.91	144.56
N3	8.58	13.02	2611.50	0.65	0.56	93.71
N4	5.13	9.03	2250.90	0.40	0.36	79.40
N5	7.20	12.29	2551.20	0.60	0.75	91.30
N6	6.99	12.15	1514.70	0.34	0.49	56.17
N7	5.37	12.98	2306.10	0.07	0.20	82.48
N8	10.20	12.25	1559.40	0.45	0.37	58.18
N9	6.77	18.16	3297.00	0.04	0.21	117.75
N10	5.15	11.83	1733.10	0.06	0.37	62.93
N11	8.86	13.69	2185.50	0.30	0.87	79.97
N12	6.44	11.16	2234.70	0.07	0.39	80.06
N13	4.73	11.08	2000.70	0.08	0.74	72.13
N14	6.11	13.82	2336.40	0.24	0.77	84.47
N15	14.91	18.24	2043.00	1.93	1.05	78.59
N16	10.65	12.04	1547.70	0.80	0.70	58.24
N17	6.52	12.56	1984.55	0.19	0.27	71.81
N18	8.34	13.29	2057.29	0.44	0.30	74.87

N19	8.04	13.57	2142.87	0.25	0.75	78.23
N20	7.13	12.31	2047.65	0.20	0.66	74.43
max	**14.91**	**18.24**	**4053.00**	**1.93**	**1.05**	144.56
min	**4.73**	**9.03**	**1514.70**	**0.04**	**0.20**	56.17
average	**7.89**	**13.27**	**2315.01**	**0.43**	**0.58**	83.76

1.6. Sediment-Water Exchange Model

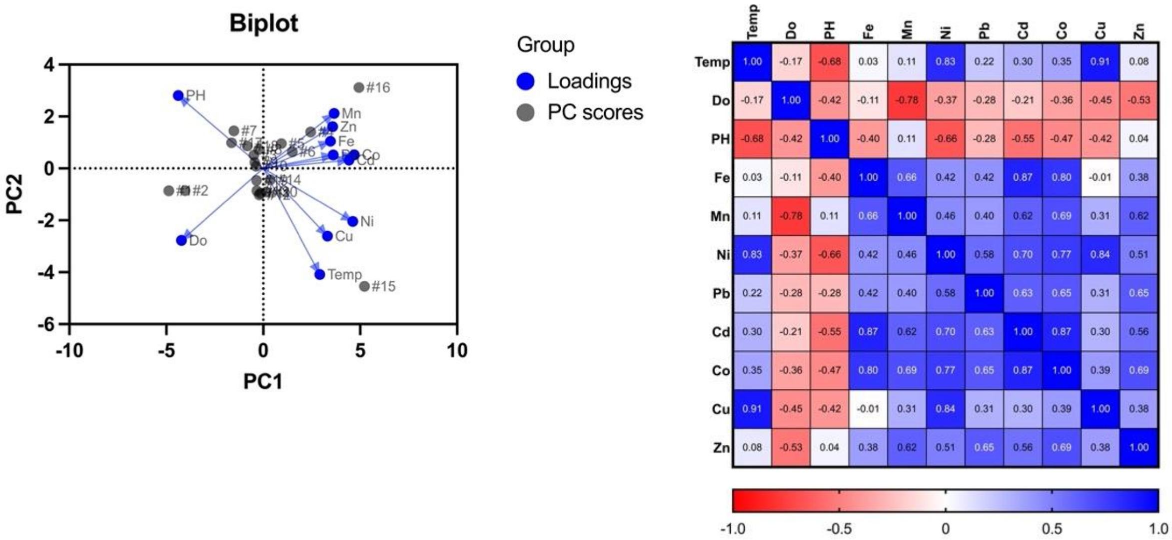
The Sediment-Water Exchange Model results indicate that several heavy metals are exhibiting negative flux values, suggesting release from sediment into the overlying water column. The most significant releases are from iron, copper, and zinc based on the magnitude of their flux values. Iron has the highest negative flux value of -3224.798 mg/m2/year, indicating it is being predominantly released from sediments. The large flux magnitude suggests there is a considerable release of iron occurring. This could potentially elevate iron concentrations in the water column to levels that could cause water quality issues. Copper and zinc also showed substantial negative flux values of -0.073 and -0.2927 mg/m^2/year, respectively, suggesting a high rate of release from sediments into the water for both metals. While not as high as iron, the flux magnitudes for copper and zinc indicate there are significant quantities of these metals being introduced to the water column from sediment stores. Over time, this sediment release could elevate copper and zinc concentrations in the water phase as well. The other metals - manganese, nickel, lead, cadmium, cobalt - showed lower magnitude negative flux values, suggesting a more minor or moderate rate of release from sediments compared to iron, copper and zinc. However, their negative flux values still indicate these metals are predominantly moving from sediment to water as well. In General, the Sediment-Water Exchange Model results highlight that sediments in this system appear to be acting as a source of several heavy metals to the overlying water column. Iron, copper and zinc seem to be experiencing the greatest releases based on their flux magnitudes. This sediment release has the potential to elevate metal concentrations in the water over time and could impair water quality if releases are substantial. Further monitoring of water column metal concentrations would help validate the extent and impacts of sediment metal release.

Coastal sediments can be both sinks and sources of metal contaminants in aquatic ecosystems (**Roussiez *et al*., 2006**). The metal emission from sediments to water depends on various physicochemical factors influencing metal mobility and solubility (**Miranda *et al*., 2021**). Fe, Cu, and Zn showed higher release rates from sediments in Oman than other metals like Ni, Mn, Co, and Cd (**Bazzi, 2014**). Multiple factors contributed to higher Zn, Cu, and Fe emission rates. 1) Zn, Cu, and Fe had the highest quantities in SedSs, which made them more susceptible to release. Higher metal quantities in SedSs often correlate with higher emission rates (**Varol & Şen, 2012**). 2) Zn, Cu, and Fe showed no apparent relationships with sediment parameters like grain size and OM, indicating they were weaker bound and thus more readily released from the sediments (**Gao *et al*., 2021**). 3) Temperature (°C) changes and pH changes related to WDP may have enhanced the release and solubility of Zn, Cu, and Fe more than the other metals due to their geochemical characteristics (**Boguta & Sokołowska, 2020**).

1.7. Statistical analysis: PCA:

Principal component analysis (PCA) was used to identify possible variations in heavy metal concentrations recorded in water and sediment samples from the study area. The PCA for water samples revealed two components, while sediment samples revealed three elements with a more than 80 percent variance.

The two components of water samples accounted for over 80.0% of the overall variation, with PC1 (Fe, Mn, Zn, Ni, Pb, Co, Cd, Cu, and temperature) accounting for 61.6% of the total variance. PC2 (dissolved oxygen and pH) was responsible for 24.55 % variation. The first component (PC1), which accounted for the bulk of variation (61.60 %), had significant loadings on all heavy metals and temperatures (Fig 5 (A). This was the first variation in the profiles of heavy metals in the study area. As an anthropogenic activity, the thermal water desalination plant in the studied locations contributed to the high concentrations of all heavy metals and temperature. The discharge from the thermal water desalination plant comprised three categories of contaminants: temperature, which hurt dissolved oxygen (DO); chemical residues such as acids, which lowered the pH; and hyper-saline water, which included a substantial quantity of heavy metals and salts (Figure 5 (B). The three components of sediment samples accounted for more than 80.0% of the total variation, with PC1 (Fe, Mn, Ni, Pb, Cu, and temperature) accounting for 44.6%, PC2 (Zn, mud, TOM, and CO_3) accounted for 25.81% of the variance, and PC3 (Cd, Co, sand, Dep, DO) was accountable for 17.50% of the variance.



	Temp	Do	PH	Fe	Mn	Ni	Pb	Cd	Co	Cu	Zn
Temp	1.00	-0.17	-0.68	0.03	0.11	0.83	0.22	0.30	0.35	0.91	0.08
Do	-0.17	1.00	-0.42	-0.11	-0.78	-0.37	-0.28	-0.21	-0.36	-0.45	-0.53
PH	-0.68	-0.42	1.00	-0.40	0.11	-0.66	-0.28	-0.55	-0.47	-0.42	0.04
Fe	0.03	-0.11	-0.40	1.00	0.66	0.42	0.42	0.87	0.80	-0.01	0.38
Mn	0.11	-0.78	0.11	0.66	1.00	0.46	0.40	0.62	0.69	0.31	0.62
Ni	0.83	-0.37	-0.66	0.42	0.46	1.00	0.58	0.70	0.77	0.84	0.51
Pb	0.22	-0.28	-0.28	0.42	0.40	0.58	1.00	0.63	0.65	0.31	0.65
Cd	0.30	-0.21	-0.55	0.87	0.62	0.70	0.63	1.00	0.87	0.30	0.56
Co	0.35	-0.36	-0.47	0.80	0.69	0.77	0.65	0.87	1.00	0.39	0.69
Cu	0.91	-0.45	-0.42	-0.01	0.31	0.84	0.31	0.30	0.39	1.00	0.38
Zn	0.08	-0.53	0.04	0.38	0.62	0.51	0.65	0.56	0.69	0.38	1.00

Figure 5: PCA and heat map (Pearson r: Correlation) for water samples' heavy metals and environmental parameters.

The first component (PC1), which explained 44.61 % of the variation, exhibited substantial loadings on the majority of heavy metals and temperature (Figure 5 (A). PC2 (Zn, mud, TOM, and CO_3), which explained 25.81% of the variance (Fig 6), were shown to be highly separated from other heavy metals in the PC1, indicating that they originate from different sources. In the present study, a flash flood from Wadi Wateir during 2018 may be a significant nonpoint source for Zn, Mud, and TOM due to an increase in flow that mobilizes many pollutants (e.g., atmospheric deposition, tires and vehicle exhausts, and road debris) dumped on the land surface and Wadi Wateir bottom (**Westerlund & Viklander, 2006 and Sakata *et al*., 2010**). The coexistence of CO_3 and Zn in PC2 may be related to the bio-mineralization-induced accumulation of Zn in calcite organisms (e.g., Foraminifera, bivalves, and coral reefs). PC3 (Cd and Co) explained 17.5% of the variation.

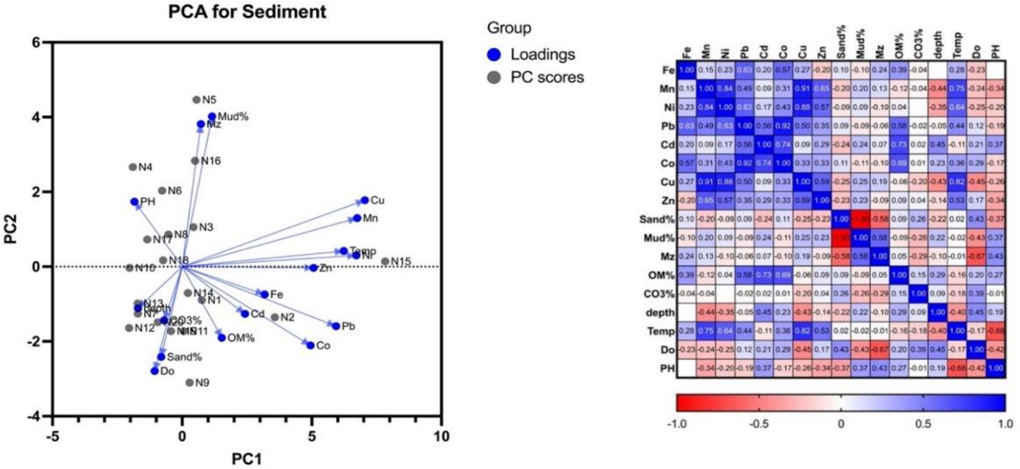


Figure 6: PCA and heat map (Pearson r: Correlation) for heavy metals and environmental parameters in sediment samples.

CONCLUSION

The investigations analyzed metal in SedSs and WatSs from the coastal area of Nuweibaa, Egypt. Results proved that the measured metal level in SedSs exceeded permissible limits, characterizing sediments as contaminated by utilizing multiple pollution indexes to analyze the causes of contamination, which were primarily anthropogenic. The various variables showed that introducing metals into the region resulted from increased human activity. The Sediment-Water Exchange Model revealed a substantial release of metals from sediment to water. This finding highlights the potential for environmental contamination and emphasizes the need for robust monitoring and effective mitigation strategies.

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