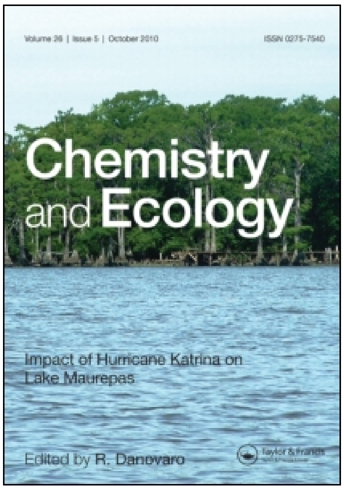

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A comparative study between the levels of some heavy metals in the sediments of two Egyptian contaminated environments

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A comparative study between the levels of some heavy metals in the sediments of two Egyptian contaminated environments

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Abu-Qir Bay and the Suez Gulf are two major economically important marine environments in Egypt. At the same time, they are exposed to intensive heavy metal contamination. A comparative study was carried out into the concentrations of some heavy metals (Fe, Mn, Cd, Cu and Ni) in the sediments of both areas. Principal component analysis (PCA), contamination factor (CF) and pollution load index (PLI) were calculated for each metal. In addition, concentrations of these metals in the studied sediments were compared with sediment quality criteria guidelines. Among the studied heavy metals, it was observed that cadmium was the only metal which showed concentrations higher than recommended levels reported for marine sediments. In general, the studied sediment metal concentrations in both environments varied according to their mineralogy and proximity to potential sources if contamination.

Keywords: heavy metals; sediment; contamination assessment; Abu-Qir Bay; Suez Gulf; Egypt

1. Introduction

Currently, environmental pollution is a major concern because of the continuous growth of urbanisation and industrial development [1,2]. Sediments can be sensitive indicators with which to monitor contaminants in aquatic environments. Sediments can be polluted with various types of hazardous and toxic substances, among which heavy metals are of great interest. Heavy metals can accumulate in sediments via several pathways, including the disposal of liquid effluent, terrestrial run-off and leachate-carrying chemicals originating from numerous urban, industrial and agricultural activities, and atmospheric deposition. One of the features that most distinguishes metals from other toxic pollutants is that they are not biodegradable. Sediments can incorporate and accumulate many of the metals added to a body of natural water. The favourable physicochemical conditions of the sediment can also remobilise and release the metals into the water column. Discharge sources from smelters, electroplating, paint and dye formulator industries, chemical manufacturing plants and petroleum refineries may lead to heavy metal accumulation in sediments [3,4].

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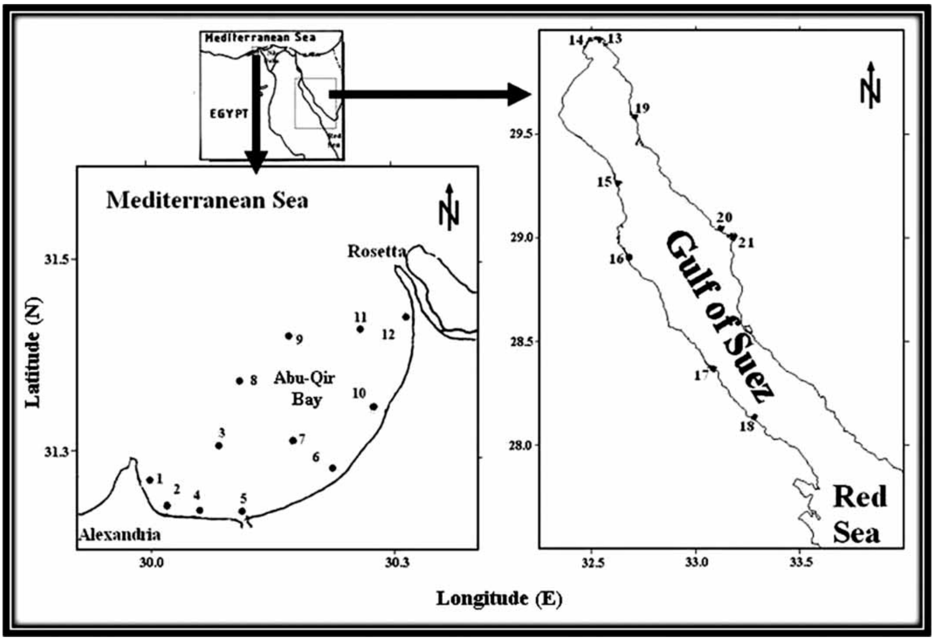

Figure 1. Sampling stations along Abu-Qir Bay and the Suez Gulf.

Abu-Qir Bay (Figure 1) is a semicircular basin on the Mediterranean coast of Egypt, it lies between 30° 40′ and 30° 21′ E and 31° 16′ and 31° 30′ N. It is bordered in the west by the Abu-Qir peninsula and the east by the Rosetta branch of the Nile River. Its shoreline is ∼50 km long with an area of ∼560 km^2, and an average depth of ∼12 m [5]. Several rocky ridges are found in the northwestern part of the bay. Because of these rocky ridges, a limited exchange of water exists between the open sea and the northwestern part of the bay [6]. The bay receives different types of water from three sources: considerable amounts of fresh water from the Rosetta branch of the Nile River, brackish water from Lake Edku ($\sim 3.3 \times 10^6$ m^3 daily) [6] through the El-Maadyia Inlet and drainage waste water from El-Tabia pumping station $\sim 2 \times 10^6$ m^3 daily [7]. The drainage water includes water from El-Behera province and from different factories representing major industrial activities (food canning, paper, fertiliser and textile manufacturing, chemical, soap and salt factories) [8].

The Suez Gulf occupies the northwestern arm of the Red Sea between Africa proper (west) and the Sinai Peninsula (east) of Egypt (Figure 1). It is the third arm of the triple junction rift system. The second arm of the triple junction system is the Gulf of Aqaba. The length of the gulf, from its mouth to its head at the city of Suez, is 314 km, and it varies in width from 19 to 32 km. The border between the continents of Africa and Asia lies along the midline of the Gulf. The Suez Gulf is perhaps the most polluted area in the Red Sea [9]. The northern part of the Suez Gulf is subjected to pollution from three main sources: industrial waste products from five large factories (three oil refineries at 34.79 ton·year^{-1}, a fertiliser factory at 28.67 ton·year^{-1} and a power station at 0.20 ton·year^{-1}), domestic drainage from Suez city at 151.57 ton·year^{-1} and oil spills and refuse from shipping [10]. A large recreational area has recently been established along the Suez Gulf.

In general, sediments contaminated with heavy metals may cause significant damage to sensitive ecosystems, decrease biodiversity and lead to a reduction in fishing, tourism and other related economies [11]. Because heavy metal contamination of sediments is one of the greatest threats to the environment, a number of research efforts in Egypt have focused primarily on heavy metal distribution in sediments from different aquatic environments including lacustrine [12–14] and marine environments [15–17]. Hence, heavy metal contamination deserves to be extensively studied.

The aim of this study is to assess and compare the quality of sediments from both areas under study using different sediment quality guidelines, contamination factor (CF) and the pollution load index (PLI), recalling that these areas are subjected to different sources of land run-off.

2. Materials and methods

2.1. *Sampling*

Twenty-one surface sediment samples representing a large area of two of the most contaminated environments in Egypt were sampled during 2004 (Figure 1). Twelve sediment samples were collected from Abu-Qir Bay, and nine sediments were sampled from the Suez Gulf. The sediment sampling location was detected using GPS. The sampling stations included areas near industrial and domestic effluent discharge points, agricultural areas and places of recreational activity. Station 2 receives drainage water from El-Tabia pumping station, whereas stations 1, 3, 4 and 5 receive waste water from different industrial activities. Station 15, a recreational beach, is affected by oil pollution from the Sumed Company pipeline. Station 17 is a centre for the collection and shipment of oil from a number of oil fields, including offshore wells. Station 19 lies within the Sinai Manganese Company which is involved in manganese production, and station 20 is subjected to petroleum pollution. However, stations 16, 18 and 21 are recreational beaches.

At each station, three replicate sediment samples were collected from the surface layer (0–5 cm depth) using a stainless steel Peterson grab sampler (20×13 cm). The three replicate samples were placed in self-sealed acid-precleaned plastic bags. All samples were immediately stored in an ice-cooled box and transferred to the laboratory. In the laboratory, samples were air dried, then oven dried at 70 °C to a constant weight and finely powdered in an agate mortar.

2.2. *Digestion of sediment samples*

Digestion of sediment samples was achieved by adding a mixture of HNO_3, $HClO_4$ and HF (3 : 2 : 1) to a 0.2 g sediment sample in a closed Teflon vessel under high pressure [18]. The residue was dissolved in a known volume of deionised water and preserved in acid-clean PVC bottles for analysis. Triplicate digestion was carried out for each sample and blank determinations were performed using the same procedure.

2.3. *Heavy metal determination*

Heavy metal (Fe, Mn, Cu, Ni and Cd) concentrations were determined using a Perkin–Elmer 2830 flame atomic absorption spectrophotometer. Working standards for the studied metals were prepared by diluting concentrated stock solutions (Merck, Germany) of 1000 $mg \cdot L^{-1}$ in metal-free distilled water. Each metal concentration was estimated quantitatively according to the standard conditions described in the instrument manual. For each sample, the mean concentrations of the studied metals were calculated and the results were expressed in $\mu g \cdot g^{-1}$ dry weight.

2.4. *Calcium, magnesium and sulphate determination*

Calcium and magnesium concentrations were determined in sediment samples following the compleximetrically method [19,20]. However, the sulphate concentration was determined using the turbidimetric method [21].

2.5. *Quality assurance*

The accuracy and precision of the results were checked by analysing standard reference material (BCSS-1; marine sediments). Analysis of the reference material showed good accuracy with metal recovery ranging between 92.43 and 108% (Table 1). All reagents were of analytical grade.

2.6. *Contamination factor*

The contamination factor (CF) was calculated as described by Tomlinson et al. [22]:

$$\text{CF} = \text{Metal concentration in sediment/Base value for that metal.}$$

The base value for each metal was reported by Martin and Meybeck [23], and represents the average composition of the surface rocks. The terminologies used to describe CF are: $\text{CF} < 1$, low contamination; $1 < \text{CF} < 3$, moderate contamination; $3 < \text{CF} < 6$, considerable contamination; and $\text{CF} > 6$, high contamination [24].

2.7. *Pollution load index*

Pollution load index (PLI) was computed according to Tomlinson et al. [22] using the following equation:

$$\text{PLI} = (\text{CF}_1 \times \text{CF}_2 \times \text{CF}_3 \times \ldots \text{CF}_n)^{(1/n)},$$

where PLI = pollution load index; CF = contamination factor; and n = the number of investigated metals.

2.8. *Statistical analysis*

All statistical aspects (Pearson's correlation coefficients matrix and principal component analysis) were calculated, using the MINTAB program v. 13.1. Principal component analysis (PCA) involves a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible.

Table 1. Heavy metal concentration in the studied certified sample (BCSS-1) (values are given in mg·kg^{-1} dry weight, except for Fe_2O_3, which is given in %).

Element	BCSS-1	Present study	Recovery %
Fe_2O_3	4.70 ± 1.40	4.50	95.74
Mn	229.00 ± 15.00	215.00	93.89
Cd	0.25 ± 0.04	0.27	108.00
Cu	18.50 ± 2.70	17.10	92.43
Ni	55.30 ± 3.60	57.00	103.07

3. Results and discussion

3.1. *Chemical composition of sediment samples*

3.1.1. *Heavy metal concentrations*

Heavy metal concentrations for Abu-Qir Bay and Suez Gulf surface sediments are shown in Tables 2 and 3.

3.1.1.1. *Iron.* Tables 2 and 3 show the dominant abundance of iron (Fe). Indeed, it is the most abundant transition metal in the Earth's crust [25]. Levels fluctuated widely in the Abu-Qir and Suez Gulf environments, ranging from 3240.0 to 30690.0 $mg \cdot kg^{-1}$ at stations 4 and 12 in Abu-Qir Bay, respectively. In addition, Fe shows a minimum concentration of 257.97 $mg \cdot kg^{-1}$ at station 15 and a maximum of 768.73 $mg \cdot kg^{-1}$ at station 20. The average concentrations are 14405.8 ± 11171.3 and 504.40 ± 144.44 $mg \cdot kg^{-1}$ for Abu-Qir Bay and the Suez Gulf, respectively. Iron concentrations are higher at Abu-Qir Bay than the Suez Gulf. This may be attributed to the mineralogy of the sediment. Abu-Qir Bay is mainly composed of clay minerals [26] which are the

Table 2. Chemical composition of the surface sediments of Abu-Qir Bay.

Station number	Fe [16] mg/kg	Mn [16] mg/kg	Cd [16] mg/kg	Cu [16] mg/kg	Ni [16] mg/kg	Ca g/kg	Mg g/kg	SO_4 g/kg
1	3860.0	187.82	3.77	5.00	15.00	1.86	2.26	0.75
2	6320.0	222.60	1.89	12.00	33.34	0.93	2.07	0.00
3	5860.0	194.78	3.39	12.00	26.67	4.04	1.13	0.00
4	3240.0	208.69	3.77	59.00	65.01	4.04	1.70	0.00
5	11410.0	278.25	2.64	8.00	23.34	1.60	1.75	0.00
6	29140.0	563.46	4.15	22.00	56.67	1.92	0.78	1.81
7	6170.0	271.29	1.89	5.00	10.00	6.21	1.13	8.21
8	4630.0	166.95	1.89	4.00	8.33	3.85	1.56	2.89
9	17890.0	841.71	3.39	17.00	46.67	4.49	1.17	25.68
10	30220.0	626.06	1.51	20.00	20.00	3.73	0.75	19.41
11	23440.0	500.85	3.02	20.00	56.67	3.11	1.51	2.61
12	30690.0	493.90	1.51	21.00	31.67	3.11	1.13	4.11
Range	3240.0–30690.0	166.95–841.71	1.51–4.15	4.00–59.00	8.33–65.01	0.93–6.21	0.75–2.26	0.75–25.68
Mean	14405.8	379.70	2.74	17.08	32.78	3.24	1.41	5.46
S.D.	11171.3	219.06	0.96	14.80	19.30	1.48	0.48	8.43

Table 3. Chemical composition of the surface sediments of the Suez Gulf.

Station number	Fe mg/kg	Mn mg/kg	Cd mg/kg	Cu mg/kg	Ni mg/kg	Ca g/kg	Mg g/kg	SO_4 g/kg
13	476.77	77.65	3.16	7.18	16.15	18.04	3.04	6.02
14	449.58	109.15	2.47	9.65	14.35	20.04	5.47	6.02
15	257.97	81.91	12.61	2.80	13.14	16.35	1.24	2.72
16	515.83	75.88	3.02	4.52	15.49	24.53	4.34	0.23
17	403.23	89.95	2.96	4.00	13.40	20.04	1.22	2.31
18	614.26	49.95	2.06	1.87	8.48	7.15	0.62	2.72
19	459.05	272.01	3.29	3.41	12.21	18.40	1.24	1.36
20	768.73	483.61	3.91	5.49	22.79	18.76	5.06	0.56
21	594.15	172.5	3.45	6.35	18.17	20.84	3.79	0.45
Range	257.97–768.73	49.95–483.61	2.06–12.61	1.87–9.65	8.48–22.79	7.15–24.53	0.62–5.47	0.23–6.02
Mean	504.40	156.96	4.10	5.03	14.91	18.24	2.89	2.49
S.D.	144.44	140.05	3.23	2.42	4.01	4.74	1.86	2.22

Table 4. Comparison between the heavy metal concentrations ($mg \cdot kg^{-1}$) in surface sediments of the Suez Gulf during the current study and those of previous studies.

Cd	Cu	Ni	Fe	Mn	References
2.06–12.61	1.87–9.65	8.48–22.79	258.0–768.7	49.95–483.61	Present study
1.29–3.23	2.79–8.65	16.84–34.31	1240.0–3280.0	12.90–64.20	Hamed and Emara [10]
0.70–4.20	4.90–20.10	1.10–9.30	37.0–2969.0	45.00–341.00	Hamed [27]

main carriers of heavy metals during mobilisation and diffusion. By contrast, Suez Gulf sediments are comprised of the disintegration products of coral reef builders, rock fragments, quartz feldspars and carbonate pellets [26]. Relatively high concentrations of 614.26 and 594.15 $mg \cdot kg^{-1}$ are recorded at stations 18 and 21 in Suez, respectively. Table 4 shows that the current sediment Fe levels in Suez Gulf sediments lie within the range determined by Hamed [27] and are lower than those detected by Hamed and Emara [10].

3.1.1.2. *Manganese.* Manganese (Mn) is one of the most abundant metals in the Earth's crust. It is widely distributed in soils, sediments, rocks and waters, as well as in biological materials. The major manganese man-made environmental pollution sources are alloys, steel and products of iron manufacture [28]. Tables 2 and 3 show that it is the second most abundant heavy metal among those studied in both areas. Abu-Qir Bay shows higher manganese concentrations than those of the Suez Gulf which is possibly attributable to the clay mineral composition [26]. The concentration of manganese fluctuated considerably within both Abu-Qir Bay and Suez Gulf sediments with averages of 379.70 ± 219.06 and $156.96 \pm 140.05\,mg \cdot kg^{-1}$, respectively. The highest level of 483.61 $mg \cdot kg^{-1}$ at station 20 is approximately one order magnitude higher than that at station 18 in the Suez Gulf. Station 19 has a considerable level of Mn (272.01 $mg \cdot kg^{-1}$); this station lies within the Sinai Manganese Company. The current Mn content is relatively similar to that determined by Hamed [27] (Table 4).

3.1.1.3. *Cadmium.* Cadmium (Cd) behaves as a cumulative poison within the environment [29]. It is known by its classification as a pollutant in addition to being a hazard [30]. Soil particles transported by the wind and volcanic emissions account for 10–30% of natural cadmium. The main anthropogenic sources into the marine environment are refining and smelting, as well as cadmium atmospheric loading which is mostly deposited into bottom sediments [2–13,30,31]. Tables 2 and 3 illustrate Cd concentration ranges of 1.51–4.15 and 2.06–12.61 $mg \cdot kg^{-1}$ and average sediment contents of 2.74 ± 0.96 and $4.10 \pm 3.23\,mg \cdot kg^{-1}$ for Abu-Qir Bay and the Suez Gulf, respectively. It seems that the Suez Gulf is more contaminated by cadmium than the Abu-Qir Bay region. The highest Cd concentrations in stations 1 and 3–6 are accompanied by discharge waters that contain wastes from different industrial activities. The high Cd content in the Suez Gulf may be related to the petroleum industry. Also, the highest Cd content at station 15 is affected by oil pollution from the Sumed Company pipeline. By contrast, station 18 has the lowest Cd concentration. The remaining stations show similar relative Cd concentrations. The current Cd concentrations in Suez Gulf sediments are considerably higher than those determined previously [10,27] (Table 4). This indicates an increase in anthropogenic cadmium discharge along the Gulf, especially at station 15.

3.1.1.4. *Copper.* Sources of natural copper (Cu) exposure include windblown dust, volcanoes, decaying vegetation, forest fires and sea spray; anthropogenic sources include smelters, iron foundries, power stations and products of combustion for example from municipal incinerators. In addition, copper can be released into the land from the tailings and overburdens of copper mines and sewage sludge. The use of agricultural copper products contributes ~2% Cu transportation into soil [32]. Table 2 shows the high incidence of Cu ($17.08 \pm 14.80\,mg \cdot kg^{-1}$) in Abu-Qir Bay sediments. The maximum concentrations at stations 2–4 and 6 are related to anthropogenic wastes. By contrast, Suez Gulf sediments show Cu levels ($5.03 \pm 2.42\,mg \cdot kg^{-1}$) lower than those of Abu-Qir Bay (Tables 2 and 3); the highest level of $9.65\,mg \cdot kg^{-1}$ in station 14 is about five times higher than that in station 18. Stations 13 and 21 have relatively high Cu concentrations of 7.18 and $6.35\,mg \cdot kg^{-1}$, respectively. Relatively moderate Cu concentrations are recorded at stations 16, 17, 19 and 20. The highest Cu concentration in station 14 is possibly due to anti-fouling paints, because the northern sector of the Suez Gulf is used as a berth for ships [10]. Comparing the levels of Cu found in this study with those from previous studies at the same area of the Gulf (Table 4), it seems that the Cu concentration is changeable over time in this area [10,27].

3.1.1.5. *Nickel.* Nickel (Ni) is a relatively abundant metal in the Earth's crust. It enters surface waters from the dissolution of rocks and soils, biological cycles, atmospheric fallout, industrial processes and waste disposal [33]. The Ni level is higher ($32.78 \pm 19.30\,mg \cdot kg^{-1}$) in Abu-Qir Bay than in the Suez Gulf ($14.91 \pm 4.01\,mg \cdot kg^{-1}$; Tables 2 and 3). The high Ni concentration for Abu-Qir Bay may be attributed to the clay mineral composition of the sediment. In addition, Ni levels fluctuated widely in Abu-Qir Bay, varying between 8.33 and $65.01\,mg \cdot kg^{-1}$ at stations 8 and 4, respectively. The highest Ni concentration ($65.01\,mg \cdot kg^{-1}$) recorded in station 4 is attributed to waste from industrial activities. By contrast, Ni is narrowly distributed in Suez Gulf sediments (Table 3). Thus, seven stations (13–17, 19 and 21) have moderate and relatively low levels of Ni. The maximum concentration of Ni at station 20 does not exceed $22.79\,mg \cdot kg^{-1}$. Among the stations studied, station 18 has the lowest Ni concentration ($8.48\,mg \cdot kg^{-1}$). The current study indicates the variability in Ni content along the Suez Gulf over time (Table 4). This variation in Ni is probably related to its adsorption onto manganese oxides [34]. Accordingly, this may account for the significant positive correlation between Mn and Ni ($r = 0.693$, $p < 0.05$). Also, the strong positive correlation between Ni and Mg ($r = 0.738$, $p < 0.05$) may reflect the presence of Ni in ferromagnesium minerals [35].

In general, heavy metal distribution along Abu-Qir Bay and Suez Gulf sediments has the same trend (Fe > Mn > Ni > Cu > Cd).

3.1.2. *Calcium, magnesium and sulphate concentrations*

Calcium (Ca), magnesium (Mg) and sulphate (SO_4) levels are used in to describe the chemical composition and to distinguish the mineralogy of a sediment; in particular aragonite and dolomite types (calcium carbonate forms) [36].

The Suez Gulf shows higher calcium and magnesium concentrations (18.24 ± 4.74 and $2.89 \pm 1.86\,g \cdot kg^{-1}$) than Abu-Qir Bay ($3.24 \pm 1.48$ and $1.41 \pm 0.48\,g \cdot kg^{-1}$; Tables 2 and 3). However, Suez Gulf sediments are mainly composed of carbonate 31.55–91.23% [36], and are also comprised of the disintegration products of coral reef framework builders (local production), rock fragments (stream transport) and carbonate pellets [37,38]. The current average calcium content is $<26.0\,g \cdot kg^{-1}$ in the Suez Gulf [39]. By contrast, lower calcium and magnesium levels in Abu-Qir Bay sediments are due to the high level of clay minerals which contain shell fragments in some stations [6]. In addition, average concentrations of Ca and Mg in Abu-Qir Bay and Suez Gulf sediments are lower than base values ($45\,g \cdot kg^{-1}$ for Ca and $16.4\,g \cdot kg^{-1}$ for Mg) [23]. The Ca/Mg ratio for Abu-Qir Bay sediments is in harmony with base ratios [23]; whereas this ratio is doubled for Suez Gulf sediments.

Abu-Qir Bay shows complete sulphate depletion at stations 2–5 and the maximum concentration does not exceed $25.68\,g \cdot kg^{-1}$ (Table 2). Complete depletion indicates strong microbial activity which is accompanied by blackish sediments and an odour of H_2S [16]. The sulphate concentration in the Suez Gulf varies between 0.23 and 6.02 $g \cdot kg^{-1}$ at stations 16 and 13–14, respectively, with an average value of 2.49 $g \cdot kg^{-1}$ (Table 3). However, sulphide production is related to the microbial reduction of sulphate in anoxic conditions as well as organic matter decomposition [40–42].

3.2. *Comparison between heavy metal concentrations in both the Abu-Qir Bay and Suez Gulf environments*

Comparison between the heavy metal concentrations in the Abu-Qir Bay and Suez Gulf environments is achieved statistically (PCA) and mathematically (CF and PLI calculations), as well as by comparing sediment quality criteria guidelines.

3.2.1. *Principal component analysis*

PCA is performed to examine the relationship among all studied heavy metals in sediment stations along both contaminated environments. The proportion and cumulative variance, expressed as a percentage of the total variance, are explained by each component score in the PCA for metals in sediments (Table 5). The first three PCA axes were selected because they explain the majority of the variance in the heavy metals in sediment. For Abu-Qir Bay (Table 5), the first three principal components explained 93.9% of the total variance, with the major percentage of cumulative variance being accounted for by the first component (47.9%). The first component (PC-1) is positively related to the concentrations of all metals. In addition, the second and the third components (PC-2 and PC-3) are positively related to the concentrations of Cu and Ni. The third component (PC-3) was the only one related negatively to the concentration of Cd. Similarly, for the Suez Gulf (Table 5), the first three principal components explained 93.7% of the total variance, with the major percentage of cumulative variance being accounted for by the first component (49.6%). The first component (PC-1) is positively related to the concentrations of all the metals, except for Cd. The second and third components (PC-2 and PC-3) are negatively related to the Cd concentration. The high negatively loading for Cd in both the Suez Gulf (−0.762) and Abu-Qir Bay (−0.717) may reflect Cd contamination. Also, moderate positive loading for Cu (0.636) in Abu-Qir Bay is possibly related to its clay mineral composition.

3.2.2. *Contamination factor (CF)*

Tables 6 and 7 show the ranges and the average values of CF in Suez Gulf and Abu-Qir Bay sediments, respectively. The average CF values for different metals in the sediments of Abu-Qir

Table 5. Principal component analysis (PCA) for the studied heavy metals in Abu-Qir Bay and Suez Gulf sediments.

	Abu-Qir Bay			Suez Gulf		
Variable	PC-1	PC-2	PC-3	PC-1	PC-2	PC-3
Fe	0.369	−0.595	0.016	0.535	0.145	0.430
Mn	0.422	−0.515	−0.275	0.500	−0.432	0.221
Cu	0.474	0.314	0.636	0.305	0.293	−0.794
Ni	0.595	0.217	0.072	0.525	−0.355	−0.308
Cd	0.327	0.485	−0.717	−0.309	−0.762	−0.205
Eigenvalue	2.395	1.644	0.656	2.481	1.180	1.027
Proportion	0.479	0.329	0.131	0.496	0.236	0.205
Cumulative	0.479	0.808	0.939	0.496	0.732	0.937

Table 6. Contamination factors (CF) for the different heavy metals in Abu-Qir Bay sediments and their pollution load index (PLI).

Station number	Fe	Mn	Cd	Cu	Ni	PLI
1	0.108	0.261	18.850	0.156	0.306	0.479
2	0.176	0.309	9.450	0.375	0.680	0.666
3	0.163	0.271	16.950	0.375	0.544	0.687
4	0.090	0.290	18.850	1.844	1.327	1.038
5	0.318	0.386	13.200	0.250	0.476	0.720
6	0.812	0.783	20.750	0.688	1.157	1.600
7	0.172	0.377	9.450	0.156	0.204	0.455
8	0.129	0.232	9.450	0.125	0.170	0.360
9	0.498	1.169	16.950	0.531	0.952	1.380
10	0.842	0.870	7.550	0.625	0.408	1.071
11	0.653	0.696	15.100	0.625	1.157	1.377
12	0.855	0.686	7.550	0.656	0.646	1.134
Range	0.090–0.855	0.232–1.169	7.550–20.750	0.125–1.844	0.170–1.327	0.360–1.600
Mean	0.401	0.527	13.675	0.534	0.669	0.914
S.D.	0.311	0.304	4.823	0.463	0.394	0.410

Table 7. Contamination factors (CF) for the different heavy metals in Suez Gulf sediments and their pollution load index (PLI).

Station number	Fe	Mn	Cd	Cu	Ni	PLI
13	0.013	0.108	15.800	0.224	0.330	0.278
14	0.013	0.152	12.350	0.302	0.293	0.291
15	0.007	0.114	63.050	0.088	0.268	0.252
16	0.014	0.105	15.100	0.141	0.316	0.252
17	0.011	0.125	14.800	0.125	0.273	0.235
18	0.017	0.069	10.300	0.058	0.173	0.165
19	0.013	0.378	16.450	0.107	0.249	0.292
20	0.021	0.672	19.550	0.172	0.465	0.468
21	0.017	0.240	17.250	0.198	0.371	0.347
Range	0.007–0.021	0.069–0.672	10.300–63.050	0.058–0.302	0.173–0.465	0.165–0.468
Mean	0.014	0.218	20.517	0.157	0.304	0.291
S.D.	0.004	0.195	16.173	0.076	0.082	0.089

Bay are Cd $>$ Ni $>$ Cu $\sim$ Mn $>$ Fe (Table 6). By contrast, for the Suez Gulf, they are in the order Cd $>$ Ni $>$ Mn $>$ Cu $>$ Fe (Table 7). Except for Cd, the CF values for different metals in Abu-Qir Bay sediments are relatively higher than those in the Suez Gulf. For all sites along the two environments, the CF value for Cd is >6. This indicates that these environments are highly contaminated with Cd. In general, the CF values for Fe, Mn, Ni and Cu for most stations along both studied environments are <1 (Tables 6 and 7). CF values for Cd and Ni in Abu-Qir Bay are >1 at station 4. Station 4 is moderately contaminated by Cu and Ni, this moderate contamination may relate to the huge industrial discharge waste waters. Accordingly, Abu-Qir Bay and the Suez Gulf are lightly contaminated with Mn, Cu and Ni heavy metals.

3.2.3. *Pollution load index (PLI)*

PLI ranges from 0.360 to 1.600 and 0.165 to 0.468 for Abu-Qir Bay and Suez Gulf sediments, respectively (Tables 6 and 7). Abu-Qir Bay shows PLI values three times higher than those of the Suez Gulf. Relatively high PLI values (>1) for Abu-Qir Bay are recorded at stations 4, 6, 9–12 (Table 8). Station 6 has the highest PLI value (1.600), this is accompanied by the maximum Cd

Table 8. Heavy metals values of NOAA and Canadian sediment quality guidelines.

	NOAA Guidelines		Canadian Guidelines	
Metal	ERL	ERM	TEL	PEL
Cadmium	1.2	9.6	0.7	4.2
Copper	34.0	270.0	18.7	108.0
Nickel	20.9	51.6Î	–	–

Notes: ERL, Effects range – low; ERM, Effects range – median; TEL, Threshold effect level; PEL, Probable effect level (mg·kg^{-1} dry weight).

levels in sediment. Station 18 in the Suez Gulf has the lowest contamination factors of all the studied heavy metals, except for Fe. Therefore, this station has the lowest PLI and it is one of the recreational beaches along the Suez Gulf. By contrast, the highest PLI value is for station 20 and reflects the highest presence of Fe, Mn and Ni metals; this station is affected by different petroleum activities.

3.2.4. *Sediment quality criteria*

Because of the varaiblity in heavy metal concentrations in both Abu-Qir Bay and the Suez Gulf, it is important to evaluate their threat to the marine environment. This is achieved by comparison with sediment criteria guidelines.

To date, there have been no established sediment quality guidelines for either of the studied environments, and so US National Oceanic and Atmospheric Administration (NOAA) and Canadian guidelines were used as interim measures. These guidelines study sediment enrichment by heavy metals and the adverse impacts of heavy metals on biological life (Table 8). NOAA expresses metal concentrations in terms of both effects range – low (ERL) and effects range – median (ERM) [43], whereas the Canadian guidelines assess heavy metals levels in terms of threshold effect level (TEL) and probable effect level (PEL) [44]. Adverse biological effects rarely occur at levels below ERL and TEL [43,44], so ERL (NOAA guidelines) and TEL (Canadian sediment quality guidelines) are recommended as proposed interim measures.

In general, Cd concentrations in Abu-Qir Bay and Suez Gulf surface sediments exceed both TEL and ERL values (Tables 2 and 3). Among all the stations studied, stations 6 and 15 show a relative Cd concentration similar to PEL (4.15 mg · kg^{-1}) and higher than ERM (12.61 mg · kg^{-1}), respectively (Tables 2 and 3). In fact, the recorded sediment Cd levels for Abu-Qir Bay and the Suez Gulf are considerably higher than those reported for uncontaminated marine sediments (0.03–1 mg · kg^{-1}) [45]. Moreover, the average Cd concentrations recorded in Abu-Qir and the Suez Gulf (Tables 2 and 3) are 27 and 18 times higher, respectively, than that determined in Fuka sediments (0.15 mg · kg^{-1}) [46]. Fuka is located along the Mediterranean Sea and far from any land sources of pollution. Accordingly, Abu-Qir Bay and the Suez Gulf can be classified as cadmium contaminated environments.

Despite the documented cadmium toxicity, the high levels recorded in both studied environments may have no hazardous effects on marine organisms. This is probably due to its absorption from surface waters by phytoplankton and its transportation into the bottom sediments via biological debris [47]. In addition, its sedimentation, incorporation into organic matter and interstitial water dissolved salts possibly reduces its toxicity [48].

Copper concentrations at stations 6, 10, 11 and 12 along Abu-Qir Bay seem to be close to TEL. Meanwhile, the Cu concentration at station 4 exceeds both TEL and ERL but is considerably lower than ERM and PEL. By contrast, Cu concentrations lower than those in the Canadian and NOAA sediment quality guidelines were found. Interestingly, the determined Cu content in Abu-Qir Bay and the Suez Gulf is within the range for marine sediments (2–740 $mg \cdot kg^{-1}$) [49] and lower than background levels for uncontaminated sediments (800–5000 $mg \cdot kg^{-1}$) [50]. Also, averaged Cu concentrations along the two investigated areas are lower than for Fuka sediment (15.0 $mg \cdot kg^{-1}$) [46]. Accordingly, Abu-Qir Bay and the Suez Gulf can be considered as copper uncontaminated regions.

Nickel concentrations at stations 2, 3, 5, 9, 12 and 20 are higher than ERL, and levels at stations 4, 6 and 11 (Abu-Qir Bay) exceed the ERM. Soil samples with 100–500 $mg \cdot kg^{-1}$ Ni can stimulate nitrification and nitrogen mineralisation by nitrogen leaching [51,52]; processes that may lead to nitrogen deficiency and thus affect the growth of marine organisms. The Ni concentrations at Abu-Qir Bay and the Suez Gulf are lower than those inducing nitrogen deficiency [51,52] and so Ni has no hazardous effects on either marine environment.

The variability in sediment mineralogy in the two studied environments possibly plays an important role in the incorporation of heavy metals. Indeed, clay minerals contain heavy metals concentrations 20 to $>$50 times higher than the concentrations of carbonate or quartz [53].

4. Conclusions

Because of the economic importance of the Abu-Qir Bay and Suez Gulf marine environments, as well as their intensive heavy metals exposure, a comparable study was carried out between these two environments. The concentrations of heavy metals (Fe, Mn, Cd, Cu and Ni) were variable in both marine environments. Abu-Qir Bay showed higher heavy metal levels (Fe, Mn, Cu and Ni) than the Suez Gulf area, however, the Suez Gulf was subjected to high cadmium contamination. Sediment mineralogy as well as the proximity of potential contamination sources plays an important role in the existence of heavy metals.

Comparison between both areas was achieved statistically (PCA), mathematically (CF and PLI) and comparably (sediment quality criteria guidelines). PCA were studied for Abu-Qir Bay and Suez Gulf sediments; the first three principal components explained 93.9 and 93.7% of the total variance, with the major percentage of cumulative variance accounted for by the first component, 47.9 and 49.6% for Abu-Qir Bay and Suez Gulf sediments, respectively. Also, PCA reflected high negative cadmium loading in both areas.

In addition, the Abu-Qir Bay and Suez Gulf marine regions showed CF $>$ 6 for Cd. Most Fe, Mn, Cu and Ni CF values for both environments were $<$1. Although all Suez Gulf stations had PLI values $<$1, some Abu-Qir Bay stations showed PLI $>$ 1. This could be explained by the highest cadmium levels in this area.

Of all the detected heavy metals, cadmium was the only one in both environments that exceeded the TEL and ERL of Canadian and NOAA guidelines. Accordingly, Abu-Qir Bay and Suez Gulf marine sediments can be considered as cadmium-contaminated environments. This contamination was mainly caused by industrial and anthropogenic activities in these two areas.

In conclusion, this study reveals that sufficient treatment of wastewaters should be carried out before fluxing into the studied areas. Also, it will be important in future to carry out seasonal and long-term studies to monitor and update the status of the studied metals concentrations.

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