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Comprehensive risk assessment of heavy metals in surface sediments along the Egyptian Red Sea coast



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Abstract The contamination of heavy metals (Fe, Zn, Mn, Cu, Ni, Pb, Cd, Co, Cr, and Hg) in 16 surface sediment samples collected from the Suez Gulf, Aqaba Gulf and the Red Sea Proper was studied to evaluate their distribution and potential ecological risk. The concentrations of the studied metals decreased in the order of Fe > Mn > Zn > Cr > Ni > Co > Pb > Cu > Cd > Hg (3490.2, 115.77, 28.66, 18.47, 11.40, 9.70, 3.26, 1.94, 6.10, 0.02 μg/g dry weight). Based on the effect-range classification (ERL–ERM, TEL–PEL, LEL–SEL), the studied heavy metals did not pose any environmental risks for all investigated stations except Marsa Alam and El-Quseir stations, which may pose an environmental risk for Cr and Ni. The ecological risk assessment for metals in surface sediments was evaluated using the metal pollution index (MPI), geoaccumulation index (*I_{geo}*), and potential ecological risk index (*E_{RI}*). Multivariate techniques including Pearson correlation, hierarchical cluster and principal components analysis were used to evaluate the metal sources.

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Introduction

Rapid industrialization and urbanization have led to the high accumulation of heavy metals and organic pollutants in soil, water, sediment, street dust, as well as organisms in urban areas (El-Hasan et al., 2002; Wei and Yang, 2010; El Nemr, 2011; Chaudhari et al., 2012; Hou et al., 2013; Hu et al., 2013; Li et al., 2013; Sedky et al., 2013). Due to their toxicity, bioaccumulation, persistence, and biomagnifications through food chains, heavy metals posed a potential threat to ecologi-

cal system and human health, and gradually drew a wide concern (El-Sikaily et al., 2004, 2005; Luo et al., 2012).

Heavy metals in aquatic environments are increasingly recognized as important intermediate sources for subsequent pollution in aquatic ecosystems or public health. Considerable efforts have been expended to assess their presence in harbors and estuaries (Khaled et al., 2006, 2010, 2012; Lin et al., 2013). After being released from natural background or anthropogenic sources near the land surface, e.g., rivers carrying significant metal loadings, soluble heavy metal species are immobilized and deposited onto the sediment surfaces through various mechanisms. The mechanisms of immobilization included adsorption on soil/sediments by coagulation, ion exchange with dissolved or suspended species in water (e.g., organic matter), incorporation into the mineral lattice structure, and precipitation due to forming insoluble species of

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heavy metals (Bryan and Langston, 1992; El Nemr et al., 2006, 2007; Du Laing et al., 2009). The aggregation of suspended particles may be enhanced by the high salinity of seawater, resulting in more rapid sedimentation of heavy metals (Du Laing et al., 2009).

Under certain environmental conditions, heavy metals might accumulate up to toxic concentrations levels, and cause ecological damage (Güven et al., 1999; Rietzler et al., 2001; Bai et al., 2011; El Nemr et al., 2012). Iron, zinc, copper and manganese are essential metals since they play important roles in biological systems (Hogstrand and Haux, 2001), but they become toxic at higher concentrations. Non-essential metals such as Pb, Cd and Hg are usually potent toxins even at relatively low concentrations and their bioaccumulation in tissues leads to intoxication, cellular and tissue damage, decreased fertility, dysfunction of a variety of organs and cell death

(Oliveira Ribeiro et al., 2002; Damek-Proprawa and Sawicka-Kapusta, 2003). Only three metals, lead, cadmium and mercury, have been included in the regulations of the European Union for hazardous metals (EC, 2001), while chromium, arsenic and nickel are listed as hazardous metals by the United States Food and Drug Administration (USFDA) (USFDA, 1993).

The distribution of metals in sediments could be used to study anthropogenic impacts on aquatic ecosystems and assess the risks posed by waste discharges (Yi et al., 2011). The concentration of metals in sediments is not an isolated factor, but interacts with surrounding environmental factors. Investigation on the relations between heavy metals and various environmental factors is beneficial to comprehensively evaluate the impacts of heavy metals on the ecosystem and grasp the pollution characteristics of local environment. Although heavy

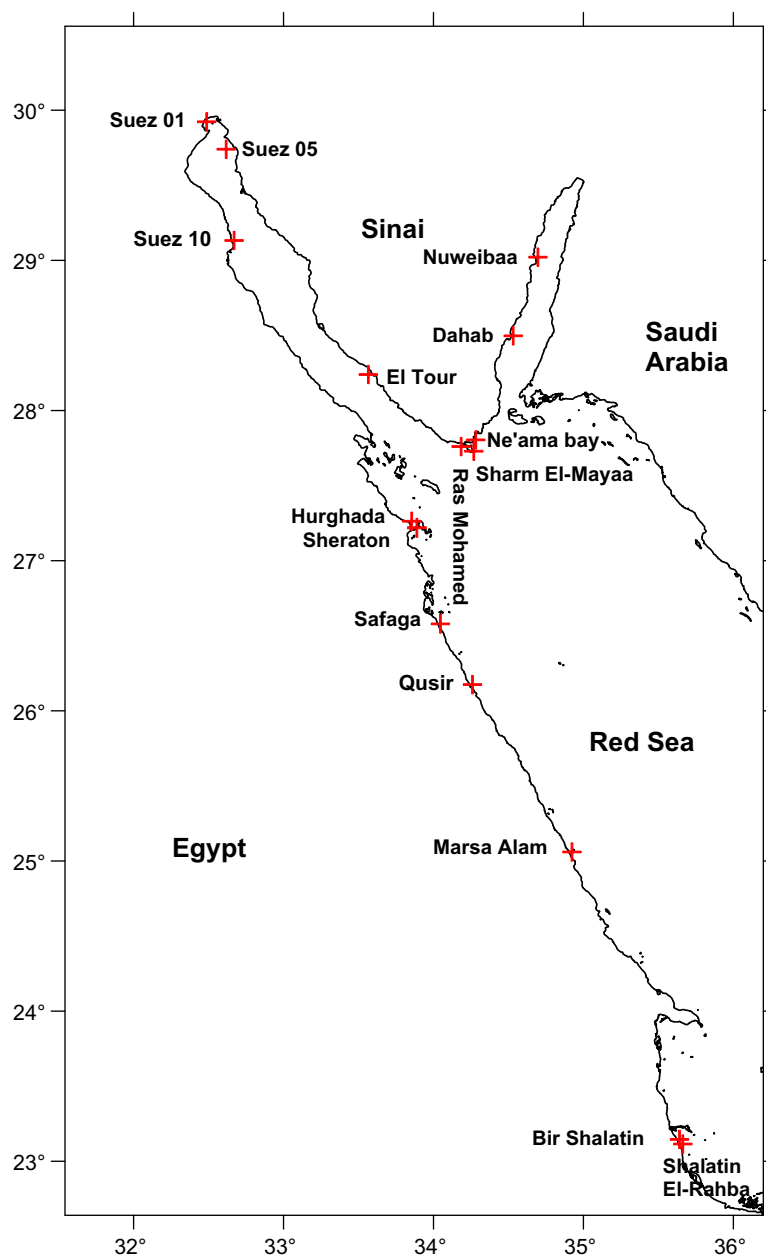


Figure 1 Map of locations.

metal analyses in sediments have been carried out extensively, unfortunately, few researches have focused on the interaction of heavy metals with the environment (Fu et al., 2014).

A number of anthropogenic and natural disturbances influence the marine environment of the Red Sea area including the pollution by: oil spills, wastewater discharge, effluents of desalination plants, and building activities along the seashore, marine traffic, land filling and dredging operations (El Nemr, 2005, 2006; El-Sikaily et al., 2004, 2005; Khaled et al., 2006). Several studies on marine surface sediments of the Egyptian Red Sea have been carried out (El-Sikaily et al., 2005; Khaled et al., 2006; Madkour et al., 2012; Mansour et al., 2013). Monitoring of chemical pollutants of the Red Sea is the initial step to ensure that a healthy marine environment can coexist with necessary human activities. The objective of this study is to determine the concentration level and distribution patterns of various heavy metals in the surface sediments of the Red Sea coast and assess the associated ecological risks of the existent concentration of heavy metals.

Materials and methods

Sixteen sampling stations were collected along approximately 1200 km of the Egyptian Red Sea coast, from Taba in Aqaba Gulf and Suez 01 from Suez Gulf to Shalatin El-Rahba in the Red Sea (Fig. 1). The surface sediment samples were collected during 2011 with a Van Veen grab from the upper 5 cm; layers were carefully taken to avoid disturbance. The upper 5 cm layer was selected because it is more chemically and biologically active than deeper layers, and substance exchanges between sediment and water occur in this layer. Immediately after collection, sediment in plastic bags were refrigerated, and transported to the laboratory. Sediments were dried at 105 °C in an oven to constant weight. After drying, the sediments were disaggregated with fingers and split to portions by the cone and quarter technique. Part of the sediment was washed and dried at 105 °C for mechanical analysis.

Grain size analysis was determined according to Folk (1974). Samples were sieved to separate stones and shells, homogenized by lightly ground in an agate mortar, and prepared for analysis. The total carbonate and silicate contents were estimated as described by Molnia (1974). About 5 g of dry sample was weighed in a clean dry beaker to which 25 ml 3N hydrochloric acid was added and heated to 50–60 °C, left to react, after complete reaction, filtered through glass filter paper, washed repeatedly with distilled water, then dried at 40 °C in an oven and reweighed the filter paper until constant weight. The difference in weight is the weight of carbonate and the residue is the non-carbonate fraction (silicate). The total organic carbon (TOC) content was determined by oxidation of sediment samples with 1 N $K_2Cr_2O_7$ acidified with concentrated H_2SO_4 followed by titration with 0.5 N $Fe(NH_4)_2(SO_4)_2$ (Loring and Rantala, 1992). Total organic matter was calculated by the equation:

$$TOM\% = TOC\% - 1.8$$

The content of total phosphorus (TP) was determined following methods of Aspila et al. (1976); sediment sample (0.5 g) was ignited for 2 h in a furnace at 550 °C. After cooling, the sample was transferred into measuring flasks (100 ml)

using 50 ml of 1 N HCl. The sample was then shaken for 14–18 h. An aliquot of the ignited solution was centrifuged for about 5 min at 2000 rpm. The clarified extracts were finally diluted and analyzed for TP according to the method reported by Murphy and Riley (1962). The inorganic phosphorus (IP) was obtained using the same method for TP omitting ignition. The organic phosphorus (OP) was calculated by the difference between TP and IP.

Determination of heavy metals in sediments was obtained using the method reported by Oregioni and Aston (1984). 0.2 g weight of dry sediment sample was digested in Teflon Vessels containing a mixture of $HNO_3:HF:HClO_4$ (3:2:1 v/v, 10 ml) (triplicate experiments were made for each sample). The obtained solution was diluted to 25 ml with double distilled water and analyzed in triplicate using an Atomic Absorption Spectrophotometer (FAAS, Shimadzo 6800, with Autosampler 6100). The AAS results were obtained in $\mu g/g$ dry weight.

For the analysis of mercury, 4 ml of concentrated sulfuric acid (H_2SO_4) and 8 ml of concentrated nitric acid (HNO_3) were added to each 0.5 g dry sediment sample in a Teflon tube. The tubes containing the reacting mixtures were heated for 24 h at 90 °C on a hot plate, and then they were left to cool down in a fume hood before opening to avoid the acid fumes' toxicity. 20 ml of double distilled water and 1 ml of $K_2Cr_2O_7$ solution were added separately and then diluted to the mark with de-ionized water.

Certified reference material (International Atomic Energy Agency, IAEA, SD-M-2/TM) was processed at the same time as the sediment samples to control the accuracy and to determine the uncertainty of metal determination. Results of the certified reference material revealed that the determined levels are within the range of certified values with 95.5–102% recovery for all studied metals.

The most common multivariate statistical methods used in environmental studies are the principal component analysis (PCA) and cluster analysis (CA). In the present study, SPSS for Windows, Version 19, was utilized for the correlation analysis and multivariate analysis.

Results and discussion

Sediment characteristics

Grain size helps in determining the textural and depositional characteristics of the environment. Particle size distribution in sediments is a function of availability of different sizes of particles in the parent material and the processes operating, where the particles were deposited (Ali et al., 1987; Mansour et al., 2013). The grain size, mean, sorting, skewness, and kurtosis of the investigated samples are shown in Table 1. The surface sediment types in the studied areas vary from very fine sand to very coarse sand, with mean grain size ranging from 3.11Φ to -0.63Φ . The texture varies from very coarse sand at El-Tour, Sharm El-Mayaa and Na'ama Bay to coarse sand at Marsa Alam to Medium sand at Suez 01 and Dahab to fine sand at Suez 05, Noweibaa, Ras Mohamed, NIOF-Hurghada, Sheraton-Hurghada, Shalatin El-Rahba and Bir Shalatin and very fine sand at Suez 10, Safaga and El-Quseir (Table 1). The occurrence of fine sediments here may be due to the dominance of terrigenous fine grain size sediments. The change of mean

Table 1 Characterization of the coastal surface sediments of Egyptian Red Sea during 2011.

Station	Mean(\bar{O})		Sorting(\bar{O})		Skewness		Kurtosis	
	Value	Character	Value	Character	Value	Character	Value	Character
Suez	Suez 01	-1.96 (Medium sand)	2.12 (Very poorly sorted)	0.19 (Coarse skewed)	0.58 (Very Platykurtic)			
Gulf	Suez 05	2.49 (Fine sand)	0.46 (Well sorted)	-0.06 (Near symmetrical)	1.21 (Leptokurtic)			
	Suez 10	3.11 (Very fine sand)	0.92 (Moderately sorted)	-0.49 (Coarse skewed)	1.58 (Very Platykurtic)			
	El-Tour	-0.63 (Very coarse sand)	1.52 (Poorly sorted)	0.65 (Strongly fine skewed)	1.35 (Leptokurtic)			
Aqaba Gulf	Noweibaa	2.09 (Fine sand)	1.5 (Poorly sorted)	-0.41 (Strongly coarse skewed)	1.36 (Leptokurtic)			
	Dahab	1.70 (Medium sand)	1.01 (Poorly sorted)	-0.15 (Coarse skewed)	0.73 (Patykurtic)			
	Sharm El-Mayaa	-0.45 (Very coarse sand)	1.00 (Moderately sorted)	0.83 (Strongly fine skewed)	0.68 (Patykurtic)			
	Ras Mohamed	2.71 (Fine sand)	0.76 (Moderately sorted)	0.02 (Near symmetrical)	1.16 (Leptokurtic)			
	Na'ama Bay	-0.04 (Very coarse sand)	0.79 (Moderately sorted)	-0.26 (Coarse skewed)	0.88 (Patykurtic)			
Red Sea Proper	NIOF-Hurghada	2.22 (Fine sand)	1.27 (Poorly sorted)	-0.24 (Coarse skewed)	0.87 (Patykurtic)			
	Sheraton-Hurghada	2.22 (Fine sand)	1.70 (Poorly sorted)	-0.16 (Coarse skewed)	0.88 (Patykurtic)			
	Safaga	3.08 (Very fine sand)	0.82 (Moderately sorted)	-0.41 (Coarse skewed)	1.17 (Leptokurtic)			
	El-Qusir	3.11 (Very fine sand)	1.10 (Poorly sorted)	-0.42 (Coarse skewed)	1.69 (Very Platykurtic)			
	Marsa Alam	0.26 (Coarse sand)	0.93 (Moderately sorted)	0.43 (Fine skewed)	0.68 (Patykurtic)			
	Shalaten	2.71 (Fine sand)	0.84 (Moderately sorted)	-0.04 (Near symmetrical)	1.37 (Leptokurtic)			
	El-Rahba							
	Bir Shalaten	2.31 (Fine sand)	1.77 (Poorly sorted)	-0.44 (Coarse skewed)	0.76 (Patykurtic)			

Table 2 Description of the coastal surface sediment of Egyptian Red Sea during 2011.

Location		TOC %	TOM %	TCO ₃ %	TSIO ₃ %	TP ($\mu\text{g/g}$)	IP ($\mu\text{g/g}$)	OP ($\mu\text{g/g}$)
Suez Gulf	Suez 01	0.66	1.18	86.88	13.12	215.48	158.11	57.37
	Suez 05	0.26	0.47	89.52	10.48	195.12	154.46	40.66
	Suez 10	0.14	0.24	96.45	3.55	652.87	446.11	206.76
	El-Tour	0.06	0.1	80.35	19.65	501.91	252.61	249.3
Aqaba Gulf	Noweibaa	0.19	0.35	78.59	21.41	452.27	279.02	173.25
	Dahab	0.14	0.24	82.08	17.92	606.73	381.03	225.7
	Sharm El-Mayaa	0.24	0.43	71.29	28.71	344.11	230.83	113.28
	Ras Mohamed	0.17	0.31	83.68	16.32	339.31	213.69	125.62
	Na'ama Bay	0.49	0.89	30.81	69.19	409.24	161.46	247.78
Red Sea Proper	Hurghada	0.42	0.76	84.16	15.83	735.69	360.15	375.54
	Sheraton	0.73	1.31	73.86	26.14	694.23	627.84	66.39
	Safaga	0.31	0.56	55.6	44.4	2634.97	2143.25	491.72
	Qusir	0.2	0.37	43.88	56.12	1444.12	1202.26	241.86
	Marsa Alam	0.23	0.42	24.58	75.42	1085.1	747.97	337.13
	Shalatin El-Rahba	0.37	0.66	98.93	1.07	554.97	344.07	210.9
	Bir Shalatin	0.35	0.63	80.27	19.73	971.41	427.79	543.62

grain size may reflect different erosions and accretions, as well as the influence of shell fragments (El Nemr et al., 2013).

The sediments in Marsa Alam, Na'ama Bay and El-Qusir are mainly silicates (75.42, 69.19, 56.12%, respectively) while the sediments of the rest of studied stations except Safaga were characterized by high carbonate contents (71.29–98.93%) as showing in Table 2. The carbonate content in Safaga sediment (55.6%) is relatively low indicating the high supply of terrigenous materials at Safaga. It seems that the richness in the carbonate content is mainly due to their biogenic origin containing coral reefs and marine shells as well as land-derived terrigenous materials (Usman et al., 2013). In general, the highest value resulted from the increase of the shell fragments; this richness in carbonate content is attributed to materials derived from terrestrial origin. Also, the carbonate distribution is affected by the flow of shells and their movements over the bottom. Lower carbonate contents are found in areas

subjected to the direct winnowing effects of water. Also, this can be attributed to the inverse relationship between the amount of terrigenous mud and carbonate content it may be due to the recent deposition of the organic carbon in reducing system which would prevent the decay of the buried shell fragments (El Nemr et al., 2013).

The OM content of sediment is a result of the decomposition of both plants and organisms by bacterial action, in addition to those derived from terrigenous deposits. It is composed generally of lightweight materials. Sedimentation of these materials follows the same laws as those of fine particles, which both accumulate in calm zones. Total organic matter of studied stations ranges between 0.10% at El-Tour and 1.31% at Sheraton (Table 2). About 87.5% of the studied locations have low TOM (except Suez 01 and Sheraton), which is an indication to the prevalence of some hydrodynamic factors that provoked winnowing any material less dense than shells. Also, the

Table 3 Mean concentrations of metals ($\mu\text{g/g}$ dry weight) in sediment samples collected along Egyptian Red Sea Coast during 2011.

Location		Concentration of metals in sediments ($\mu\text{g/g}$ dry weight)										MPI
		Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	
Suez Gulf	Suez 01	0.126 ± 0.003	1.763 ± 0.215	10.571 ± 0.264	1.729 ± 0.029	1458.641 ± 0.434	0.034 ± 0.0015	38.802 ± 0.688	7.457 ± 0.303	3.742 ± 0.212	25.941 ± 1.172	4.73
	Suez 05	0.146 ± 0.001	1.547 ± 0.015	7.756 ± 0.358	0.852 ± 0.141	1256.313 ± 0.649	0.032 ± 0.0004	45.271 ± 1.261	5.809 ± 0.094	2.229 ± 0.042	12.162 ± 2.263	3.66
	Suez 10	0.215 ± 0.016	1.434 ± 0.007	9.005 ± 0.525	2.013 ± 0.177	869.030 ± 11.778	0.031 ± 0.0011	50.430 ± 1.968	6.616 ± 0.043	3.186 ± 0.003	20.232 ± 0.969	4.47
	El-Tour	0.026 ± 0.001	53.472 ± 0.017	2.625 ± 0.118	1.314 ± 0.077	6163.124 ± 28.777	0.021 ± 0.0031	52.885 ± 2.828	2.641 ± 0.106	1.928 ± 0.214	10.871 ± 0.19	4.22
Aqaba Gulf	Nuweiba	0.063 ± 0.003	4.652 ± 0.231	6.573 ± 0.245	1.373 ± 0.152	3661.741 ± 25.222	0.007 ± 0.0002	126.402 ± 5.714	4.502 ± 0.117	3.450 ± 0.089	16.685 ± 0.129	4.33
	Dahab	0.027 ± 0.003	39.783 ± 1.242	8.865 ± 0.155	1.978 ± 0.106	10413.600 ± 11.244	0.003 ± 0.0002	453.907 ± 5.656	4.236 ± 0.111	3.246 ± 0.087	30.101 ± 0.94	6.37
	Sharm El-Maya a	0.150 ± 0.006	4.084 ± 0.182	4.909 ± 0.829	1.493 ± 0.22	2867.447 ± 7.248	0.029 ± 0.001	299.877 ± 11.704	3.763 ± 0.309	2.883 ± 0.235	22.316 ± 0.64	5.53
	Ras Mohamed	0.032 ± 0.003	4.409 ± 0.133	4.107 ± 0.396	0.940 ± 0.088	1666.731 ± 27.04	0.009 ± 0.0006	64.010 ± 5.126	3.393 ± 0.305	2.599 ± 0.234	12.711 ± 0.842	3.00
	Na'ama Bay	0.046 ± 0.001	3.234 ± 0.079	3.929 ± 0.248	0.898 ± 0.015	3170.594 ± 14.634	0.021 ± 0.001	91.587 ± 2.992	6.992 ± 0.264	5.358 ± 0.203	18.463 ± 0.812	4.31
Red Sea proper	NIOF-Hurghada	0.089 ± 0.001	1.429 ± 0.01	9.161 ± 0.087	0.958 ± 0.089	831.815 ± 7.344	0.017 ± 0.0005	51.722 ± 1.696	5.710 ± 0.11	2.451 ± 0.249	17.795 ± 0.429	3.39
	Sheraton-Hurghada	0.031 ± 0.005	1.945 ± 0.096	10.679 ± 0.432	1.870 ± 0.043	1721.482 ± 11.705	0.030 ± 0.0021	52.314 ± 0.991	10.566 ± 0.583	4.345 ± 0.224	22.609 ± 1.906	4.49
	Safaga	0.104 ± 0.018	4.542 ± 0.189	23.714 ± 0.375	1.804 ± 0.077	5381.603 ± 11.816	0.033 ± 0.0026	206.989 ± 0.951	10.058 ± 0.345	5.125 ± 0.093	38.094 ± 0.782	8.24
	El-Qusir	0.307 ± 0.005	7.783 ± 0.28	97.432 ± 1.546	3.652 ± 0.26	5048.326 ± 12.753	0.035 ± 0.0008	169.268 ± 1.579	31.592 ± 2.865	4.277 ± 0.444	39.628 ± 0.992	12.99
	Marsa Alam	0.061 ± 0.008	15.089 ± 0.133	98.968 ± 0.023	9.066 ± 0.131	9946.273 ± 8.391	0.018 ± 0.0007	242.937 ± 1.416	72.499 ± 2.684	2.854 ± 0.046	39.003 ± 0.128	13.97
	Shalaten El-Rahba	0.132 ± 0.003	0.923 ± 0.075	4.800 ± 0.036	0.642 ± 0.056	398.073 ± 13.949	0.037 ± 0.0008	36.697 ± 1.849	4.663 ± 0.142	1.958 ± 0.048	16.712 ± 0.639	2.81
	Bir Shalaten	0.086 ± 0.009	2.654 ± 0.089	16.116 ± 0.132	1.483 ± 0.082	1175.539 ± 22.246	0.028 ± 0.0007	50.426 ± 2.412	14.570 ± 0.38	2.686 ± 0.237	26.777 ± 0.002	4.98
	Average	0.102	9.696	18.465	1.938	3490.174	0.024	127.085	11.404	3.255	22.636	5.72

low value attributes to the position of the sampling from the terrestrial discharge, which is regarded as the main contributor of the organic detritus; thus may indicate that the oxidizing conditions is dominance due to a low sedimentation rate and permanent sediment reworking (El-Askary et al., 1988; El Nembr et al., 2013).

An abundant trace element such as phosphorus is considered as one of the most important nutrients for all living organisms (Codispoti, 1989).

The dissolved form of phosphorus which enters the aquatic environment may be associated with particulates and settle out of the water column (Bloesch et al., 1988). During erosion, a large quantity of phosphorus was liberated from minerals (Khorolef, 1975; Liss, 1976). The results of TP, IP and OP contents are listed in Table 2. The TP ranged from 195.12 $\mu\text{g/g}$ at Suez 05 to 2634.97 $\mu\text{g/g}$ at Safaga. Results showed that the inorganic phosphorus was the dominant form (70%), while the OP comprises about 31% of the TP.

Heavy metals

The concentration levels of the studied heavy metals (Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn) detected in the surface

sediments of the Suez Gulf, Agaba Gulf and the Red Sea proper are presented in Table 3. Iron, Manganese and Zinc exhibited relatively high concentrations while mercury was generally the lowest one (Förstner and Wittmann, 1983). Most of the iron is present in association with the carbonate fraction, probably sorbed on the surface of the particles or more likely substitutes Ca in the calcite crystals (Beltagy, 1984). In the present study, iron was detected in an amount that fluctuated between 398.1 and 10413.6 $\mu\text{g/g}$ dry weight at Shalaten El-Rahba and Dahab, respectively with an average value of 3490.2 $\mu\text{g/g}$ dry weight. In the study areas, these high values are related to terrestrial inputs and the drainage of waste water. Mansour et al. (2000) found that Fe concentrations of the shallow marine sediments in different transects along the Red Sea coast are relatively high indicating the terrigenous contamination. Fe level in all studied sediment samples was below lowest effect level (LEL) and sever effect level (SEL) (Persaud et al., 1993) (Table 4).

Manganese is an essential element for both plants and animals; its deficiency may cause severe skeletal and reproductive abnormalities in mammals (Sivaperumal et al., 2007). There is no information on the carcinogenicity of manganese (Agency for Toxic Substances and Disease Registry, 2004). Manganese

Table 4 Sediment quality guidelines for metals. Concentration unit is in $\mu\text{g/g}$, except Fe in %.

The guide line	Heavy metals									References	
	Fe (%)	Mn	Zn	Cu	Pb	Ni	Cd	Hg	Cr		
Sediment quality guidelines (ERM)			410	270	218	51.6	9.6	0.71	370	NOAA (2012)	
Sediment quality guidelines (ERL)			150	34	46.7	20.9	1.2	0.15	81	NOAA (2012)	
Metal background guidelines			100	15	5	10	0.3	0.08		SEPA (1998)	
Canadian sediment quality guidelines (TEL)			124	18.7	30.2		0.7	0.13	37.3	CCME (2002), Mac Donald et al. (2000)	
Canadian sediment quality guidelines (PEL)			271	108	112		4.2	0.7	90	CCME (2002), Mac Donald et al. (2000)	
Guidelines for Metals in sediments (LEL)	2		460	120	16	31	16	0.6	0.2	26	Persaud et al. (1993), Mac Donald et al. (2000)
Guidelines for Metals in sediments (SEL)	4		1100	820	110	250	75	10	2	110	Persaud et al. (1993), Mac Donald et al. (2000)

Table 5 Correlation coefficient among metals, total organic carbon, total carbonate, total silicate and total phosphate in marine sediments.

	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	TOC	TCO3	TSiO3	TP
Cd	1													
Co	-0.372	1												
	0.155													
Cr	0.420	0.013	1											
	0.105	0.962												
Cu	0.075	0.132	0.855**	1										
	0.784	0.625	0.000											
Fe	-0.247	0.695**	0.502*	0.631**	1									
	0.356	0.003	0.048	0.009										
Hg	0.633**	-0.426	0.136	-0.065	-0.464	1								
	0.008	0.100	0.617	0.810	0.070									
Mn	-0.070	0.398	0.273	0.361	0.781**	-0.401	1							
	0.796	0.127	0.306	0.170	0.000	0.124								
Ni	0.126	0.015	0.901**	0.971**	0.525*	0.026	0.239	1						
	0.643	0.957	0.000	0.000	0.037	0.923	0.373							
Pb	0.079	-0.260	0.177	0.052	0.136	0.131	0.175	0.063	1					
	0.771	0.330	0.513	0.850	0.616	0.628	0.517	0.818						
Zn	0.320	-0.027	0.762**	0.665**	0.550*	0.180	0.544*	0.662**	0.493	1				
	0.227	0.921	0.001	0.005	0.027	0.506	0.030	0.005	0.052					
TOC	-0.137	-0.506*	-0.156	-0.145	-0.428	0.379	-0.363	-0.072	0.414	0.046	1			
	0.614	0.045	0.565	0.592	0.098	0.147	0.166	0.791	0.111	0.866				
TCO3	0.009	-0.028	-0.682**	-0.644**	-0.542*	0.054	-0.337	-0.692**	-0.581*	-0.601*	-0.039	1		
	0.974	0.918	0.004	0.007	0.030	0.843	0.201	0.003	0.018	0.014	0.885			
TSiO3	-0.009	0.028	0.682**	0.644**	0.542*	-0.054	0.337	0.692**	0.581*	0.601*	0.039	-1.000**	1	
	0.974	0.918	0.004	0.007	0.030	0.843	0.201	0.003	0.018	0.014	0.885	0.000		
TP	0.214	-0.044	0.467	0.301	0.318	0.250	0.244	0.334	0.469	0.727**	-0.075	-0.427	0.427	1
	0.427	0.871	0.068	0.258	0.230	0.350	0.362	0.205	0.067	0.001	0.783	0.099	0.099	

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

is a naturally occurring element and comprises about 0.1% of the Earth's crust (NAS, 1973). The manganese content in sediments of the studied stations ranges between 453.907 $\mu\text{g/g}$ at Dahab and 36.697 $\mu\text{g/g}$ dry weight at Shalaten El-Rahba. Nawar and Shata (1989) related the increase of Mn in the near-shore sediments of the northern Red Sea to its incorporation in the crystal lattice of calcite. Dar (2002) stated that the highest Mn contents in Hurghada area and its surroundings recorded with the high mud content sediments indicate terrigenous origin. The concentration level of Mn in all collected sediment samples was below LEL, lowest effect level and SEL, and severe effect level (Persaud et al., 1993) (Table 4). The sources of Mn in the marine environment of studied area are the same as Fe (significant correlation $r = 0.781$, Table 5).

Zinc is one of the most important essential trace metals for enzyme and protein productions (Vallee, 1978). Zinc appears to have a protective effect against the toxicities of both cadmium and lead (Calabrese et al., 1985). Zinc is widely distributed in nature, making up between 0.0005% and 0.02% of the Earth's crust (Irwin et al., 1997). It is widely detected in industrial and mining wastewaters (Cameron, 1992; Mulligan et al., 2001). Hamed et al. (2009) reported that Zn can be precipitated as ZnCO_3 which is a result of the high content. The mean concentrations of zinc were ranging from 10.87 $\mu\text{g/g}$ at El-Tur to 39.63 $\mu\text{g/g}$ dry weight at El-Quseir with an average value of 22.64 $\mu\text{g/g}$ dry weight. El-Quseir, Marsa Alam and Safaga have the highest Zn concentrations among the other studied stations. The average concentration of Zn in the present study

was lower than the effect range medium (ERM), the effect range low (ERL), threshold effect level (TEL), probable effect level (PEL), lowest effect level (LEL), and severe effect level (SEL) (NOAA, 2012; CCME, 2002, Mac Donald et al., 2000; Persaud et al., 1993) (Table 4).

Copper is necessary for the synthesis of hemoglobin and it is an essential part of several enzymes (Underwood, 1977). However, a high intake of Cu has been recognized to cause adverse health problems (Gorell et al., 1997). Copper concentrations ranged from 0.64 µg/g at Shalaten El-Rahba to 9.066 µg/g dry weight at Marsa Alam with an average concentration of 1.94 µg/g dry weight (Table 3). Marsa Alam, El-Quseir and Suez 10 have the highest Cu concentrations among the other studied stations. The concentrations of Cu in all studied samples were below the toxic limit (30 µg/g) (FAO, 1983). The concentration level of copper in all studied stations was below ERL which means that biological effects are rarely observed. It is also lower than Threshold effect level (TEL) (CCME, 2002); PEL, probable effect level (CCME, 2002); LEL, lowest effect level; SEL, severe effect level (Persaud et al., 1993) and the background level which is suggested by SEPA (1998) (Table 4).

Cobalt is an essential metal for man, and is an integral part of vitamin B12. The cobalt average daily intake ranged from 0.3 to 1.77 mg (Underwood, 1977) which helps in the blood pressure regulation (Perry et al., 1954) and necessary for thyroid function (Blakhima, 1970). On the other hand, high dose of cobalt may cause polycythemia, anemia and congestive heart failure (Alexander, 1972).

Sediments collected from El-Tur presented the highest concentration value of Co (53.47 µg/g dry weight) followed by Dahab (39.78 µg/g dry weight) and Marsa Alam (15.09 µg/g dry weight), while the lowest value was detected in Shalaten El-Rahba (0.92 µg/g dry weight).

Among the different metals analyzed, mercury, cadmium, lead, nickel and chromium are classified as chemical hazards (EC, 2001; USFDA, 1993). Traces of Cadmium were detected in all collected samples. The highest concentrations were recorded at El-Quseir (0.31 µg/g dry weight) and Suez 10 (0.22 µg/g dry weight) followed by those detected in sediments collected from Sharm El-Maya, Suez 05, Shalaten El-Rahba, Suez 01 and Safaga stations (Table 3). The lowest cadmium concentrations were observed at El-Tur and Dahab stations (0.03 and 0.03 µg/g dry weight, respectively). The use of Cd in batteries, pigments, plating, and stabilizers ensures the continuing demand for Cd in the market which are possible sources for its environmental occurrence (Boehme and Panero, 2003; Lin et al., 2013). The Cd concentrations in the sediments of studied area may be attributed to the terrigenous origin and the increase of human activities in the region such as tourism, land-filling, marinas, the wastewater discharging pipes and industrial activities. The concentration level of cadmium in all collected sediment samples is below ERL indicating that biological effects are rarely observed. It is also lower than Threshold effect level (TEL) (CCME, 2002); probable effect level (PEL) (CCME, 2002); lowest effect level (LEL) (Persaud et al., 1993) and severe effect level (SEL) (Persaud et al., 1993). Cadmium levels in all studied stations are below the background level which is suggested by SEPA (1998), except El-Quseir station which exhibits Cd concentration equal to the background level (Table 4).

Chromium is generally produced by industrial processes; trivalent and hexavalent forms are used in chemical industries including chrome plating, dye and pigment manufacture, leather tanning, and wood preserving (Lin et al., 2013). The average daily intake of chromium is 1 µg (Mertz, 1969) while its deficiency causes glucose, lipid, and protein metabolism disturbance (Calabrese et al., 1985). In the current study, chromium was detected in all the studied samples and ranged between 2.63 µg/g at El-Tur and 98.97 µg/g at Marsa Alam, with an average value of 18.47 µg/g dry weights. All the collected samples showed Cr concentrations below ERL except Marsa Alam (98.97 µg/g dry weights) and El-Quseir (97.43 µg/g dry weights) stations, which exhibit a relatively high Cr concentration than ERL, but still less than ERM (Table 4), representing a range within which biological effects occur occasionally. Also Marsa Alam and El-Quseir stations presented Cr concentrations higher than TEL (CCME, 2002); PEL (CCME, 2002) and LEL (Persaud et al., 1993) but lower than SEL (Persaud et al., 1993).

WHO (2003) reported that, even regions without mercury emissions can have substantial environmental mercury levels due to global mercury cycling through air and water. Mercury concentrations ranged from 0.003 to 0.037 µg/g dry weight in all the analyzed samples, with an average value of 0.024 µg/g dry weight (Table 3). Mercury concentrations in all sediment samples were below ERL value (0.15 µg/g) where biological effects are rarely observed. Also it is lower than TEL (CCME, 2002); PEL (CCME, 2002); LEL (Persaud et al., 1993); SEL (Persaud et al., 1993) and the background level which is suggested by SEPA (1998), (Table 4).

Lead occurs naturally from the decomposition of parent rocks and may accumulate from anthropogenic sources, including traffic exhaust, lead-zinc smelters, dumps and other sites receiving industrial and household lead, e.g., paints and batteries (Cameron, 1992). Adsorption on organic matter and clay minerals effectively removed Lead from the water column to the sediment (Irwin et al. (1997). The Pb concentrations of the marine sediments in the studied stations range between 1.93 µg/g dry weight at El-Tur and 5.36 µg/g dry weight at Na'ama Bay with an average value of 3.26 µg/g dry weight. The highest concentrations of Pb were detected at Na'ama Bay, Safaga, Sheraton-Hurghada and El-Quseir (Table 3). This may be attributed to anthropogenic activities in Safaga and Hurghada Harbors including oil spills, motor boats, coal shipment in Safaga Harbor and untreated wastes as previously mentioned by Mansour et al. (2011). Lead concentrations in all sediment samples were below ERL value (16.7 µg/g) where biological effects are rarely observed. It is also lower than TEL; PEL; LEL; SEL and the background level (Table 4).

The essential function of nickel, in enzymes such as urease and hydrogenase, in most plants and some microorganisms is well-known. On the other hand, nickel is a carcinogenic metal and overexposure to it can cause heart and liver damage, decreased body weight and skin irritation (Homady et al., 2002). The nickel concentration in studied samples showed a wide variation where the highest concentration was detected at Marsa Alam station (72.5 µg/g); while the lowest was observed at El-Tur station (2.64 µg/g) with an average value of 11.40 µg/g dry weight. Sediment samples from Marsa Alam, El-Quseir and Bir Shalaten stations recorded the highest values of nickel. This may be attributed to terrigenous input and

Table 6 Mean or range of heavy metal concentrations ($\mu\text{g/g}$ dry weight) in marine sediments collected along Egyptian Red Sea Coast during 2011 in comparison with other studies in the same area, other areas of Red Sea and the world.

Location	Fe	Mn	Zn	Cu	Pb	Ni	Cd	Hg	Cr	Co	References
Red Sea, Egypt	3490	127.085	22.636	1.938	3.255	11.404	0.102	0.024	18.465	9.696	The present work
Hurghada area and surroundings	9500	354.255	27.5525	20.3025	40.225	33.2925	1.34				Mansour et al. (2000)
North of Suez Gulf			4.26–23.68	1.84–10.25	13.9–28.34			2.26–4.4			El-Moselhy and Gabal (2004)
El-Hamrewein Harbour	1800	529	73.4	17.9	38.5	42.2	2.3				Madkour et al. (2006)
Hurghada area	2000	177.78	4.66	0.67	12.89	1.91	0.52				Mansour et al. (2007)
Hurghada area and surroundings	10,725	578	15.1	23.5	15.725	20.9	0.6				Mansour et al. (2011)
Hurghada area		415.55	42.28	25.975	40.955	29.7975	0.6975				El-Taher and Madkour (2011)
Hurghada area and surroundings	2600	49	12.41	4.57	1.51	7.21	0.11	0.02			Mansour et al. (2013)
Aqaba Gulf, Jordan	3400–14,600	68.2–263	24–195	7.1–24	96.3–182	30–62.1	3.9–13.7				Abu-Hilal et al. (1988)
Adriatic sea, Italy	8800		95.8	16.98	4.43		0.2	0.28			Storelli et al. (2001)
Caspian Sea, Iran					11.3–24.6	29.4–67.8	0.098–0.244				Mora and Sheikholeslami (2002)
Black Sea, Turkey	5000–54,000	206.6–870.3	33.9–267.4	4–95.5	0.05–31.1	13.55–65.2	0.02–0.93				Topcuoglu et al. (2002)
Al-Hodeidah coast, Yemen	100–200	9.17–24.21	4.02–18.25	36.7–79.9	4.99–6.26	7.1–116.4	0.2–5.8				Heba et al. (2004)
Jeddah coast	5000	105	18	11							Basaham et al. (2009)
Mediterranean Sea, Egypt				30.3	27.84	38.76					Ahdy and Khaled (2009)

wastewater discharge. Nickel concentrations in all studied samples were below ERL value; however, El-Quseir station presented Ni value greater than ERL, but less than ERM representing a range within which biological effects occur occasionally. At Marsa Alam station, Ni concentration was above ERM values representing a probable effect range within which adverse biological effects frequently occur. Also Marsa Alam and El-Quseir stations presented Ni concentrations higher than LEL (Persaud et al., 1993), but lower than SEL (Persaud et al., 1993). Ni levels at Sheraton-Hurghada, Safaga, El-Quseir, Marsa Alam and Bir Shalaten stations were higher than the background level suggested by SEPA (1998) (Table 4).

Comparisons of the heavy metal levels in the three studied areas, Suez Gulf, Agaba Gulf and the Red Sea proper showed that Fe and Mn levels at Agaba Gulf are higher than those detected at Suez Gulf and the Red Sea proper, while Co and Cd show higher values at Suez Gulf than those detected at the two other areas. However, Zn, Cr, Cu and Ni recorded higher concentrations at the Red Sea proper.

Comparisons of the metals in the present study with others collected from Hurghada area (Table 6) show that Mn and Pb are lower than the levels reported by Mansour et al. (2000), El-Moselhy and Gabal (2004), Madkour (2005, 2011), and El-Taher and Madkour (2011) but higher than those reported by Mansour et al. (2013). Iron, copper, nickel and cadmium recorded lower values than those reported by Mansour et al. (2000) but zinc recorded a comparable value. Meanwhile, the concentrations of Zn, Cu, Ni, and Cd were lower than those reported by Madkour et al. (2006) and El-Taher and

Madkour (2011). On the other hand, the present concentrations of Zn, Cu and Ni are higher than those reported by Mansour et al. (2007) but lower than the Cd concentration. Iron in the present study recorded a higher value than those reported by Madkour et al. (2006) and Mansour et al. (2007, 2013). Meanwhile Zn recorded a higher value than those recorded by Mansour et al. (2011, 2013) and recorded a comparable value with that reported by El-Moselhy and Gabal (2004). Cd and Cu in the present study recorded concentration levels lower than those reported by El-Moselhy and Gabal (2004) and a higher value of Cu, comparable values for Cd and Hg were recorded than those published by Mansour et al. (2013).

Fe and Mn in the present study showed lower concentrations than those found in the sediments of Black Sea, Turkey (Topcuoglu et al., 2002) but higher concentrations than those found in the sediments of Al-Hodeidah area, Yemen (Heba et al., 2004). Cu and Pb showed values lower than those demonstrated by Abu-Hilal et al. (1988), Heba et al. (2004), Storelli et al. (2001), Topcuoglu et al. (2002) and Ahdy and Khaled (2009). Additionally, levels of Cd and Zn recorded by Abu-Hilal et al. (1988), Storelli et al. (2001), and Topcuoglu et al. (2002) are higher than those in the current results; whereas Mora and Sheikholeslami (2002) recorded lower concentrations of Cd and Ni than those found in the current study. Zn recorded higher values than those reported by Heba et al., 2004 and Basaham et al. (2009), while Hg recorded lower values than those reported by Storelli et al. (2001). The cobalt concentrations in the present study are higher than those found in the sediments of the Florida Bay (5.0 $\mu\text{g/g}$ dry weight)

Table 7 Müller’s classification for the geoaccumulation index (Müller, 1981).

Igeo value	Class	Quality of sediment
≤0	0	Unpolluted
0–1	1	Unpolluted to moderately polluted
1–2	2	Moderately polluted
2–3	3	Moderately to strongly polluted
3–4	4	Strongly polluted
4–5	5	Strongly to extremely polluted
≥6	6	Extremely polluted

(Caccia et al., 2003) but lower than those detected in the sediment of the Black Sea (17.8 µg/g dry weight) (Secrieru and Secrieru, 2002).

Metal pollution index (MPI)

The overall heavy metal content of sediments at the studied locations in the current study was compared using MPI and calculated with the following formula (Usero et al., 1996, 1997).

$$MPI = (Cf_1 \times Cf_2 \times \dots \times Cf_n)^{1/n}$$

where *n* is the number of metals studied. The highest metal pollution indices were recorded for Marsa Alam and El-Quseir stations (13.97 and 12.99, respectively) followed by Dahab, Sharm El-Maya and Bir Shalaten stations (8.24, 6.37, 5.53 and 4.98, respectively); while the lowest MPI was recorded for Shalaten El-Rahba (2.81). This high MPI may be due to marine transportation, industrial and human activities in these locations. On the other hand, Shalaten El-Rahba recorded the lowest MPI (2.81), while the other stations fluctuated between 3.00 and 4.73 (Table 3).

Geoaccumulation index

To understand the current status of the environment and the heavy metal contamination with respect to the natural

environment for the Suez Gulf, Agaba Gulf and the Red Sea Proper, geoaccumulation index (*Igeo*) was applied using the following equation (Müller, 1979):

$$Igeo = \log_2[C_n / (1.5 \times B_n)]$$

where, *C_n* is the concentration of the examined metal in the studied surface sediment and *B_n* is the geochemical background of a given metal (Adamo et al., 2005) and the factor 1.5 is the matrix correction factor of the background due to the lithogenic effects. Müller (1981) has distinguished seven classes of *Igeo* (Table 7). The *Igeo* values for the three studied areas were represented in Table 8. According to the Müller scale, the calculated *Igeo* values for Cu, Fe, Mn, Pb and Zn in all studied sediments belong to class zero which indicate that the sediments in all stations are uncontaminated by these metals. On the other hand, sediments of El-Quseir station fluctuated from uncontaminated to moderately contaminated by Cd (*Igeo* = 0.033) and Ni (*Igeo* = 0.696) and moderately contaminated by Cr (*Igeo* = 1.934). Moreover, Marsa Alam sediment is moderately contaminated by Cr (*Igeo* = 1.956) and Ni (*Igeo* = 1.894) (Table 7). Results of *Igeo* are in agreement with these shown from MPI.

Potential risk index

To evaluate the potential risk posed by the heavy metals to the marine ecosystem in the surface sediments of the Suez and Aqaba Gulfs as well as the Red Sea, ecological risk assessment was conducted. The ecological risk index (*E_{RI}*) that was originally introduced by Hakanson (1980), was obtained from the following equations:

$$E_r^i = T_r^i \times \frac{C^i}{C_0^i}$$

$$E_{RI} = \sum_{i=1}^7 E_r^i$$

where *E_rⁱ* is the monomial potential ecological risk factor; *Cⁱ* and *C₀ⁱ* are the obtained concentration of specific metal and its reference value in sediment (µg/g dw), respectively; *T_rⁱ* is

Table 8 Geoaccumulation index (*Igeo*) values of heavy metals of sediment samples in the investigated areas.

Location		Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Suez Gulf	Suez 01	-1.252	-1.270	-3.495	-3.741	-4.055	-1.387	-2.588	-1.695
	Suez 05	-1.039	-1.717	-4.516	-3.956	-3.833	-1.747	-3.335	-2.788
	Suez 10	-0.481	-1.502	-3.276	-4.488	-3.677	-1.559	-2.820	-2.054
	El-Tour	-3.528	-3.280	-3.891	-1.662	-3.608	-2.884	-3.545	-2.950
Agaba Gulf	Nuweiba	-2.252	-1.956	-3.828	-2.413	-2.351	-2.115	-2.705	-2.332
	Dahab	-3.474	-1.524	-3.301	-0.905	-0.507	-2.203	-2.793	-1.481
	Sharm El-Mayaa	-1.000	-2.377	-3.707	-2.766	-1.105	-2.374	-2.964	-1.912
	Ras Mohamed	-3.229	-2.634	-4.375	-3.548	-3.333	-2.523	-3.114	-2.724
	Na’ama Bay	-2.705	-2.698	-4.441	-2.621	-2.816	-1.480	-2.070	-2.186
Red Sea proper	NIOF-Hurghada	-1.753	-1.477	-4.347	-4.551	-3.640	-1.772	-3.198	-2.239
	Sheraton-Hurghada	-3.275	-1.256	-3.382	-3.502	-3.624	-0.884	-2.372	-1.893
	Safaga	-1.528	-0.105	-3.434	-1.857	-1.640	-0.955	-2.134	-1.141
	El-Qusir	0.033	1.934	-2.417	-1.950	-1.930	0.696	-2.395	-1.084
	Marsa Alam	-2.298	1.956	-1.105	-0.971	-1.409	1.894	-2.979	-1.107
	Shalaten El-Rahba	-1.184	-2.409	-4.925	-5.614	-4.136	-2.064	-3.522	-2.330
	Bir Shalaten	-1.803	-0.662	-3.717	-4.052	-3.677	-0.420	-3.066	-1.649

Table 9 Ecological risk factor (E_r^i) and potential risk index (E_{RI}) of the surface sediments along the coast of the Egyptian Red Sea estimated from their heavy metal contents.

Location		E_r^i						E_{RI}
		Cd	Cr	Cu	Ni	Pb	Zn	
Suez Gulf	Suez 01	54.00	0.20	0.43	1.49	3.74	0.38	60.24
	Suez 05	62.57	0.14	0.21	1.16	2.23	0.18	66.50
	Suez 10	92.14	0.17	0.50	1.32	3.19	0.30	97.62
	El-Tour	11.14	0.05	0.33	0.53	1.93	0.16	14.14
Aqaba Gulf	Nuweiba	27.00	0.12	0.34	0.90	3.45	0.25	32.06
	Dahab	11.57	0.16	0.49	0.85	3.25	0.44	16.77
	Sharm El-Maya a	64.29	0.09	0.37	0.75	2.88	0.33	68.72
	Ras Mohamed	13.71	0.08	0.24	0.68	2.60	0.19	17.49
	Na'ama Bay	19.71	0.07	0.22	1.40	5.36	0.27	27.04
Red Sea Proper	NIOF-Hurghada	38.14	0.17	0.24	1.14	2.45	0.26	42.41
	Sheraton-Hurghada	13.29	0.20	0.47	2.11	4.35	0.33	20.74
	Safaga	44.57	0.44	0.45	2.01	5.13	0.56	53.16
	El-Qusir	131.57	1.81	0.91	6.32	4.28	0.59	145.47
	Marsa Alam	26.14	1.84	2.27	14.50	2.85	0.58	48.18
	Shalaten El-Rahba	56.57	0.09	0.16	0.93	1.96	0.25	59.96
	Bir Shalaten	36.86	0.30	0.37	2.91	2.69	0.40	43.52
Min		11.14	0.05	0.16	0.53	1.93	0.16	14.14
Max		131.57	1.84	2.27	14.50	5.36	0.59	145.47
Average		43.96	0.37	0.50	2.44	3.27	0.34	50.88
± SD		32.94	0.57	0.50	3.51	1.05	0.14	34.12

the toxicity factor of metal (values for Cd, Ni, Cu, Pb, Cr and Zn are 30, 5, 5, 5, 2 and 1, respectively) (Wang et al., 2011). E_{RI} is the potential ecological risk of a region based on the sensitivity of biological communities to various metals. According to Chapman (1995) the sediment quality assessment confidence depends mainly on the comparison of accurate reference value. Due to the lack of relevant background data for the unpolluted sediment in the studied marine area, the background values of national soil published by Li (1994) and Liu et al. (2009) were used in this study. The potential ecological risk of coastal sediments posed by metals can be classified into the following categories (Gan et al., 2000):

Low risk: $E_r^i < 30$; $E_{RI} < 100$

Moderate risk: $30 < E_r^i < 50$; $100 < E_{RI} < 150$

Considerable risk: $50 < E_r^i < 100$; $150 < E_{RI} < 200$

Very high risk: $100 < E_r^i < 150$; $200 < E_{RI} < 300$

Disastrous risk: $E_r^i > 150$; $E_{RI} > 300$.

Table 9 summarizes the calculated values of E_r^i and E_{RI} for metals in the sediments of the three studied areas. Among the studied heavy metals, Cd reported the highest ecological risk, because of its high toxicity factor. The mean value of E_r^i Cd is 43.96 ± 32.94 , which indicated that Cd concentrations varied greatly through the studied area. The E_r^i values for Cd were lower than 30 indicating a low risk from Cd (El-Tur, Nuweiba, Dahab, Ras Mohamed, Na'ama Bay, Sheraton-Hurghada, Marsa Alam), and about 19% of stations (Suez 01, Suez 05, Suez 10, Sharm El-Maya, and Shalaten El-Rahba) recorded E_r^i lower than 50 indicating moderate risk while 31% of stations recorded E_r^i higher than 50 for Cd which indicate a considerable risk. El-Quseir station recorded E_r^i higher than 100 for Cd which indicate very high risk. All stations in the studied area recorded $E_r^i \ll 30$ for the other five metals Zn, Cr, Cu,

Ni and Pb which is a considerable low risk where their corresponding averages were $(0.34 \pm 0.14, 0.37 \pm 0.57, 0.50 \pm 0.50, 2.44 \pm 3.51, \text{ and } 3.27 \pm 1.05, \text{ respectively})$. Overall, the ecological risk of heavy metals in the surface sediments for the study area recorded a low risk ($E_r^i \ll 100$) except in El-Quseir station which recorded $E_r^i > 100$ indicating a considerable risk which was dominated by Cd. The obtained data indicated that the sediments in the three studied area have the order: Aqaba Gulf (32.42 ± 21.30) < Suez Gulf (59.63 ± 34.45) \leq the Red Sea (59.06 ± 40.17).

Statistical analyses

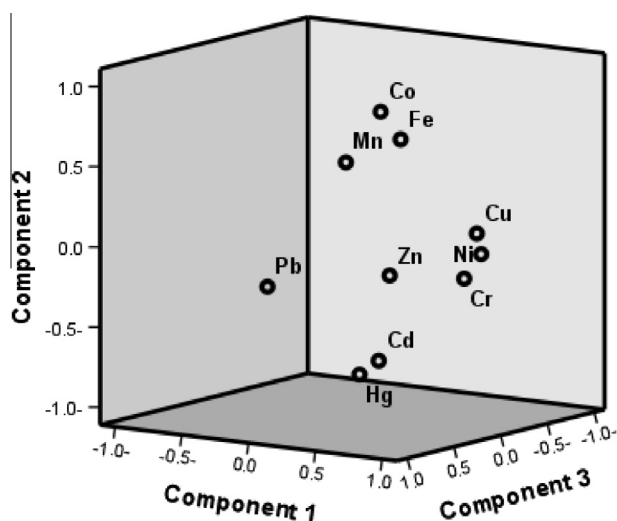
By applying the Pearson (parametric) rank order correlations, the results revealed that the Fe is well correlated with Co, Cu, Mn and moderately correlated with Cr and Ni ($r = 0.695, 0.631, 0.781, 0.502, 0.525, \text{ respectively}$). Furthermore, there is a good correlation between Ni with both Cr and Cu ($r = 0.901, 0.971, \text{ respectively}$). There are significant correlations between Zn and each of Cr, Cu, Mn and Ni ($r = 0.762, 0.665, 0.544, 0.662, \text{ respectively}$). There are good correlations noticed between Cr and Cu, Cd and Hg ($r = 0.855, 0.633, \text{ respectively}$) as shown in Table 5. This result revealed that these metals have the same source of contamination. The results in Table 5 also showed that Cr, Cu, Fe, Ni, Pb, and Zn are negatively correlated with TCO_3 ($r = -0.682, -0.644, -0.542, -0.692, -0.581, -0.601, \text{ respectively}$) and of course positively correlated with TSiO_3 , as well as Zn is well correlated with total phosphorus ($r = 0.727$).

By applying the principal component analysis (PCA) on the ten metals under investigation; three principal components have been extracted covering 81.61% of the cumulative variance (Table 10). The loading of the variables on the three

Table 10 Factor loadings (varimax normalized with Kaiser normalized: marked loadings are >0.70) for three principal component factors (PCFs).

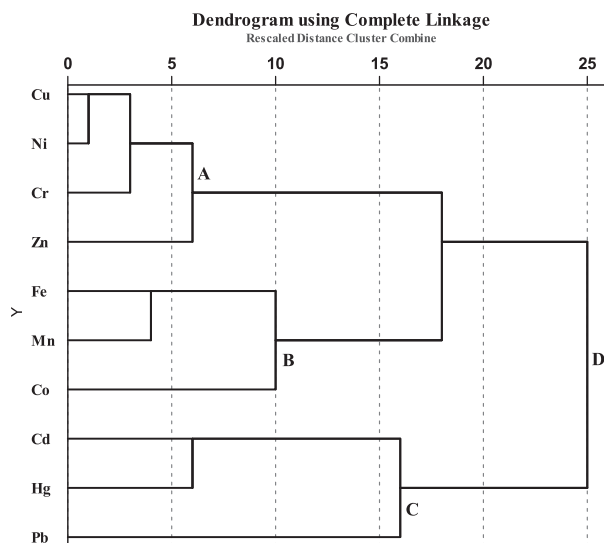
Element	Components		
	PCF1	PCF2	PCF3
Cd	0.291	-0.710	0.133
Co	0.121	0.789	-0.129
Cr	0.946	-0.129	0.155
Cu	0.952	0.136	0.028
Fe	0.577	0.726	0.309
Hg	0.085	-0.830	0.045
Mn	0.325	0.588	0.534
Ni	0.961	0.003	0.004
Pb	-0.014	-0.170	0.889
Zn	0.716	-0.064	0.625
% of variance	37.838	27.549	16.221
Cumulative%	37.838	65.387	81.608

Note: Bold is the marked loading.

**Figure 2** Component plot in rotated space.

principal components shows that Cr, Cu, Ni, and Zn were the dominant variables on the PC1 (0.946, 0.952, 0.961, 0.716, respectively); while Co, Fe, Mn, Cd, Hg (0.789, 0.726, 0.588, -0.710, -0.830, respectively) were the dominant variables on the PC2, and Pb was the dominant in the PC3 (Fig. 2).

By applying the cluster analysis for both the complete and centroid linkages, similar relations between pollutants were obtained by the two studied clustering methods. The resultant dendrograms (Fig. 3) confirm the results obtained with PCA. Indeed, there were two clusters, which can be identified as follows: the first cluster (A) contains (Cu, Ni, Cr, Zn) at distance 6 (which was well correlated in Factor 1 in PCA); the second cluster (B) contains (Fe, Mn, Co) at distance 10 (which was well positively correlated) and (Hg and Cd) at distance 5 (which was negatively correlated) in Factor 2 in PCA. Pb which appears at Factor 3 was fused at distance 16 (C) with cluster (B). At a higher distance (about 25) the two clusters fused formed cluster (D) as shown in Fig. 3.

**Figure 3** Dendrogram for hierarchical clusters analysis of ten metals concentrations in sediments collected from Egyptian Red Sea coast using complete linkage.

Conclusions

Heavy metal contamination along the Egyptian Red Sea was investigated by analyzing the concentrations in sediments at sixteen monitoring locations. The contamination was characterized using multivariate statistical analysis, including correlation analysis, PCA, and cluster analysis. However, the levels of the investigated metals in sediments were lower than the corresponding consensus-based ERL, ERM, LEL, SEL indicating that adverse effects do not occur frequently for all studied stations except El-Quseir and Marsa Alam. Meanwhile, by applying MPI, El-Quseir station fluctuated from uncontaminated to moderately contaminated by Cd and Ni and moderately contaminated by Cr. Moreover, the Marsa Alam sediment is moderately contaminated by Cr and Ni. From the point of integrated assessments of multiple heavy metal pollution, the ecological risk of heavy metals in the surface sediments for the study area recorded a low risk except at El-Quseir station which recorded $E_r^i > 100$ indicating a considerable risk which was dominated by that from Cd.

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