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Assessing of Metals and Metalloids in Surface Sediments along the Gulf of Aqaba Coast, Northwestern Saudi Arabia

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ABSTRACT

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The Gulf of Aqaba in northwestern Saudi Arabia is among the world's most important areas in terms of marine diversity and economic potential. Its coastal area witnessed significant anthropogenic changes as a result of rapid economic development and urbanization during recent decades. To document the impacts of these changes on the local environment, the distribution of heavy metal and metalloid pollutants (Fe, Al, As, Cu, B, Zn, Ba, Cr, Pb, Mn, Hg, V, Co, Mo, Se, Sb, Cd, and Be) and their variations in the surface sediments were investigated. Based on average concentrations, the dominance is as follows: Fe > Al > As > Cu > B > Zn > Ba > Cr > Pb > Mn > Hg > V > Co > Mo > Se > Sb > Cd > Be. The results showed a strongly positive linear correlation among Ba, Cr, Pb, and V. The studied sediments' quality was assessed using the geoaccumulation index (*Igeo*), an enrichment factor (*EF*), and two other sediment testing criteria (China State Bureau of Quality and Technical Supervision, or CSBTS, and Canadian guidelines). Hg is the only element with a moderate-to-strong concentration in terms of the *Igeo*, exceeding the primary, secondary, and tertiary CSBTS criteria and the threshold and probable effect levels of the Canadian guidelines. As causes moderate pollution, because its presence in the sediments exceeds the threshold effect level of the Canadian guidelines. The *EF* results showed Hg as a strong pollutant metal in the surface sediments of the study area, followed by As and Cu metals.

ADDITIONAL INDEX WORDS: *Trace elements, contamination assessment, geoaccumulation index, enrichment factor.*

INTRODUCTION

Trace elements are released through both natural and anthropogenic processes. While some are essential, others are toxic and can cause damage to ecosystems. Soils generally inherit trace elements from their parent materials, some of which may carry background trace elements with extremely high concentrations that are toxic to plants and wildlife. Anthropogenic processes include inputs of trace elements through the use of fertilizers, organic manures, industrial and municipal wastes, irrigation, and wet and dry deposits.

Concentrations of trace elements are generally low (1 mg kg^{-1} or less) in soils, plants, and living organisms. Trace elements have been extensively studied in the past decade, and seven are of environmental concern. Al, As, Cu, Zn, Pb, Cd, and Se should be taken seriously in terms of soil, water, and food-chain contamination (Al-Taani *et al.*, 2012; Bai *et al.*, 2011a, c, 2012; Batayneh, 2012; Batayneh *et al.*, 2012; Gao *et al.*, 2013; He, Yang, and Stoffella, 2005; Henry *et al.*, 2004; Sakan *et al.*, 2012).

The Earth's crust comprises 95% igneous and 5% sedimentary rocks. However, sediments are more frequently found at the surface, because they tend to overlie the igneous rocks from which they were derived. Basaltic igneous rocks generally contain higher concentrations of metals (*e.g.*, Cu, Zn, Cr, Co, and Mn), which mainly occur in the easily weathered constituents of igneous rocks. Among the sedimentary rocks, sandstones carry minerals that are resistant to weathering and usually contain small amounts of trace elements. However, shale, which is derived from fine inorganic and organic sediments, contains larger amounts of trace elements (including Cu, Zn, Mn, Pb, and Cd). Soils developed from these parent materials tend to reflect their parent's chemical composition, though pedogenetic processes may modify their relationships. According to He, Yang, and Stoffella (2005) soils derived from weathered, coarse-grained sedimentary rocks (*e.g.*, sands and sandstones) and from acidic igneous rocks (*e.g.*, rhyolites and granites) tend to contain smaller amounts of nutritionally essential metals (including Cu, Zn, and Co) compared with those derived from basic igneous and fine-grained sedimentary rocks (clays and shale).

Because of regional political problems, the Gulf of Aqaba (GOA) remained inaccessible for scientific expeditions until the 1980s. As a result, the characteristics of the physical, chemical, and biological nature of the GOA were largely unexplored until

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recently. The scientific data available from the GOA were mostly reported from the Jordanian coast (*e.g.*, Abu-Hilal and Al-Najjar, 2004; Al-Rousan *et al.*, 2002, 2007; Badran, 2001; Batayneh, 2013; Batayneh, Elawadi, and Al-Arifi, 2010) and along the Egyptian coast (*e.g.*, Abdel-Halim *et al.*, 2007; Shriadah, Okbah, and El-Deek, 2004; Youssef and El-Said, 2011), whereas only a few scientific results have been reported from the Saudi GOA coast (Al-Trabulsy, Khater, and Habbani, 2013; Batayneh *et al.*, 2014b). The GOA region is threatened by some level of pollution or contamination from urban, industrial, tourism, shipping, and port activities. Land-based operations, including clinker production, fertilizer manufacturing, and seawater desalinization in the Elat and Haql areas (Batayneh *et al.*, 2014a; Ben-Sasson, Brenner, and Paldor, 2009), also contribute to the presence of heavy metals and pose serious threats to the GOA region.

The present study attempts to investigate the distribution and concentration of 18 heavy metals and metalloids (Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Pb, Sb, Se, V, and Zn) in the surface sediments across the Saudi GOA coast. It also aims to assess the extent of metal and metalloid concentrations and determine whether there is contamination in the study area from such elements. This assessment helps ascertain whether sediments are the major contributor to these pollutants in the surrounding environment. This is critically important to local and regional stakeholders, because it provides a reference database to implement their development and management agenda in the GOA coast and assess the future impacts of human activities in the area.

METHODS

In aquatic systems, many contaminants may accumulate in sediments, and these sediments become repositories for many toxic chemicals. Contaminated sediments represent a hazard to aquatic life and human health. Assessment of surface sediment quality is useful to identify sources of sediment contamination and provide essential information for source controls, remediation, or both. Accurate assessment of sediment contamination depends largely on the accuracy and representativeness of sediment collection and analyses. Therefore, sampling collection, storage, handling, and analysis methods were adapted from the standard procedure recommended by of the U.S. Environmental Protection Agency (U.S. EPA, 1984) to yield accurate and representative sediment-quality data.

Description of the Study Area

The GOA is one of two waterways that originate from the northern margin of the Red Sea. It is located between 34°20′ E and 35°00′ E and between 27°54′ N and 29°35′ N (Figure 1). The GOA, which is about 180 km long, has an average width of 20 km and a mean depth of 800 m. This structure is part of the Syrian–African rift valley, which is flanked to the east and the west by a mixture of mountains and deserts. The GOA is of interest because it hosts unique ecological systems of coral reefs and other tropical biota. The climate of this region is arid, with an average evaporation rate of 5 to 10 mm day^{-1} and no permanent rivers flowing into the gulf. As a result, the water in the gulf is among the most saline in the world, with typical salinity values of 40 to 41 practical salinity units (Batayneh *et al.*, 2014a; Manasrah *et al.*, 2004; Plaehn *et al.*, 2002).

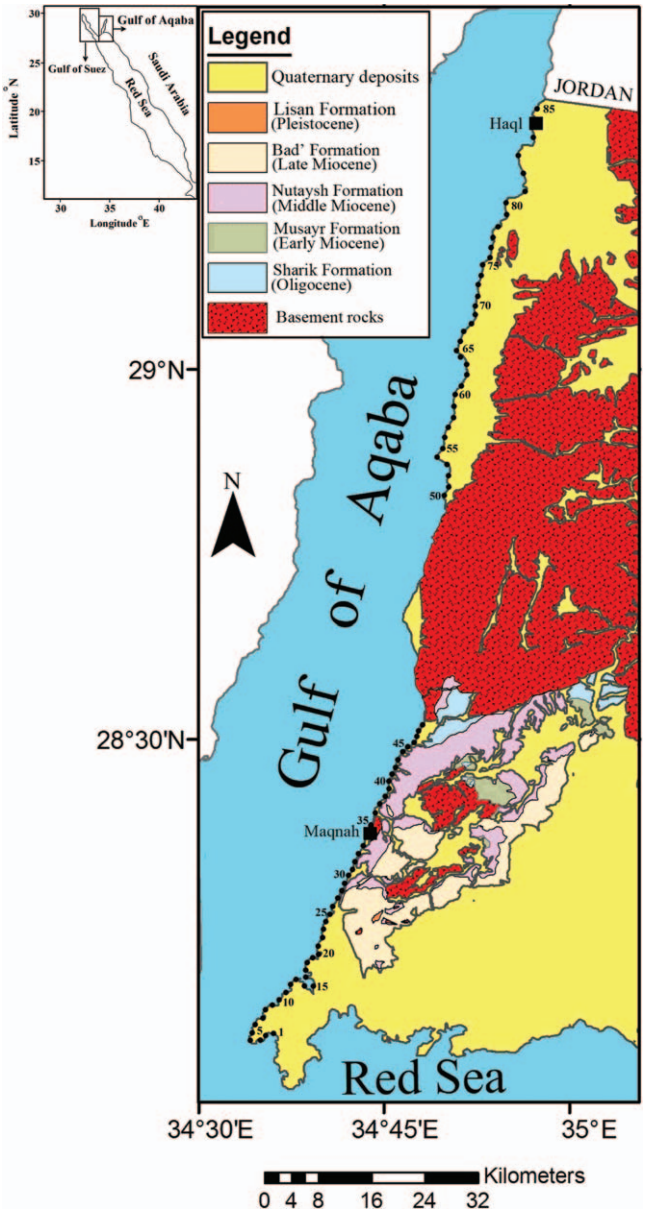

Figure 1. Geological map for the GOA–Red Sea region (modified from Clark, 1986). The inset map shows the Red Sea, the Gulf of Suez, and the GOA. Black circles indicate sampling sites.

According to Clark (1986), the Oligocene conglomerates and sandstones of the Sharik Formation (which is rich in iron oxides) are the oldest sedimentary rocks in the area and unconformably overlie the Proterozoic basement (Figure 1). The Sharik Formation is unconformably overlain by the deep marine Musayr Formation (early Miocene) made of sandstone, conglomerate, limestone, shale, and gypsum (undifferentiat-

Table 1. *Average concentration and SD obtained for four replicates of the standard reference material BCSS-1.*

Metal	Detection Limit	Measured Value (mg kg^{-1})	Certified Value (mg kg^{-1})	Recovery (%)	Acceptance (%)
Al_2O_3[1]	0.12	12.12	11.83 ± 0.41	102.45	—
As	0.06	10.86	11.1 ± 1.4	97.84	90–120
B	0.03	—	—	—	—
Ba	0.10	—	—	—	—
Be	0.10	1.28	1.3 ± 0.3	98.46	—
Cd	0.03	0.26	0.25 ± 0.04	104.00	—
Co	0.09	17.43	18 ± 2.1	96.8	—
Cr	0.30	120.71	123 ± 14	98.1	—
Cu	0.10	18.04	18.5 ± 2.7	97.52	90–115
Fe_2O_3[1]	0.06	4.78	4.7 ± 1.4	101.70	—
Hg	0.10	0.165	0.176 ± 0.023	93.75	85–110
Mn	0.10	224.90	229 ± 15	98.21	85–100
Mo	0.01	—	—	—	—
Pb	0.03	21.82	22.7 ± 3.4	96.12	90–110
Sb	0.03	0.56	0.59 ± 0.06	94.92	—
Se	0.03	0.43	0.43 ± 0.06	100	—
V	0.06	108.3	110 ± 4.9	98.45	—
Zn	0.03	120.81	119 ± 12	101.52	85–110

[1] Values in milligrams per kilogram except for Al_2O_3 and Fe_2O_3, whose values are percentages.

ed). The Musayr Formation is then overlain by middle Miocene marine mudstones, carbonates, and evaporates (undifferentiated) of the Nutaysh Formation. The next overlying unit is the late Miocene Al Bad' Formation of gypsum and anhydrite, which is unconformably overlain by Pleistocene sandstone, conglomerate, sand, and local gypsum of the Lisan Formation. The youngest unconsolidated Quaternary deposits at the surface are sands and gravels.

Sampling

Eighty-five samples (0–5 cm) were collected from the surface sediments along the Saudi GOA coast during January 2013 (Figure 1). Methods adopted for the collection and analysis of sediment samples are essentially the same as suggested in the standard procedure of the U.S. EPA (1984). Samples were collected by stainless-steel Peterson grab samplers (20 × 13 cm). Three replicas were taken from each sampling location. After collection and before processing and analysis, sediment samples were placed in a clean plastic vessel and kept frozen at –20°C. In the laboratory, the collected samples were defrosted at room temperature and air dried in a controlled, clean environment. Samples were then transferred into an oven and dried at 70°C up to a constant weight. Each sample was homogenized, sieved (through a 0.75-mm plastic sieve), and finally powdered by agate mortar.

Sediments Digestion

Dried sediment samples (0.25–0.50 g each) were stored in closed Teflon vessels with 3-mL nitric acid (HNO_3), 2-mL perchloric acid ($HClO_4$), and 1-mL hydrofluoric acid (HF). The vessels were placed inside a well-enclosed stainless-steel block and heated by a thermostatically controlled hot plate at 70°C for about 12 hours to reach a high pressure. To eliminate HF, the digested mixture was nearly evaporated with 2-mL sulfuric acid (H_2SO_4). Next, the residue was dissolved to a specific volume with diluted HNO_3 in vinyl chloride bottles and filtered through Whatman No. 1 paper. For each digestion program, a blank was prepared using the same procedure. Before their use in the experiments, all glassware and Teflon vessels were soaked overnight with 20% HNO_3 and then rinsed with metal-free distilled water.

Heavy Metal and Metalloid Analysis

The digested sample solutions and their reagent blanks were analyzed for trace metals using a Perkin Elmer 2830 flame atomic absorption spectrophotometer. Working standards were prepared by diluting the concentrated stock solutions (Merck, Germany) of 1000 mg L^{-1} in metal-free distilled water. Each metal concentration was estimated quantitatively according to the standard procedure and conditions described in the instrument manual. Triplicate measurements were made for each sample by direct aspiration into the air acetylene flame of the instrument. Sediment hydrogen ion concentration (pH) and electrical conductivity (EC; sediment/water = 1:5) were measured using the pH and a conductivity meter, respectively (Bai *et al.*, 2011b).

Quality Assurance

For quality control, replicates (approximately 20% of the total number of samples) were analyzed under the same procedures as described earlier. A standard sediment reference material (BCSS-1) was digested and analyzed in a similar way to ensure quality control and accuracy. Analytical results of the selected samples reveal good agreement between the values of the referenced and those of the analyzed materials. Table 1 shows the certified and analyzed results, as well as the recovery rates of the studied metals.

Statistical Analysis

Multivariate statistical analysis, a quantitative and independent approach, has been implemented to deal with the large number of chemical and physical variables. It also permits grouping of sediment samples and reveals the correlations among them. In this study, hierarchical cluster analysis (HCA) is applied to a subgroup of the hydrogeochemical dataset. Factor analysis was performed by evaluating the principle components analysis (PCA) and computing the eigenvectors to

Table 2. *Sampling stations and some characteristics of the studied GOA sediments.*

Station. No.	Longitude (E)	Latitude (N)	Color	Sediment Size	TOM%	TC%
1	34°36.552′	28°05.769′	Brown	Medium	1.034	5.2
2	34°36.022′	28°06.024′	Brown	Medium	0.992	4.6
3	34°35.516′	28°05.867′	Dark brown	Fine	0.954	4.3
4	34°34.921′	28°05.402′	Brown	Fine	0.98	9.8
5	34°34.397′	28°05.658′	Brown	Medium	1.012	9.2
6	34°34.620′	28°06.223′	Reddish	Fine	0.758	10.6
7	34°34.816′	28°06.783′	Brown	Fine	0.921	14.5
8	34°35.492′	28°07.241′	Brown	Medium	0.886	9.0
9	34°35.515′	28°07.863′	Brown	Coarse	0.905	33.6
10	34°36.100′	28°08.364′	Many colors	Coarse	0.685	6.5
11	34°36.935′	28°09.004′	Many colors	Coarse	0.744	9.8
12	34°37.427′	28°09.431′	Many colors	Coarse	0.682	6.8
13	34°37.625′	28°10.089′	Many colors	Coarse	0.82	10.2
14	34°38.398′	28°10.298′	Brown	Fine	1.482	5.4
15	34°38.786′	28°09.814′	Many colors	Coarse	1.335	9.1
16	34°39.505′	28°09.848′	Brown	Coarse	1.42	9.6
17	34°39.289′	28°10.951′	Brown	Coarse	1.384	12.1
18	34°39.071′	28°11.875′	Brown	Fine	0.852	40.7
19	34°39.914′	28°12.384′	Many colors	Coarse	0.755	7.9
20	34°39.759′	28°13.069′	Many colors	Medium	1.022	10.3
21	34°40.116′	28°13.669′	Brown	Coarse	0.921	8.4
22	34°40.164′	28°14.358′	Many colors	Medium	0.935	7.8
23	34°41.569′	28°17.306′	Many colors	Medium	0.911	6.5
24	34°41.814′	28°17.819′	Brown	Fine	0.895	6.8
25	34°42.017′	28°18.335′	Brown	Fine	0.668	9.2
26	34°42.256′	28°18.862′	Brown	Fine	0.711	7.8
27	34°42.520′	28°19.408′	Brown	Fine	0.692	7.9
28	34°42.781′	28°19.923′	Brown	Fine	0.882	10.1
29	34°43.025′	28°20.440′	Many colors	Coarse	0.755	7.3
30	34°43.345′	28°20.896′	Many colors	Medium	1.02	8.6
31	34°43.538′	28°21.502′	Many colors	Medium	0.995	6.0
32	34°43.638′	28°22.086′	Many colors	Coarse	0.855	6.8
33	34°43.920′	28°22.652′	Brown	Fine	1.44	8.8
34	34°44.166′	28°23.282′	Brown	Medium	0.668	6.5
35	34°44.460′	28°24.021′	Many colors	Coarse	0.712	9.8
36	34°44.638′	28°24.599′	Many colors	Medium	0.722	9.0
37	34°45.102′	28°25.216′	Many colors	Medium	0.689	5.3
38	34°45.303′	28°25.812′	Many colors	Coarse	0.88	5.6
39	34°45.351′	28°26.429′	Yellowish brown	Medium	0.911	4.9
40	34°45.642′	28°26.882′	Brown	Fine	0.722	6.8
41	34°46.045′	28°27.641′	Many colors	Coarse	0.854	6.3
42	34°45.254′	28°28.413′	Dark brown	Fine	0.942	5.0
43	34°46.573′	28°28.973′	Many colors	Medium	1.011	12.0
44	34°46.985′	28°29.459′	Many colors	Coarse	0.822	9.8
45	34°47.558′	28°29.766′	Many colors	Coarse	0.788	8.7
46	34°47.598′	28°30.330′	Many colors	Coarse	0.882	7.8
47	34°47.905′	28°30.921′	Many colors	Coarse	0.924	7.3
48	34°48.342′	28°31.405′	Many colors	Coarse	0.862	5.2
49	34°48.256′	28°32.565′	Many colors	Coarse	0.556	3.7
50	34°50.182′	28°50.348′	Many colors	Coarse	0.926	6.8
51	34°49.993′	28°49.253′	Many colors	Coarse	0.855	5.4
52	34°49.945′	28°49.117′	Many colors	Coarse	0.795	7.2
53	34°49.153′	28°46.870′	Many colors	Coarse	0.884	5.6
54	34°49.039′	28°46.448′	Dark brown	Medium	1.11	5.0
55	34°49.930′	28°52.675′	Many colors	Fine	0.684	6.8
56	34°49.449′	28°53.301′	Many colors	Coarse	0.722	7.0
57	34°49.891′	28°53.961′	Many colors	Coarse	0.645	6.5
58	34°49.931′	28°54.710′	Many colors	Coarse	0.726	8.4
59	34°50.237′	28°55.584′	Many colors	Coarse	0.685	8.6
60	34°50.603′	28°56.210′	Many colors	Coarse	0.744	7.4
61	34°50.670′	28°57.244′	Dark brown	Medium	0.682	8.0
62	34°50.645′	28°57.877′	Dark brown	Coarse	0.82	5.3
63	34°51.246′	28°58.862′	Dark brown	Coarse	0.655	5.2
64	34°51.639′	28°59.622′	Many colors	Medium	0.788	8.8
65	34°51.656′	29°00.047′	Many colors	Coarse	0.652	9.6
66	34°51.466′	29°01.070′	Many colors	Medium	0.742	6.7
67	34°51.009′	29°01.930′	Brown	Fine	0.852	6.0
68	34°51.215′	29°02.663′	Many colors	Fine	0.755	6.2

Table 2. *Continued.*

Station. No.	Longitude (E)	Latitude (N)	Color	Sediment Size	TOM%	TC%
69	34°51.758′	29°03.426′	Many colors	Coarse	1.022	7.5
70	34°52.368′	29°04.216′	Many colors	Fine	0.966	8.4
71	34°52.420′	29°05.264′	Many colors	Medium	0.875	7.8
72	34°52.496′	29°05.840′	Brown	Fine	0.912	6.5
73	34°52.632′	29°07.024′	Brown	Fine	1.125	6.8
74	34°52.831′	29°07.692′	Brown	Fine	1.014	5.5
75	34°53.051′	29°08.656′	Many colors	Coarse	0.926	7.8
76	34°53.569′	29°09.030′	Brown	Coarse	0.775	8.1
77	34°53.663′	29°09.827′	Many colors	Medium	0.965	6.6
78	34°54.411′	29°11.583′	Many colors	Coarse	0.886	7.8
79	34°54.994′	29°12.342′	Many colors	Coarse	0.912	8.6
80	34°54.752′	29°12.972′	Many colors	Coarse	1.02	6.0
81	34°55.297′	29°13.767′	Many colors	Medium	0.788	5.6
82	34°56.239′	29°14.213′	Many colors	Coarse	1.142	8.8
83	34°55.871′	29°16.700′	Many colors	Coarse	1.205	6.4
84	34°56.913′	29°17.920′	Many colors	Coarse	0.998	7.8
85	34°57.033′	29°20.296′	Many colors	Coarse	0.864	8.2

TOM = total organic matter, TC = total carbonate.

determine the common pollution sources. HCA and PCA techniques were applied using the SPSS 20 software package. A description of the HCA and PCA techniques and their application can be found in Cloutier *et al*. (2008), Kanade and Gaikwad (2011), Batayneh and Zumlot (2012), and Zumlot *et al*. (2013). The heavy metals, metalloids, and other sediment parameters—pH, EC, total organic matter (TOM), and total carbonate (TC)—were tested for correlations using Pearson's correlation coefficient based on the assumption that data were normally distributed.

RESULTS

Grain-size analysis of samples is presented in Table 2. The texture of the studied samples varies from coarse to fine grained. Table 2 also shows that the TOM of the sediment samples ranged between 0.56% and 1.48% (with an average of 0.89%). These TOC values suggest they originate mainly from a marine environment. In addition, TC ranges from 3.7% to 40.7% (with an average of 8.23%), which is predominantly biogenic in origin.

Heavy Metal and Metalloid Concentrations

Statistical analysis of heavy metal and metalloid concentrations, namely the minimum and maximum values, average values, and standard deviations (SDs) are given in Table 3. The distribution of trace element concentrations in sediments (in milligrams per kilogram) along the GOA coastline is shown in Figure 2. Fe is the most abundant heavy metal, with a concentration ranging between 0.048% and 0.311% and averaging 0.133% (Table 3). Al is the second most abundant element, with concentrations that vary from 0.045% to 0.226% and an average value of 0.131%. The average values of Fe and Al concentrations determined by the present study are lower than the average values previously reported (Table 3) of 0.304% and 0.202%, respectively, from the study area.

Statistical Analysis

A dendrogram in Figure 3 shows concentrations of the 18 elements (using HCAs) deduced from 85 sediments sampled by HCAs. These elements are classified into four groups (C1–C4), although some similarity exists among the classes. Cluster C3 (Al, Fe, and Cu) and cluster C4 (Cd, Zn, As, B, Co, and Se) have lower linkage distances but greater similarity compared with other clusters. This may be because of some type of identicalness in the geochemistry of the studied samples from these groups. However, cluster C1 (Cr, V, Pb, and Ba) and cluster C2 (Mn, Mo, Be, Hg, and Sb) have relatively higher linkage distances among the defined clusters. The lowest linkage distances observed in the dendrogram are (Cr, V) and (As, B).

Table 3. *Basic statistics of heavy element and metalloid content of sediment and rock samples along the Saudi GOA coastline.*

	Fe[1]	Al[1]	As	Cu	B	Zn	Ba	Cr	Pb	Mn	Hg	V	Co	Mo	Se	Sb	Cd	Be
Sediment Samples (n = 85)																		
Min. (mg kg^{-1})	0.048	0.045	3.8	0.6	5.0	5.0	3.3	2.8	2.4	2.3	1.6	0.3	0.3	0.3	0.3	0.04	0.04	0.02
Max. (mg kg^{-1})	0.311	0.226	18.1	17.3	9.9	9.2	9.6	9.8	9.2	6.2	3.1	3.9	0.9	1.0	0.9	0.1	0.12	0.05
Average (mg kg^{-1})	0.1324	0.131	13.9	9.41	7.95	7.43	6.06	5.49	5.0	3.79	2.37	1.25	0.66	0.63	0.59	0.06	0.059	0.03
SD	0.06	0.047	2.64	3.72	1.03	1.06	1.54	2.22	1.92	0.95	0.35	1.0	0.19	0.18	0.16	0.012	0.013	0.007
BG (mg kg^{-1})[2]	0.438	0.244	6.99	6.26	12.9	24.34	24.09	8.19	9.14	295.9	0.37	25.7	3.38	1.08	0.848	0.352	0.269	0.3
Rock Samples (n = 32)																		
Min. (mg kg^{-1})	0.0187	0.0129	0.2	0.6	2.0	2.0	1.0	1.0	0.9	6.0	0.06	8.0	0.1	0.04	0.05	0.01	0.01	0.02
Max. (mg kg^{-1})	1.80	0.944	23.0	30.0	54.0	112.0	154.0	62.0	68.0	2840.0	1.0	58.0	25.0	7.0	2.0	3.2	1.5	0.8
Average (mg kg^{-1})	0.438	0.244	6.99	6.26	12.9	24.34	24.09	8.19	9.14	295.9	0.37	25.7	3.38	1.08	0.848	0.352	0.269	0.3
SD	0.4618	0.256	4.92	7.1	10.8	23.96	38.4	10.8	14.3	537.5	0.25	11.3	5.32	1.79	0.495	0.646	0.327	0.21

[1] Values in milligrams per kilogram except for Fe and Al, whose values are percentages.
[2] Background concentrations represent average values of rock samples from the study area.
Min. = minimum, Max. = maximum, SD = standard deviation, BG = background concentration.

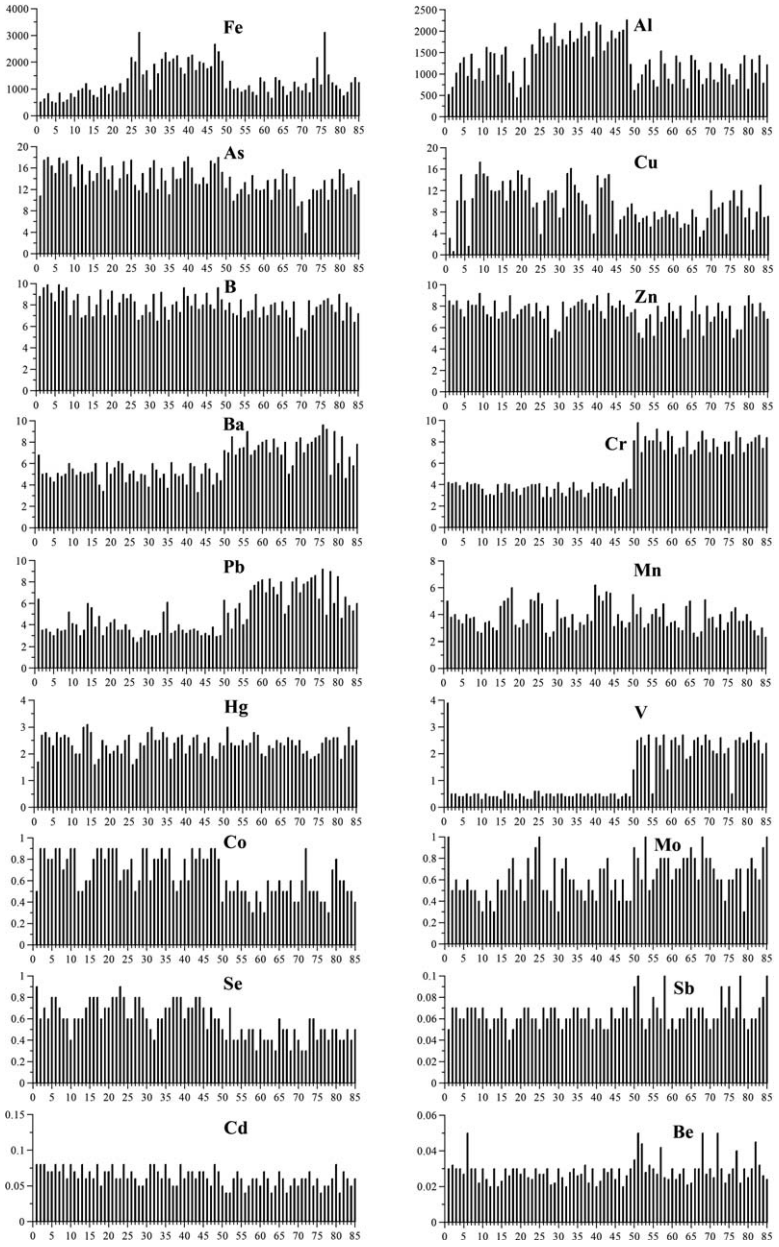

Figure 2. Distribution of heavy metals and metalloids (in milligrams per kilogram) along stations in Saudi GOA surface sediments. Horizontal axis = station number, vertical axis = metal and metalloid concentrations.

These results are supported by Pearson's correlation coefficient matrix (Table 4). There are strongly positive linear correlations among the elements of cluster C1, *i.e.* between Ba and Cr ($r = 0.72$), Cr and Pb ($r = 0.74$), Cr and V ($r = 0.84$), and Pb and V ($r = 0.71$). Moderate positive linear correlations are observed between Ba and Pb ($r = 0.59$) and between Ba and V ($r = 0.68$). A weak positive linear correlation ($r = 0.19$) is observed among the elements of cluster C2 (*i.e.* between Mn and Mo), whereas a moderate positive linear correlation ($r = 0.53$) is detected between Fe and Al in the C3 cluster. As shown in Table 4, elements in cluster C4 show moderate positive correlations between As and B ($r = 0.62$), Zn and Cd ($r = 0.48$), and Co and Se ($r = 0.40$).

Assessment of Sediment Contamination

Geoaccumulation Index

The geoaccumulation index (*Igeo*) is a common criterion used for the heavy metal pollution evaluation in sediments (El-Sikaily, 2008; Leopold *et al.*, 2008). It was originally defined by Muller (1979), where heavy metal contamination in sediments was determined by comparing their current concentration levels with those from preindustrial times. The *Igeo* can be

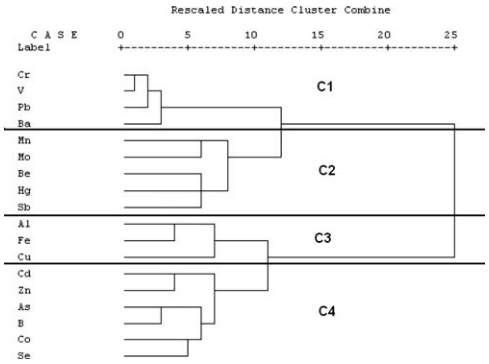

Figure 3. The dendrogram of HCAs for the studied heavy metal and metalloid concentrations in the bulk sediments from the Saudi coast of the GOA.

defined as

$$Igeo = \log_2\left(Cn/(1.5{*}Bn)\right) \quad (1)$$

where Cn is the measured concentration of the examined metal n in the sediments, Bn is the geochemical background concentration of the metal n, and 1.5 is a background matrix correction factor for lithogenic effects. Following this, Muller (1981) determined seven classes of *Igeo* in the sediments: (1) $Igeo < 0$ for unpolluted, (2) $0 < Igeo < 1$ for unpolluted to moderately polluted, (3) $1 < Igeo < 2$ for moderately polluted, (4) $2 < Igeo < 3$ for moderately to strongly polluted, (5) $3 < Igeo < 4$ for strongly polluted, (6) $4 < Igeo < 5$ for strongly to very strongly polluted, and (7) $Igeo > 5$ for very strongly polluted conditions.

In the present study, the *Igeo* values are calculated using background-analyzed values of 32 rock samples (Table 3). Basic statistics of these calculations for heavy metals and metalloids are listed in Table 5 and graphically presented in Figure 4. Results from this study are compared with the Muller scales (Muller, 1981), which place Hg as a moderate-to-strong pollutant among the detected heavy metals and metalloids in the GOA area (*i.e. Igeo* ranging from 1.53 to 2.48). The second most polluting metalloid is As, covering a range from unpolluted to moderately polluted ($0 < Igeo < 1$). All other elements (Fe, Al, Cu, B, Zn, Ba, Cr, Pb, Mn, V, Co, Mo, Se, Sb, Cd, and Be) in the studied samples have been placed in the unpolluted category ($Igeo < 0$). On the basis of mean *Igeo* values, heavy metals and metalloids are placed in the following order: Hg (2.08) > As (0.37) > Cu (–0.15) > Se (–1.17) > Cr (–1.28) > B (–1.30) > Mo (–1.42) > Pb (–1.55) > Al (–1.58) > Zn (–2.31) > Fe (–2.45) > Ba (–2.62) > Cd (–2.72) > Co (–3.01) > Sb (–3.05) > Be (–4.00) > V (–5.46) > Mn (–6.16). As is evident from these *Igeo* values, elements like Fe and Al have relatively higher concentrations between sites 25 and 49 along the Saudi GOA coast (Figure 4), which could be because of iron oxide–rich sandstone exposures in the area.

Enrichment Factor

Enrichment factor (*EF*) analysis, a method proposed by Simex and Helz (1981) to assess trace element concentration, is mathematically expressed as

$$EF = \frac{(M/\mathrm{Fe})_{\mathrm{sample}}}{(M/\mathrm{Fe})_{\mathrm{crust}}} \quad (2)$$

where $(M/\mathrm{Fe})_{\mathrm{sample}}$ is the ratio of metal and Fe concentrations in the sample and $(M/\mathrm{Fe})_{\mathrm{crust}}$ is the ratio of metal and Fe concentrations in the Earth's crust.

The *EF* values calculated by statistical analysis are given in Table 5, and their distributions along the GOA coast are presented in Figure 5. Because of naturally mineralogical diversity among types of sediments and analytical uncertainty, sediments with $EF > 2$ are considered enriched as per the

Table 4. *Correlation matrix between trace element contents and selected soil properties in the study area.*

	Fe	Al	As	Cu	B	Zn	Ba	Cr	Pb	Mn	Hg	V	Co	Mo	Se	Sb	Cd	Be	pH	EC	TOM	TC
Fe	1.00	0.53[3]	0.07	0.10	−0.02	−0.02	−0.16	−0.22	−0.18	0.06	−0.11	−0.33	0.07	−0.10	0.15	−0.04	−0.18	−0.20	−0.02	−0.11	−0.23	−0.11
Al		1.00	0.31	0.18	0.02	0.13	−0.43	−0.53	−0.49	0.10	−0.09	−0.45	0.27	−0.28	0.36	−0.13	0.04	−0.34	0.11	0.13	−0.09	−0.02
As			1.00	0.13	0.62[4]	0.21	−0.50	−0.51	−0.50	0.16	0.10	−0.54	0.44	−0.23	0.40	−0.14	0.23	−0.11	0.25	0.29	0.05	0.13
Cu				1.00	0.02	0.14	−0.35	−0.46	−0.27	0.02	0.01	−0.49	−0.32	−0.27	0.23	−0.09	0.15	−0.31	0.24	0.28	0.18	0.31
B					1.00	0.17	−0.28	−0.32	−0.27	0.09	0.11	−0.30	0.42	−0.13	0.32	−0.05	0.41	0.17	0.14	0.17	0.13	−0.14
Zn						1.00	−0.27	−0.31	−0.18	0.07	−0.04	−0.19	0.35	−0.15	0.26	−0.25	0.48[4]	−0.15	0.20	0.15	0.14	0.11
Ba							1.00	0.72[1]	0.59	−0.10	−0.14	0.68	−0.60	0.26	−0.52	0.16	−0.36	0.16	−0.38	−0.38	−0.13	−0.23
Cr								1.00	0.74[1]	−0.14	0.03	0.84[1]	−0.64	0.46	−0.73	0.32	−0.48	0.33	−0.39	−0.43	−0.06	−0.21
Pb									1.00	−0.14	−0.03	0.71[1]	−0.56	0.37	−0.56	0.20	−0.23	0.10	−0.39	−0.34	0.21	−0.13
Mn										1.00	−0.05	−0.13	0.09	0.19[2]	0.26	−0.12	0.09	−0.03	−0.01	0.08	0.05	0.17
Hg											1.00	−0.12	−0.05	0.05	−0.10	0.11	−0.03	0.15	0.09	−0.05	0.07	0.07
V												1.00	−0.65	0.48	−0.57	0.21	−0.25	0.27	−0.32	−0.40	−0.02	−0.21
Co													1.00	−0.37	0.40[4]	−0.25	0.38	0.00	0.36	0.45	0.11	0.23
Mo														1.00	−0.29	0.07	−0.15	0.11	−0.16	−0.18	−0.04	−0.04
Se															1.00	−0.18	0.37	−0.18	0.35	−0.34	0.21	0.10
Sb																1.00	−0.24	0.09	−0.19	−0.10	−0.07	−0.13
Cd																	1.00	−0.10	0.24	0.16	0.21	−0.04
Be																		1.00	−0.03	0.00	−0.05	−0.08

[1] Elements of cluster C1.
[2] Elements of cluster C2.
[3] Elements of cluster C3.
[4] Elements of cluster C4.
pH = hydrogen ion concentration, EC = electrical conductivity, TOM = total organic matter, TC = total carbonate.

Table 5. Igeo *and* EF *of heavy metals and metalloids in sediments.*

	Fe	Al	As	Cu	B	Zn	Ba	Cr	Pb	Mn	Hg	V	Co	Mo	Se	Sb	Cd	Be
Igeo																		
Min.	−3.77	−3.04	−1.46	−3.97	−1.95	−2.87	−3.45	−2.13	−2.51	−7.59	1.53	−7.01	−4.08	−2.43	−2.08	−3.72	−3.33	−4.49
Max.	−1.08	−0.69	0.79	0.88	−0.97	−1.99	−1.91	−0.33	−0.58	−6.16	2.48	−3.31	−2.49	−0.70	−0.50	−2.40	−2.33	−3.17
Average	−2.45	−1.58	0.37	−0.15	−1.30	−2.31	−2.62	−1.28	−1.55	−6.91	2.08	−5.46	−3.01	−1.42	−1.17	−3.05	−2.72	−4.00
SD	0.63	0.56	0.32	0.77	0.19	0.22	0.37	0.58	0.54	0.36	0.22	1.23	0.44	0.43	0.41	0.25	0.29	0.30
EF																		
Min.	—	—	1.98	0.67	0.72	0.29	0.25	0.65	0.37	0.01	6.84	0.03	0.17	0.65	0.83	0.24	0.21	0.11
Max.	—	—	20.85	20.18	6.25	2.98	2.41	6.0	6.03	0.14	60.95	1.30	2.31	7.91	9.06	1.72	2.54	0.87
Average	—	—	7.95	5.95	2.48	1.23	1.01	2.70	2.21	0.05	25.61	0.21	0.78	2.33	2.76	0.73	0.94	0.39
SD	—	—	4.06	3.86	1.24	0.59	0.49	1.48	1.23	0.03	11.85	0.21	0.45	1.19	1.61	0.34	0.51	0.20

Min. = minimum, Max. = maximum, SD = standard deviation.

criteria of Zhang and Liu (2002) and Barakat *et al*. (2012). Accordingly, elements in which $EF < 2$ are considered to entirely originate from the crustal materials or natural processes. On the contrary, those with $EF > 2$ are most likely the product of anthropogenic activities.

Most trace elements have mean *EF* values of greater than 2 and are ordered as follows: Hg (25.61) > As (7.95) > Cu (5.95) > Se (2.72) > Cr (2.70) > B (2.48) > Mo (2.33) > Pb (2.21). This suggests that they probably originate from anthropogenic activities along the GOA coast. Natural sources contribute to the presence of the remaining elements, because they have mean *EF* values of less than 2: Zn (1.23) > Ba (1.01) > Cd (0.94) > Co (0.78) > Sb (0.73) > Be (0.39) > V (0.21) > Mn (0.05).

DISCUSSION

The mean concentrations of As, Cu, and Hg (13.9 mg kg^{-1}, 9.41 mg kg^{-1}, and 2.37 mg kg^{-1}, respectively) exceed the background concentrations previously reported (Table 3) for these elements (6.99 mg kg^{-1} for As, 6.26 mg kg^{-1} for Cu, and 0.37 mg kg^{-1} for Hg). The current data are elevated compared with previous reports by a factor of 2 for As, a factor of 1.5 for Cu, and a factor of 6.4 for Hg. The average concentrations observed for all other elements are below the background concentrations (Table 3). Higher Fe concentrations exist between sampling sites 25 and 49 (Figure 2), which is probably attributed to iron oxide–rich Oligocene sandstone in the surrounding area. Similarly, the concentrations of Al show higher values between sites 25 and 49.

The concentrations of some elements (including As, Cu, Co, and Se) show a relative decrease toward the north along the GOA coastline (Figure 2), which is likely related to the absence of rock formations in the northern half of the gulf coast where Quaternary deposits overlie the basement rocks. However, relatively higher concentrations of Ba, Cr, Pb, V, and Mo are recorded in the northern half of the study area (between sites 50 and 85). Higher values of these elements and other metals are possibly discharged from thermal desalination plants in the cities of Elat in Israel and Haql in Saudi Arabia (Al-Rousan *et al*., 2007; Batayneh *et al*., 2014a). Thermal desalination plants can discharge Cu, Ni, Fe, Cr, Zn, and other heavy metals depending on the alloys present in the process line, which may have adverse effects on water and sediment quality (Hoepner, 1999; Lattemann and Höpner, 2008). In contrast to the varying concentrations of these elements (*i.e*. Ba, Cr, Pb, V, and Mo), almost constant behavior is observed for B, Mn, Sb, Cd, and Be along the GOA coastline.

Heavy metal and metalloid concentrations in the studied sediments are compared with those reported from other countries (Table 6). Based on this comparison, the mean concentration of Fe in the present study is almost double the value reported from the Gulf of Suez and the GOA in Egypt (Youssef and El-Said, 2010, 2011), and one-fifth of that reported from the Gulf of Mannar in India (Jonathan and Mohan, 2003). Overall, mean element concentrations obtained from this study are considerably lower than those from Quanzhou Bay in China (Ruilian *et al*., 2008). The average level of Cu estimated by this study is nearly the same as that reported from the Gulf of Suez and the GOA but considerably lower than the values reported from the Gulf of Riga in the Baltic Sea (Leivuori *et al*., 2000) and from Quanzhou Bay in China. The average concentrations of Zn, Cr, Pb, Mn, Co, and Cd determined in this study are also much lower than the averages reported from the areas mentioned in Table 6. In contrast, the average concentration of Hg in this study is noticeably higher than those reported from the Gulf of Riga (Baltic Sea), Quanzhou Bay (China) and the harbor of Bremen in Germany (Hamer and Karius, 2002). These variations in metal concentrations from one gulf to another are probably attributed to variable geological distribution of their parent minerals, to different sources and levels of contaminants, or both.

As, Cu, Co, and Se show more positive *Igeo* values in the southern half of the GOA compared with its northern half. This may be because of high As, Cu, Co, and Se concentrations in the southern parts, where different sedimentary rock units cover the shoreline. The Hg values show a remarkable positive behavior with little variation in *Igeo* across the sampling sites. As shown in Figure 4, elevated *Igeo* levels of Ba, Cr, Pb, V, and Mo are recorded in the northern half of the study area (between sites 50 and 85), which is likely related to discharge of effluent from thermal desalination plants in Elat (Israel) and Haql (Saudi Arabia). An almost constant presence of B, Zn, Mn, Sb, Cd, and Be is observed along the studied gulf coastline.

Figure 5 shows the distributions of *EF* for heavy metals and metalloids along the Saudi GOA coast. It shows very high *EF* values (>10) for Hg, As, and Cu along the gulf, indicating that sediments are highly contaminated with these metals. In addition, moderately high EF values (>3) for As, Cr, B, and Mo are detected in the southern region, whereas moderate enrichment (<3) is observed for Pb, Zn, Ba, Cd, Co, Sb, and Be. As shown in Table 5 and Figure 5, a depletion trend is indicated in the *EF* values of V and Mn (<1). Almost uniform

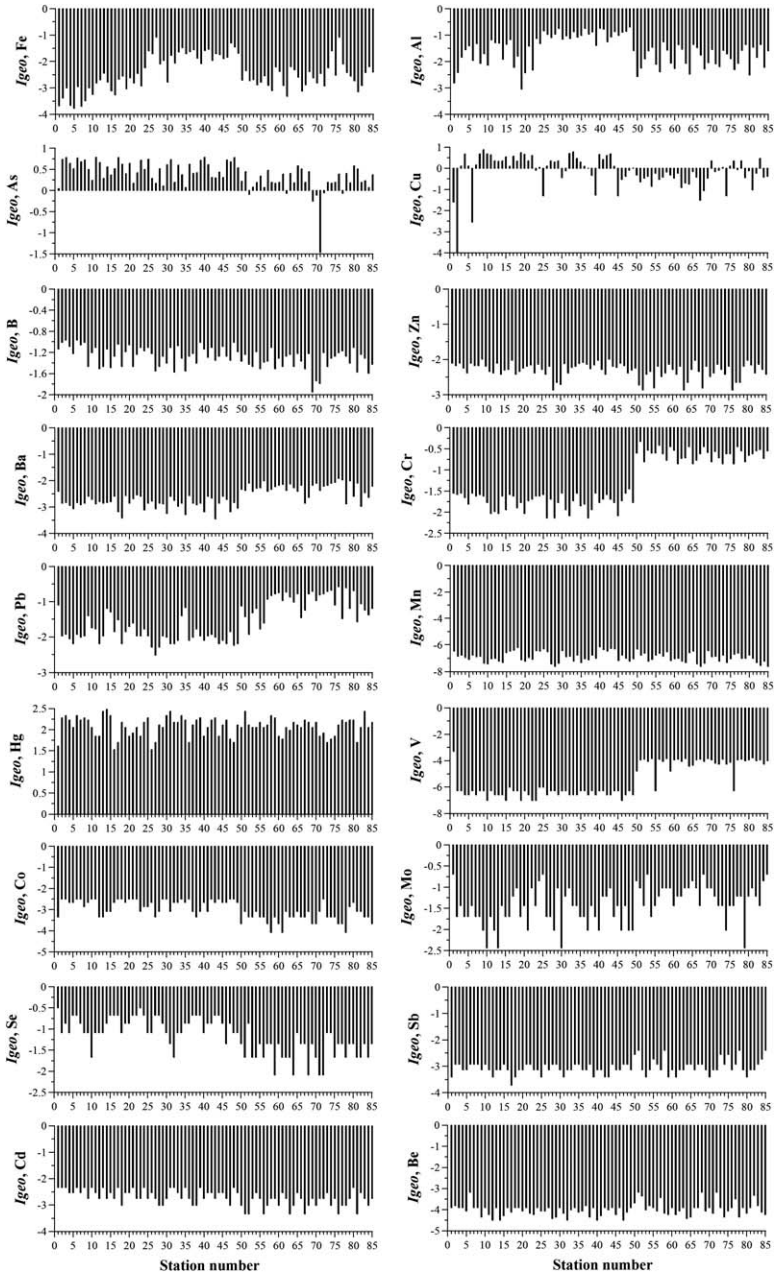

Figure 4. Distribution of *Igeo* for heavy metals and metalloids along the Saudi GOA coast.

low values of *EF* dominate the central part of the Saudi GOA coast, indicating the presence of local *EF*s in the area.

Multivariate analysis (*i.e.* PCA) and a correlation matrix have proved to be effective tools for identifying the origin of contaminant (Bai *et al.*, 2011b; Han *et al.*, 2006; Mico *et al.*, 2006; Panda *et al.*, 2010). The results of factor analysis for total heavy metal and metalloid concentrations in surface sediments from the GOA coast are listed in Table 7. These factors (F1–F5) elucidate a relatively large extent of the total variance (64.435%) of the 18 variables used in this analysis. Al, As, B, Co, and Se metals showed a strong positive association with the first factor (F1) 29.87% of the total variance. This is an indication of the close relationships among the concentrations of the five metals. It also indicates that all metals had the same source, which might be related to a lithologic component. In addition, application of agrochemicals and fertilizers in the upstream agricultural farms along the eastern GOA coastal plain may led to increased heavy metal concentrations (*e.g.*, As). Correlation analysis also showed in Table 4 that there were significant correlations between As and Al (0.31), B and As (0.62), Co and As (0.44), Co and B (0.42), Se and Al (0.36), Se and As (0.40), and Se and B (0.32).

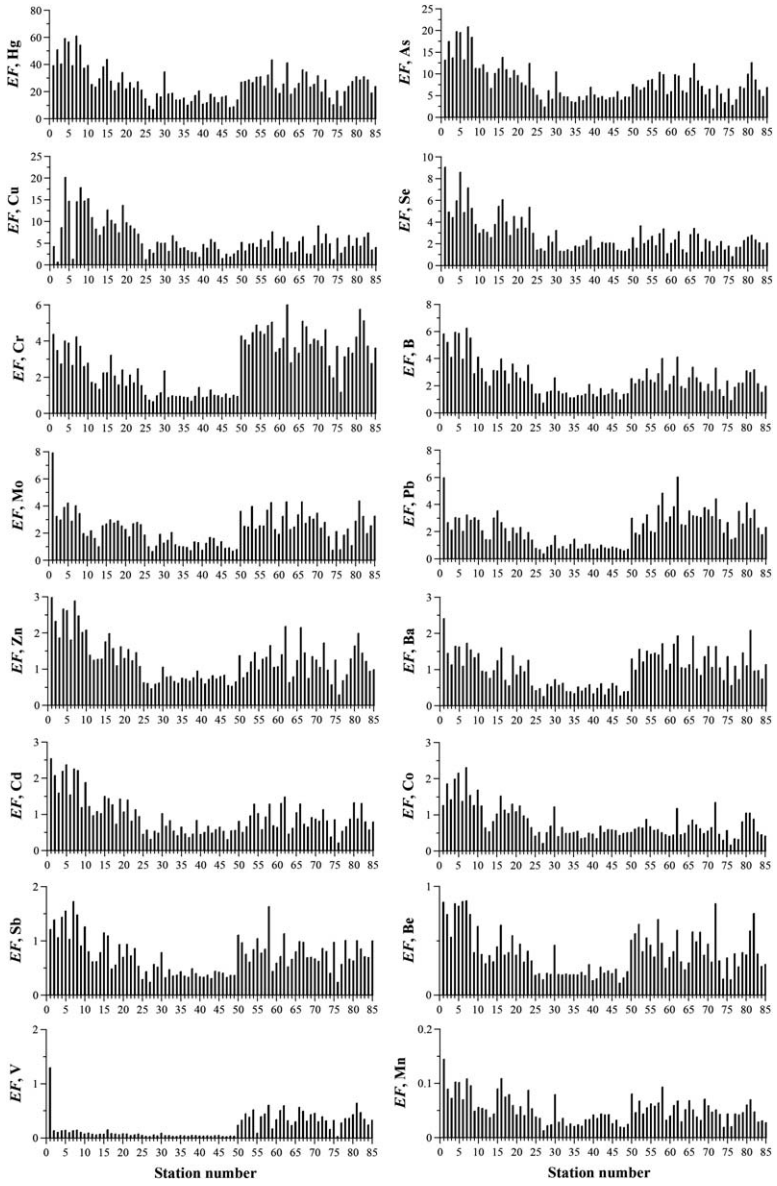

Figure 5. Distribution of *EF* for heavy metals and metalloids along the Saudi GOA coast.

The second factor, F2, which explained 10.64% of the total variance, shows highly positive factor loading for Zn and Cd (Table 7). Correlation analysis shown in Table 4 indicates a significant correlation between Cd and Zn (0.48). Zn and Cd concentrations may be elevated because of inputs either from agricultural sources or from fertilizer and phosphate plants.

The third factor, F3, accounting for 10.25% of the total variance, is strongly positively correlated with the concentration of Be. B metal is distributed in both F1 and F3 factors. The fourth factor (F4; 6.913%) contains a high positive loading of Hg, whereas the fifth factor (F5; 6.759%) contains a high positive loading of Mn and Mo. Hg is released into the air through fuel combustion, mining, and agricultural fertilizers. Several plants for fertilizer and phosphate ore production and handling, as well as storage and loading facilities located south of the main port of Aqaba city, may contribute large concentrations of heavy metals to the GOA.

Environmental factors influencing metal mobility, such as pH, EC, TOM, and TC, can also be used to explain the differences of trace element contents (Laing *et al*., 2008). Soil pH is positively correlated with Co and Se ($P < 0.05$; Table 4). This is associated with the low mobility of these trace elements in the alkaline environment (Gao *et al*., 2013). Zeng *et al*. (2001) also reported a negative correlation between soil pH and extractable trace element contents. Thus, higher soil pH values would lead to the accumulation of these trace elements in soil.

Soil EC did not significantly influence the mobility of trace elements in sediments (except for Co; Table 4). The significant

Table 6. *Heavy metal and metalloid concentrations in the GOA sediments and other gulfs all over the world.*

Location	Fe	Al	As	Cu	B	Zn	Ba	Cr	Pb	Mn	Hg	V	Co	Mo	Se	Sb	Cd	Be
Present study																		
Mean (mg kg^{-1})	1324	1310	13.9	5.49	7.95	7.43	6.06	5.49	5	3.79	2.37	1.25	0.66	0.63	0.59	0.065	0.063	0.029
SD	598.56	471.49	2.64	2.22	1.03	1.06	1.45	2.22	1.92	0.95	0.35	1	0.19	0.18	0.16	0.012	0.013	0.007
Gulf of Suez, Egypt[1]																		
Mean (mg kg^{-1})	504.4	—	—	5.03	—	64.8	—	13.6	—	157	—	—	12.3	—	—	—	4.1	—
SD	144.4	—	—	2.42	—	69.1	—	14.1	—	140	—	—	3.04	—	—	—	3.23	—
GOA, Egypt[2]																		
Mean (mg kg^{-1})	544.8	—	—	5.81	—	35.15	—	7.9	—	230	—	—	11.2	—	—	—	2.86	—
SD	170	—	—	5.57	—	25.0	—	10.4	—	170	—	—	3.0	—	—	—	0.66	—
Gulf of Riga, Baltic Sea[3]																		
Mean (mg kg^{-1})	—	—	—	103	—	438	—	—	162		1.5	—	—	—	—	—	3.31	—
SD	—	—	—	3.0	—	12.0	—	—	8.0		0.11	—	—	—	—	—	0.30	—
Gulf of Mannar, India[4]																		
Mean (mg kg^{-1})	6500	—	—	—	—	—	—	172	—	296	—	—	—	—	—	—	—	—
SD	7495	—	—	—	—	—	—	33	—	7.8	—	—	—	—	—	—	—	—
Gulf of Mexico[5]																		
Mean (mg kg^{-1})	—	—	—	—	—	—	—	52	—	231	—	—	—	—	—	—	—	—
SD	—	—	—	—	—	—	—	68.6	—	309	—	—	—	—	—	—	—	—
Arabian Gulf[6]																		
Mean (mg kg^{-1})	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.65	—
SD	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.06	—
GOA, Jordan[7]																		
Mean (mg kg^{-1})	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8.9	—
SD	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	7.07	—
Quanzhou Bay, China[8]																		
Mean (mg kg^{-1})	—	—	21.7	71.4	—	179.6	—	82	67.7	—	0.4	—	—	—	—	—	0.59	—
SD	—	—	3.8	29.4	—	33.2	—	19.4	16.9	—	0.23	—	—	—	—	—	0.18	—
Harbor of Bremen, Germany[9]																		
Mean (mg kg^{-1})	—	—	—	87	—	790	—	131	122	—	0.3	—	—	—	—	—	6.0	—
SD	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

[1] Youssef and El-Said (2010).
[2] Youssef and El-Said (2011).
[3] Leivuori *et al*. (2000).
[4] Jonathan and Mohan (2003).
[5] Macias-Zamora *et al*. (1999).
[6] Al-Sayed *et al*. (1994).
[7] Abu-Hilal (1987).
[8] Ruilian *et al*. (2008).
[9] Hamer and Karius (2002).
SD = standard deviation.

relationship ($P < 0.01$) between EC and Co suggests that they were derived from a similar source, which is consistent with the preceding result of the first factor (F1). Table 4 shows insignificant correlations between TOM and trace elements. However, TC has a moderate positive correlation with Cu ($r = 0.31$). This is possibly because of the occurrence of copper in the studied sediments (Lin and Chen, 1996; Okbah, Shata, and Shriadah, 2005).

Heavy metal and metalloid concentrations in the Saudi GOA sediments (Table 3) were compared with standard-quality marine sediments from China (GB 18668-2002; Table 8). The comparison indicates that Hg concentrations in the study area (Table 3) are in excess of the primary, secondary, and tertiary standard criteria (Table 8). The concentrations of other heavy metals and metalloids meet all standard criteria (GB 18668-2002) of marine sediments.

The Canadian guidelines assess heavy metal concentrations in the sediments and their biological impacts. A threshold effect level (TEL) and a probable effect level (PEL) are the only two criteria of the Canadian guidelines (Table 8). The Canadian Council of Ministers of the Environment has established these

Table 7. *Factor analysis for heavy metals and metalloids in surface sediments from the GOA coast.*

	F1[1]	F2[1]	F3[1]	F4[1]	F5[1]
Fe					
Al	0.530				
As	0.717				
Cu					
B	0.550		0.546		
Zn		0.665			
Ba					
Cr					
Pb					
Mn					0.818
Hg				0.866	
V					
Co	0.702				
Mo					0.641
Se	0.704				
Sb					
Cd		0.767			
Be			0.712		
Variance (%)	29.87	10.64	10.25	6.91	6.76
Cumulative (%)	29.87	40.51	50.76	57.67	64.43

[1] Factor loadings smaller than 0.5 have been removed.

Table 8. *Canadian and China State Bureau of Quality and Technical Supervision (CSBTS) sediment guidelines for some studied heavy metals and metalloids*.

	CSBTS Guidelines (mg kg^{-1})			Canadian Guidelines (mg kg^{-1})	
Metal	Primary	Secondary	Tertiary	TEL	PEL
As	20.0	65.0	93.0	7.24	41.6
Cd	0.5	1.5	5.0	0.7	4.2
Cr	80.0	150.0	270.0	52.3	160.0
Cu	35.0	100.0	200.0	18.7	108.0
Hg	0.20	0.50	1.0	0.13	0.7
Pb	60.0	130.0	250.0	30.2	112.0
Zn	150.0	350.0	600.0	124.0	271.0

levels, which have been routinely used as screening tools by different stakeholders in sediment management activities. Values below the TEL have no adverse biological effects. However, above the PEL, adverse effects frequently occur. The present results show considerably high concentrations of Hg in the studied sediments (Table 3) compared with those mentioned in the TEL and PEL (Table 8). Specifically, even the lowest Hg concentration (1.6 mg kg^{-1}; Table 3) in the studied sediments is about 12 times higher than the TEL and about two times higher than the PEL. The average concentration of As (13.9 mg kg^{-1}; Table 3) is also found to be two times higher than the Canadian TEL (Table 8). However, for other metals, the average concentrations are noticeably lower than the TEL values. Accordingly, it appears that sediments along the GOA coast are, to some extent, contaminated by Hg and As metals.

CONCLUSION

This study focuses on the assessment of heavy metals and metalloids in surface sediments collected from the Saudi GOA coast. The mean concentrations of the heavy metals and metalloids in the studied sediments have been found in the following order: Fe > Al > As > Cu > B > Zn > Ba > Cr > Pb > Mn > Hg > V > Co > Mo > Se > Sb > Cd > Be. Based on the HCAs, the studied elements were classified into four cluster groups (C1–C4). Cluster C1 (Cr, V, Pb, and Ba) and cluster C2 (Mn, Mo, Be, Hg, and Sb) have higher linkage distances compared with the remaining clusters. However, although cluster C3 (Al, Fe, and Cu) and cluster C4 (Cd, Zn, As, B, Co, and Se) have lower linkage distances, they have greater similarity. Using Pearson's correlation coefficient matrices, strong positive linear correlations have been observed among the elements of cluster C1, *i.e.* between Ba and Cr ($r = 0.72$), Cr and Pb ($r = 0.74$), Cr and V ($r = 0.84$), and Pb and V ($r = 0.71$). The same assessment indicates moderate positive linear correlations between Ba and Pb ($r = 0.59$) and between Ba and V ($r = 0.68$). In the case of cluster C2, a weak positive linear correlation was observed between the cluster components, *i.e.* between Mn and Mo ($r = 0.19$). For cluster C3, a moderate positive linear correlation was found between Fe and Al ($r = 0.53$). However, cluster C4 presented moderate positive correlations among its elements, *i.e.* between As and B ($r = 0.62$), between Cd and Zn ($r = 0.48$), and between Co and Se ($r = 0.40$). No significant correlations have been detected among the remaining elements of these clusters, which is probably attributed to different anthropogenic and natural sources of these metals.

The sediment quality is assessed by *Igeo*, *EF*, and the sediment-quality guidelines from China and Canada. The *Igeo* results reveal that Hg metal causes moderate-to-strong pollution in the sediments along the Saudi GOA. Next in order is As, which causes moderate pollution in most studied locations, whereas Cu is found to cause low pollution in the southern half of the gulf area. Concentrations of Hg well exceeded the primary, secondary, and tertiary criteria of the Chinese guidelines and the TEL and PEL of the Canadian guidelines. As concentrations also exceed the Canadian TEL. The *EF* results indicated that Hg is a strong pollutant in the study area, whereas As and Cu are moderate pollutants. The differences in the reported values of *EF* are probably related to variations in the input of each metal in the sediments, differences in the removal rates of each metal from the sediments, or both.

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