Marine Pollution Bulletin 137 (2018) 198–208

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Spatial distribution and ecological risk assessment of the coastal surface sediments from the Red Sea, northwest Saudi Arabia

Ali Y. Kahal[a], Abdelbaset S. El-Sorogy[a,b,*], Hussain J. Alfaifi[a], Sattam Almadani[a], Habes A. Ghrefat[a]

[a] Geology and Geophysics Department, College of Science, King Saud University, Saudi Arabia
[b] Geology Department, Faculty of Science, Zagazig University, Egypt

ARTICLE INFO

Keywords:
Spatial distribution
Ecological risk assessment
Heavy metals
Coastal sediments
Red Sea
Saudi Arabia

ABSTRACT

To assess the spatial distribution and ecological risk assessment along the Red Sea coast, Saudi Arabia, 30 samples were collected for aluminum, chromium, copper, zinc, cadmium, lead, mercury, iron, cobalt, nickel and organic matter analysis. The descending order of metal concentrations was Al > Fe > Cr > Cu > Zn > Ni > Co > Pb > Hg > Cd. Average values of enrichment factor of Hg, Cd, Cu, Co, Cr, Ni, Pb and Zn were higher than 2 (209.50, 25.52, 20.36, 9.62, 7.28, 6.52, 6.21 and 6.07 respectively), which means anthropogenic sources of these metals. The average levels most of the studied metals were lower than those of the background shale and the earth crust and those recorded along most worldwide coasts, while the average values of zinc, copper, cobalt and nickel were higher than the values recorded from the Red Sea coast, the Gulf of Aqaba and some Caspian Sea coasts. The Duba bulk plant-Saudi Aramco, Duba refinery station and the tourist resort were the possible anthropogenic sources of pollutants in the southern part of the study area; and the landfilling, cement factory and Duba port and shipment operations in the central part, while the landfilling resulting from construction of the green Duba power plant and crowded fish boats were the possible sources in the northern part.

1. Introduction

Heavy metals (HMs) are highly toxic, non-biodegradable, and easily enriched in aquatic organisms. They discharged into the marine environment through surface runoff, especially with the development of industry, agriculture, and urbanization (Diagomanolin et al., 2004; Zhang and Gao, 2015; Jafarabadi et al., 2017; Liu et al., 2018). Sediments represent the major component of metal storage in marine environments, where metals scavenge by particulate matter and deposited to coastal bottom sediments after entering coastal waters (Pan and Wang, 2012). The accumulation of HMs in the sediments and seawater is a critical problem and a serious threat to aquatic organisms and directly or indirectly to human health.

Currently, researches on heavy metal pollution status in coastal sediments, seawater and marine skeletons of the Arabia Gulf and Red Sea coasts of Saudi Arabia have become increasingly common (Sadiq and Alam, 1989; de Mora et al., 2004a, 2004b; Naser, 2011, 2012, 2013; Youssef et al., 2015; Almasoud et al., 2015; El-Sorogy and Youssef, 2015; Al-Kahtany et al., 2015, 2018; El-Sorogy et al., 2016a, 2016b; Youssef et al., 2016; Youssef and El-Sorogy, 2016; Alharbi and El-Sorogy, 2017; Alharbi et al., 2017a, 2017b; El-Sorogy et al., 2018).

The study area of the present work is very important, where it includes the southern part of the new transnational city and economic zone to be constructed in the border region of Saudi Arabia and Egypt. Also, field survey indicated some anthropogenic sources for HMs along the studied coast. Therefore, the main objectives of the present study are to evaluate the levels of metals in the coastal sediments between Duba and Sharma along the Red Sea coast, northwest Saudi Arabia (Fig. 1), assess the impact of human activities and compare the rate of pollution in the study area.

2. Material and methods

2.1. Study area

The coastline between Duba and Sharma along the Saudi Red Sea coast is differentiated into raised reef-dominated, sandy-dominated, rocky shore-dominated, tidal flat-dominated and mangrove-dominated sediments (Fig. 2). The raised reef-dominated sediments are represented by the Pleistocene lower reef unit, 1.3–1.8 m above the present sea level. It occurs directly along the coastline in many sites and composed of scleractinian corals as frame-builders and foraminifers and

* Corresponding author.
E-mail address: asmohamed@ksu.edu.sa (A.S. El-Sorogy).

https://doi.org/10.1016/j.marpolbul.2018.09.053
Received 2 August 2018; Received in revised form 12 September 2018; Accepted 29 September 2018

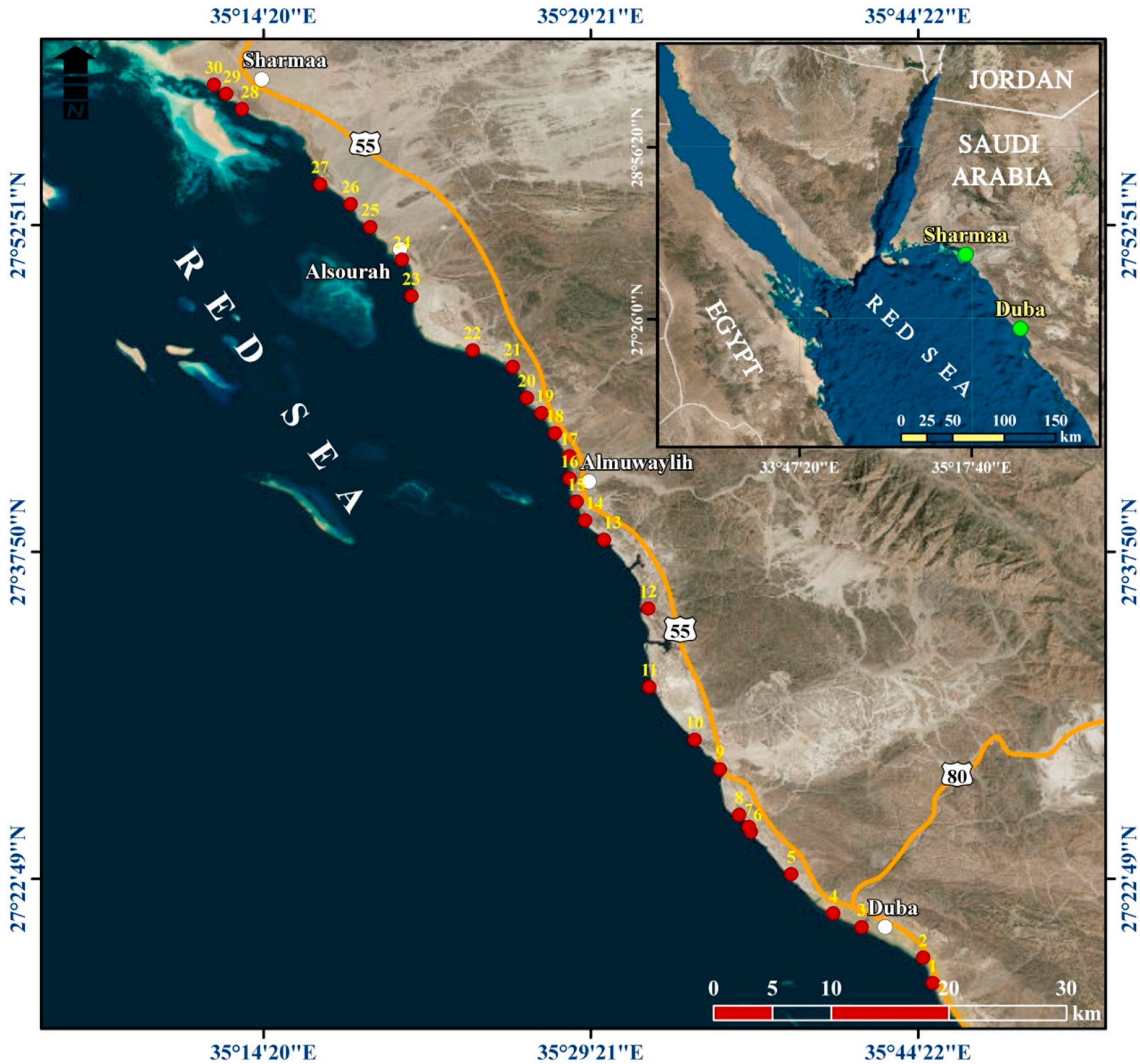

Fig. 1. Location map of the study area and coastal sediment locations.

coralline algae as secondary reef encrusters (e.g. sites 1, 3, 4, 5, 6, 7, 9, 10, 13, 14, 22). The sandy-dominated sediments are composed of medium to very coarse sand, mostly of biogenic origin (fragments of corals, bivalves, gastropods, foraminifers, crustaceans, bryozoans and sea grass). Sand sediments of detrital origin are derived from the hinterland (e.g. sites 2, 15, 16, 17, 18, 19, 20, 21, 23, 24). In wadi entrances, the sand sized sediments changed to gravels and cobbles and in protected areas sediments changed to fine sand to mud. The rock shore-dominated sediments are rare and composed of very hard gravelly, conglomeratic in parts, coarse biogenic sands (e.g. sites 25, 26, 27, 28, 29, 30). The tidal flat-dominated sediments are composed of very fine sand and muddy sediments (e.g. sites 11, 12). Many molluscs flourish in these flats. The mangrove-dominated beach are very restricted and composed of *Avicennia marina*. The sediments under mangrove trees are composed of sand, silt and clay fractions with rare shell fragments (e.g. site 8).

2.2. Sampling strategy and analytical methods

Thirty samples of surface sediment (from 1 to 40 cm deep) were collected in April 2018, using a grab sampler, from the subtidal zone of the Red Sea coast, northwest Saudi Arabia (Fig. 1, Table 1). Methods of US Environmental Protection Agency (EPA/CE-81-1 Protocol) were followed in sample preparation and handling. Al, Cr, Cu, Zn, Cd, Pb, Hg, Fe, Co and Ni analyses were calculated (ICP-MS: NexION 300D, Perkin Elmer, USA), in the laboratory of King Saud University, using formal methods of preparation, digestion and analysis (Table 2). Also, loss on ignition (LOI) analysis is used to determine the organic matter content (%OM). Enrichment Factor, Geoaccumulation Index and Contamination Factor (Muller, 1979; Hökanson, 1980; Leopold et al., 2008; Sinex and Helz, 1981) were used as contamination indices to detect the sources of metals. Also, dendrogram for hierarchal clusters analyses (HCA), Pearson's correlation coefficients and principal component analysis (PCA) were performed.

Fig. 2. A. Raised reef-dominated shore, which represented by the lower reef unit of Pleistocene age, site 6; B. Sandy-dominated shore, site 15; C. Consolidated conglomeratic beaches in wadi entrance, site 7; D. Hard rocky shore with reworked mollusc and coral fragments, site 28; E. tidal flat-dominated shore, site 11; F. Mangrove-dominated shore, site 8.

3. Results and discussion

3.1. Spatial distribution and worldwide comparison of HMs

Table 2 summarized the concentration of 10 HMs and organic matter in 30 costal sediments in northwest Saudi Arabia. Al was the most abundant HMs (average 4876.56 μg/g), followed by Fe (1413.34 μg/g), Cr (20.18 μg/g), Cu (18.67 μg/g), Zn (16.75 μg/g), Ni (13.66 μg/g), Co (5.34 μg/g), Pb (3.54 μg/g), Hg (1.83 μg/g) and Cd (0.18 μg/g). The HMs are fluctuated throughout the studied area and based on their distribution pattern they subdivided into two groups, each one has the same pattern. The first one includes Al, Zn, Pb, Fe, Cr, Co and Ni, while the second one includes Cu, Hg and Cd.

3.1.1. Aluminum, iron, chromium, zinc, nickel, lead and cobalt

All of the Al, Fe, Cr, Zn, Ni, Pb and Co exhibited a similar spatial distribution pattern throughout the studied coastline (Figs. 3, 4). Aluminum varied from 235 μg/g in site 13 to 8468 μg/g at site 25, while the highest value of iron (2278 μg/g) is recorded in site 18 and the lowest one (444 μg/g) in site 7. Sites 27 and 28 recorded the highest value of chromium (33.8 μg/g), while site 4 recorded the lowest one (7.5 μg/g). Zinc values range from 7.7 μg/g in site 4 to 27.1 μg/g in site 15, while nickel values ranged from 4.6 μg/g in site 7 to 24 μg/g in site 17. The highest lead level (5.7 μg/g) is recorded in site 19, while the lowest one (1.5 μg/g) is recorded in site 4. The highest value of cobalt (8.8 μg/g) is recorded in site 17, while the lowest one (2.1 μg/g) is recorded in site 20. Table 3 illustrates the comparison between the average levels of our HMs with those recorded in coastal sediments

Table 1
Location and composition of the coastal sediment samples along the Red Sea coast, northwest Saudi Arabia.

Sample number	Latitudes	Longitudes	Sediment type and characteristics
1	27° 30′ 04″	35° 75′ 07″	Biogenic medium to coarse sand
2	27° 32′ 00″	35° 74′ 33″	Biogenic medium to coarse sand
3	27° 34′ 32″	35° 69′ 62″	Biogenic medium to gravely sand
4	27° 35′ 40″	35° 67′ 45″	Biogenic medium to coarse sand
5	27° 38′ 39″	35° 64′ 23″	Biogenic medium to gravely sand
6	27° 41′ 62″	35° 61′ 15″	Varicolored medium sand of basement origin
7	27° 42′ 01″	35° 60′ 98″	Biogenic medium to coarse sand
8	27° 42′ 93″	35° 60′ 26″	Fine clayey sand
9	27° 46′ 42″	35° 58′ 79″	Biogenic medium to coarse sand
10	27° 48′ 69″	35° 56′ 85″	Biogenic medium sand
11	27° 58′ 73″	35° 53′ 31″	Fine clayey sand
12	27° 52′ 55″	35° 52′ 53″	Biogenic medium sand
13	27° 64′ 00″	35° 49′ 92″	Biogenic medium to coarse sand
14	27° 65′ 30″	35° 48′ 92″	medium sand
15	27° 66′ 91″	35° 47′ 82″	Fine sand
16	27° 68′ 69″	35° 47′ 30″	Fine to medium sand
17	27° 70′ 39″	35° 49′ 96″	Very fine sand
18	27° 72′ 16″	35° 46′ 18″	Fine sand
19	27° 73′ 70″	35° 45′ 14″	Clayey to silty sand
20	27° 74′ 87″	35° 44′ 02″	Medium sand
21	27° 77′ 25″	35° 42′ 94″	Coarse to gravely sand
22	27° 78′ 52″	35° 39′ 88″	Fine to medium sand
23	27° 82′ 66″	35° 35′ 20″	Clayey to very fine sand
24	27° 85′ 46″	35° 34′ 47″	Fine sand
25	27° 87′ 95″	35° 32′ 05″	Fine sand
26	27° 89′ 70″	35° 30′ 55″	Fine sand
27	27° 91′ 22″	35° 28′ 22″	Fine to medium sand
28	27° 96′ 99″	35° 22′ 24″	Fine sand
29	27° 98′ 16″	35° 21′ 01″	Clayey to fine sand
30	27° 98′ 86″	35° 20′ 08″	Clayey to sand

from some worldwide oceans, seas and gulfs. In general, the average values of Zn, Co and Ni in the present coastal sediments were higher than the values recorded from the Red Sea coast, the Gulf of Aqaba and some Caspian Sea coasts. In the other hand, the averages of the studied metals were lower than those of the earth crust and shale background and those recorded along most worldwide coasts mentioned in Table 3.

3.1.2. Copper, cadmium and mercury

The spatial distribution of Cu, Cd and Hg are closely similar throughout the study area (Fig. 5). Levels of Cu ranged from 5.6 μg/g in site 20 to 33 μg/g in site 22. The highest Cd level (0.26 μg/g) is recorded in site 5, while the lowest one (0.1 μg/g) is recorded in site 9. The levels of Hg ranged from 0.68 in sites 23 and 28 to 3.8 μg/g, in site 1, with an average value of 1.83 μg/g. The average Cu value is significantly lower than those from the Arabian Gulf, the sediment quality guidelines, and the probable effects level. It exceeds the values recorded from the Red Sea coast of Saudi Arabia and Egypt, the Gulf of Aqaba and coasts of Kazakhstan and Russia. The average value of Cd is less than levels recorded in the ERL and ERM values, the probable effects level and Mediterranean Sea, Egypt. It is higher than the values of Gokcekaya Dam Lake, Turkey and the Gulf of Aqaba. The average Hg value exceeds the values recorded from the Caspian Sea, the Arabian Gulf, the ERL value and the earth crust and shale background. Present average value of Hg is lower than the levels recorded from the coastal sediments of the Gulf of Aqaba (Table 3).

3.2. Risk assessment of HMs and possible sources

Statistical analyses and the values of EF, Igeo and CF indicated that, the studied sediments exhibited a wide range of element enrichment (Tables 4 and 5). Mercury had the highest degree of enrichment (EF = 209.50, Igeo = 1.55 and CF = 4.48), i.e. the sediments are

Table 2
Levels of 10 metals (μg/g) and organic matter (%) in 30 coastal sediments along the Red Sea coast, northwest Saudi Arabia.

Sample number	Cadmium	Cobalt	Chromium	Cupper	Mercury	Lead	Nickel	Aluminum	Iron	Zinc	Organic matter (%)
1	0.23	2.9	10.5	30.8	3.8	2.7	6.5	3540	926	13	0.714
2	0.24	3	10.8	32	3.3	2.8	7.1	3600	955	12.5	0.726
3	0.25	2.6	11	31.2	3.4	2.6	6.9	3465	972	13.3	0.784
4	0.16	2.7	7.5	24.6	1.8	1.5	4.7	1624	453	7.7	0.665
5	0.26	3.1	11.2	32.2	3.2	2.8	6.9	3508	938	12.8	0.786
6	0.16	6	23.8	21.8	2.9	3.8	13.1	6488	1542	15.6	0.972
7	0.15	2.8	7.7	25	1.7	1.6	4.6	1710	444	7.8	0.644
8	0.19	8.5	33.2	12.1	0.7	5	23.2	8365	2190	26.9	1.222
9	0.1	3.5	11	6.5	0.71	2.3	9.8	244	1038	8.7	0.666
10	0.24	3.2	10.7	32.3	3.2	2.7	6.8	3538	946	13	0.775
11	0.15	5.9	23.6	21	2.6	3.7	13.3	6501	1554	15.5	1.112
12	0.12	3.5	10.8	6.5	0.0.71	2.2	9.7	240	1026	8.6	0.625
13	0.11	3.3	10.3	6.3	0.75	2.3	9.9	235	1029	8.4	0.686
14	0.25	2.8	10.8	31	3.2	2.8	6.8	3498	940	12.5	0.726
15	0.18	8.7	33.6	12.5	0.72	5.2	23	8298	2180	27.1	1.378
16	0.11	3.6	10.8	6.7	0.72	2.2	9.7	240	1031	8.5	0.665
17	0.16	8.8	33	12.5	0.68	5.2	24	8400	2210	27	1.454
18	0.19	8.3	33.2	12.2	0.8	5.7	23	8453	2278	26.3	1.28
19	0.17	8.6	33.5	12.3	0.72	4.8	23.7	8352	2193	26.7	1.056
20	0.14	2.1	11	5.6	1	2	8.8	332	706	9.4	0.458
21	0.15	2.6	7.6	24.8	1.7	1.6	4.9	1628	449	7.8	0.681
22	0.25	3.4	10.8	33	3.4	2.8	6.6	3502	956	13.1	0.786
23	0.18	8	32.8	12	0.68	5.4	23	8388	2181	26.4	1.205
24	0.17	8.2	33.2	11.8	0.71	5.2	23.5	8412	2179	27	1.495
25	0.18	8	33.6	12	0.72	5	23	8468	2198	26.3	1.335
26	0.16	8.5	33.2	12.4	0.7	5.1	22.6	8375	2200	27	1.365
27	0.15	6.2	23.8	21.4	2.5	3.8	13.1	6538	1537	15.2	0.995
28	0.18	8.4	33.8	12.3	0.68	5.4	23.6	8405	2166	26.8	1.254
29	0.16	6.2	24	21.8	2.7	3.9	13.3	6496	1540	15.4	0.972
30	0.15	6.6	23.6	22.1	2.5	4	13.5	6504	1548	15	0.985
Minimum	0.1	2.1	7.5	5.6	0.68	1.5	4.6	235	444	7.7	0.458
Maximum	0.26	8.8	33.8	33	3.8	5.7	24	8468	2278	27.1	1.495
Average	0.18	5.34	20.18	18.67	1.83	3.54	13.66	4876.56	1413.34	16.75	0.95

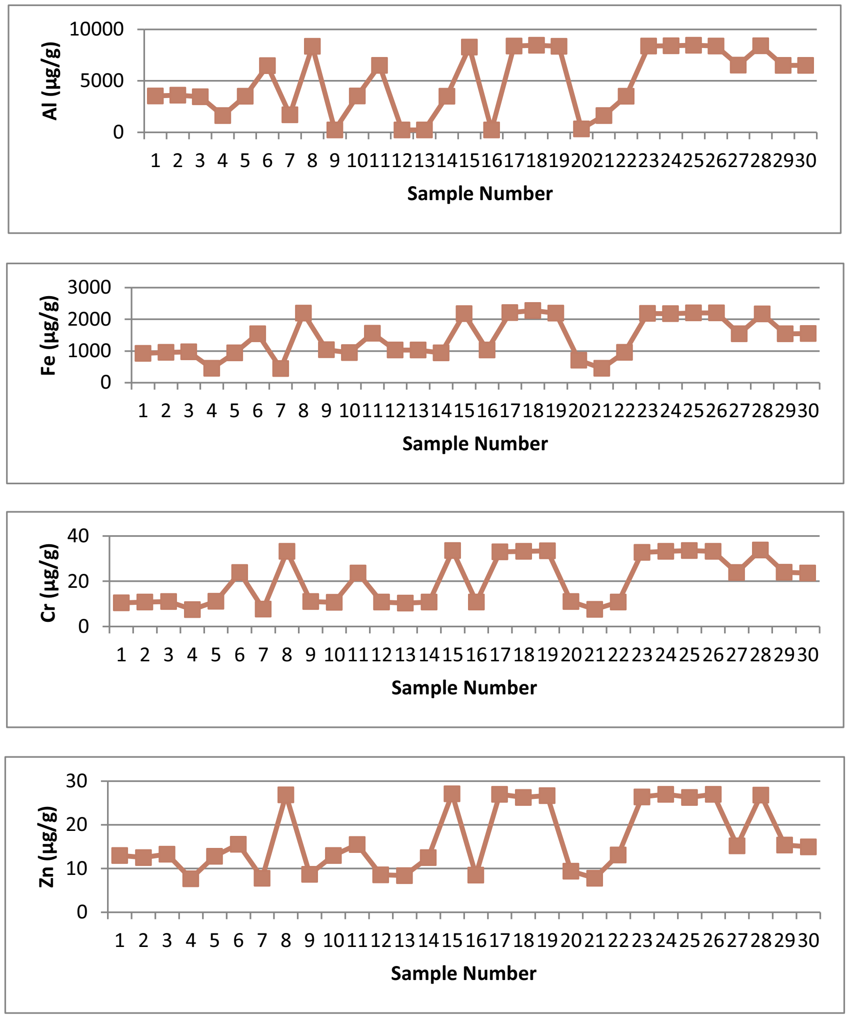

Fig. 3. Spatial distribution of aluminum, iron, chromium and zinc in the coastal sediments along the Red Sea coast, northwest Saudi Arabia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extremely severe enrichment, moderately polluted and considerably contaminated with Hg. In the next highest rank, the sediments are very severe enriched with cadmium (EF = 25.52) and severe enriched with copper (EF = 20.36). The coastal sediments are moderately severe enriched with Co, Cr, Ni, Pb and Zn (EF = 9.62, 7.28, 6.52, 6.21 and 6.07 respectively). Average value of EF for Al (1.88) indicated a minor enrichment and probably originated from natural sources, while elements gave enrichment factors higher than 2 suggested anthropogenic sources of these metals. HCA analyses subdivided HMs into two different groups (Fig. 6). The first includes Cd, Hg, Co, Pb, Ni, Zn, Cr, Cu and Fe, has greater similarity and lower linkage distances (except Fe to some extent) in comparison with the second group, which includes Al. Correlations between HMs may reflect the sources of pollution, where the high correlated elements may share common sources, migrate under certain physiochemical circumstances and show similar behaviors during transformation (Wang et al., 2012; Wang et al., 2015). Pearson's correlation analysis indicated extremely positive correlations between several elemental pairs: Co-Cr (r = 0.990), Co-Fe (r = 0.976), Co-Ni (r = 0.970), Co-Pb (r = 0.963), Co-Zn (r = 0.939) and Co-Al (r = 0.924) and might have common sources. In contrast there are negative correlation between Cu and each of Pb, Ni, Al, Fe and Zn (Table 6). The high levels of organic matter are associated with clayey to very fine sediments, such as sites 8, 11, 15, 17–19, 23, 24 and 28.

The results of the PCA reduced the number of variables into two principal components (PCs), which explain 95.67% of the total variance (Table 7). The first factor (PC1) explains 72.417% of the total variance and contains high positive loading for Co, Cr, Pb, Ni, Fe, Zn and Al. The second factor (PC2) and accounts 23.253% of the total variance and shows positive loading for Cd, Cu and Hg. The results of PCA indicated that Co, Cr, Pb, Ni, Fe, Zn and Al might originate from similar sources,

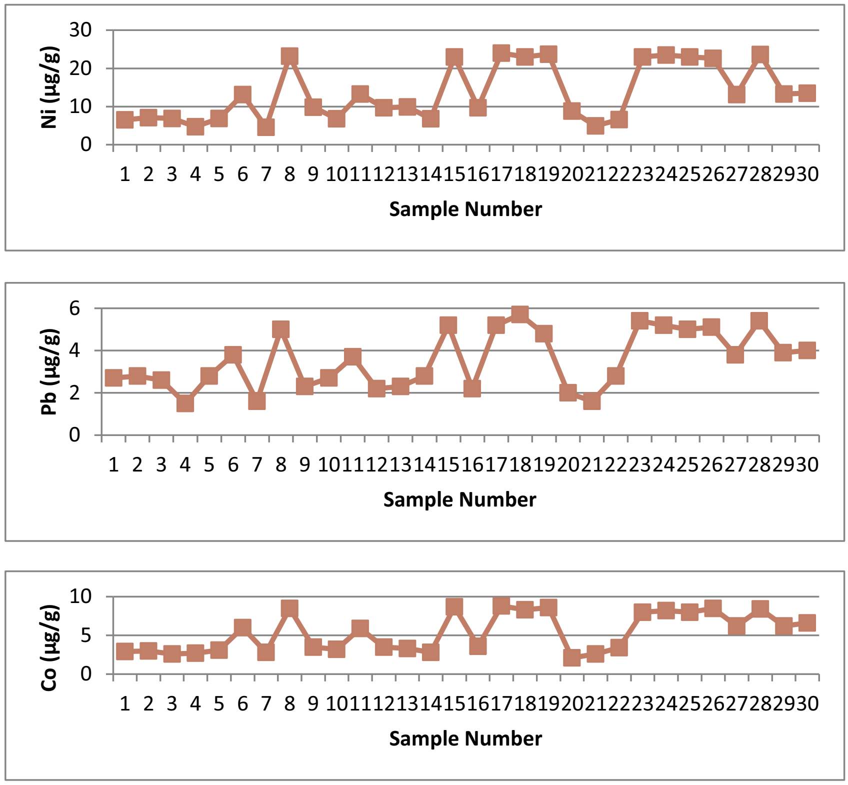

Fig. 4. Spatial distribution nickel, lead and cobalt in the coastal sediments of the study area.

Table 3
Comparison between metals in the studied sediments and other worldwide sites.

Location	Fe	Cr	Ni	Zn	Cu	Co	Al	Hg	Cd	Pb	Reference
Red Sea coast, northwest Saudi Arabia	1413.34	20.18	13.66	16.75	18.67	5.34	4876.56	1.83	0.18	3.54	Present study
Arabian Gulf, Saudi Arabia	8474.21	63.79	77.07	48.26	297.29	4.01	1887.07	2.02	2.13	5.25	El-Sorogy et al. (2018)
Red Sea, Egypt	355.44		1.74	7.77	1.26	1.66			0.14	42.38	Nour et al. (2018)
Red Sea, Saudi Arabia	2249.42	20.62	8.69	39.71	16.00	4.77		0.01	0.26	50.87	Youssef and El-Sorogy (2016)
Gokcekaya Dam Lake, Turkey	15,495	216.65	125.7	265.8	108.99	85.57			0.007	74.44	Akin and Kırmızıgul (2017)
Mediterranean Sea, Libya	2084		22.65	26.36	17.30	5.95			0.83	11.69	Nour and El-Sorogy (2017)
Mediterranean Sea, Egypt	109,560	0.18	480.86	183.23	24.57	69.78			28.88	384.68	El-Sorogy et al. (2016c)
North Morocco	33,000–51,100	88.4–161	34.2–79.9	65.7–115.3	2.8–29.1	18.1–31.7			0.1–0.3	35.1–447.8	Omar et al. (2015)
Arabian Gulf, Saudi Arabia	3447	27.10	–	17.57	5.78	6.35		0.55	0.66	58.68	Youssef et al. (2015)
Gulf of Aqaba	1172–1437	3. 7–8.0	–	7.0–7.7	7.6–10.8	0.51–0.77	1044–1506	2.36–2.37	0.06–0.07	3.7–6.8	Al-Taani et al. (2014)
Azerbaijan	37,100	85.3	50.1	83.2	31.9	14.9	69,200	0.15	0.14	19.6	de Mora et al. (2004b)
Iran	35,500	85.2	51.6	85.3	34.7	15.9	60,500	0.05	0.16	18.0	
Kazakhstan	6730	31.4	10.4	11.1	6.4	3.0	17,100	0.01	0.05	5.75	
Russia	5520	32.0	14.0	17.1	8.3	3.8	18,800	0.02	0.06	4.19	
Sediment quality guidelines (ERL)		81	21		34			0.15	1.2	47	Long et al. (1995)
Sediment quality guidelines (ERM)		370	52		270			0.71	9.6	220	
Interim sediment quality guideline		52.3		124	18.7			0.13	0.7	30.2	ISQG (1995)
Probable effects level (PEL)		160		271	108			0.7	4.2	112	
Spain		31.8–394.7	0.1–11.6	22.3–103.2	4.4–29.2	3.6–30.1			0.003–0.28	7.7–30.4	Diaz-de Alba et al. (2011)

(*continued on next page*)

Table 3 (*continued*)

Location	Fe	Cr	Ni	Zn	Cu	Co	Al	Hg	Cd	Pb	Reference
Salaam coast, Tanzania	461–5352	1–9.6	0.4–2.9	2.6–9.3	0.3–2.1	0.21–2.75			0.01–0.4	0.8–2.2	Rumisha et al. (2012)
Background shale	47,200	90	68	95	45	19	80,000	0.4	0.3	20	Turekian and Wedepohl (1961)
Background continental crust	56,300	100	75	70	55	25	82,300	0.08	0.2	12.5	Taylor (1964)
Daliao River System, China	–	43–45	18.7–19.0	43–657	15–20	8.1–13.2			0.1–4.2	20–100	Lin et al. (2012)

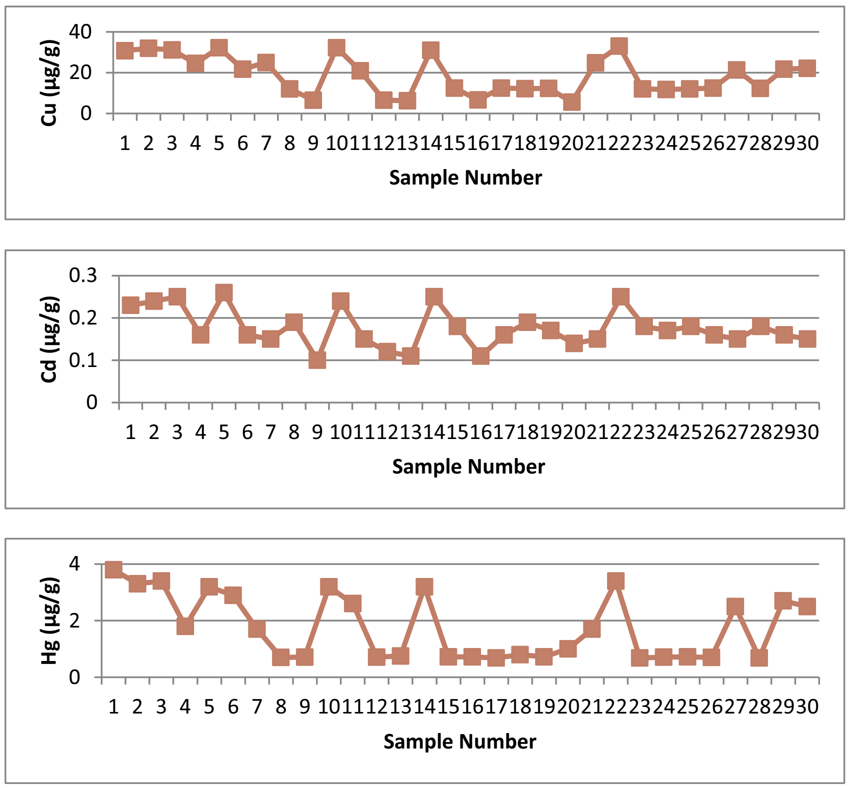

Fig. 5. Spatial distribution of copper, cadmium and mercury in coastal samples of the study area.

Table 4
The contamination indices (geo-accumulation index, contamination factor and enrichment factor). Data are adapted from the references of Hökanson, 1980; Müller, 1981; Birch, 2003; Alahabadia and Malvandi, 2018.

No. class	Geo-accumulation index (Igeo)		Contamination factor (CF)		Enrichment factor (EF)	
	Igeo value	Contamination level	CF value	Contamination level	EF value	Contamination level
1	0 Igeo ≤ 0	Practically unpolluted	1 CF < 1	Low	EF < 1	No enrichment
2	0 < Igeo < 1	Unpolluted to moderately polluted	1 < CF < 3	Moderate	1 < EF < 3	Minor enrichment
3	1 < Igeo < 2	Moderately polluted	3 < CF < 6	Considerable	3 < EF < 5	Moderate enrichment
4	2 < Igeo < 3	Moderately to heavily polluted	CF > 6	Very high	5 < EF < 10	Moderately severe enrichment
5	3 < Igeo < 4	Heavily polluted	–	–	10 < EF < 25	Severe enrichment
6	4 < Igeo < 5	Heavily to extremely polluted	–	–	25 < EF < 50	Very severe enrichment
7	Igeo > 5	Extremely polluted	–	–	EF > 50	extremely severe enrichment (Ultra-high)

Table 5
Values of enrichment factor (EF), geoaccumulation index (Igeo) and contamination factor (CF) of the determined metals.

Metals	Parameters	Min.	Max.	Average
Pb	EF	5.04	8.50	6.21
	Igeo	−2.30	−0.97	−1.53
	CF	0.08	0.29	0.18
Hg	EF	36.31	484.23	209.50
	Igeo	0.82	2.54	1.55
	CF	1.70	9.50	4.48
Cd	EF	11.39	55.57	25.52
	Igeo	−0.81	0.14	−0.28
	CF	0.33	0.87	0.59
Zn	EF	4.06	8.73	6.07
	Igeo	−2.22	−0.97	−1.56
	CF	0.08	0.29	0.18
Cr	EF	5.25	9.10	7.28
	Igeo	−2.20	−0.69	−1.37
	CF	0.08	0.38	0.22
Ni	EF	4.79	8.65	6.52
	Igeo	−2.41	−0.75	−1.48
	CF	0.07	0.35	0.20
Cu	EF	5.62	59.06	20.36
	Igeo	−3.59	−1.03	−2.08
	CF	0.12	0.73	0.41
Fe	Igeo	−7.32	−4.96	−5.83
	CF	0.01	0.05	0.03
Co	EF	6.65	15.67	9.62
	Igeo	−3.76	−1.70	−2.59
	CF	0.11	0.46	0.28
Al	EF	0.135	2.510	1.88
	Igeo	−9.00	−3.82	−5.34
	CF	0.00	0.11	0.06

while Cd, Cu and Hg might share other common sources. The association of elements with principal component analyses has been used to distinguish natural or anthropogenic sources in some studies (Wang et al., 2014; Zhang et al., 2016). The component plot accepted the same result of PCA, where the studied metals are concentrated in two zones (Fig. 7), which is highly consistent with the distribution of metals throughout the studied area in two groups.

Three main sources of pollutants could be identified according to PCA, correlation analysis and the EF values of metals: 1) Hg, Cd and Cu, mostly originated from anthropogenic sources; 2) Co, Cr, Ni, Pb and Zn, represented a mixture anthropogenic and natural sources; 3) Al and Fe mainly originated from natural sources. Fig. 8 illustrates some possible sources of pollutants throughout the study area. The southern samples are characterized by the highest levels of Hg and Cd, in sites 1 and 5 respectively. This area is characterized by the Duba bulk plant-Saudi Aramco, Duba refinery station and some tourist resorts, as well as the landfilling through wadi entrances. The central samples are characterized by the highest levels of Zn, Co, Ni, Pb and Fe, in sites 15, 17 and 18. This area has cement factory along the coast (Fig. 8), as well as Duba port with its shipment operations. The northern samples are characterized by the highest levels of Cu, Al and Cr, in sites 25, 27 and 28. This area is characterized by the landfilling resulting from construction of the green Duba power plant and crowded fish boats.

4. Conclusions

The average levels of HMs in 30 surface coastal sediments along the Red Sea coast, northwest Saudi Arabia were in the following order: Al > Fe > Cr > Cu > Zn > Ni > Co > Pb > Hg > Cd. These averages were lower than those of the earth crust and shale background and those recorded along most worldwide coasts and were higher than

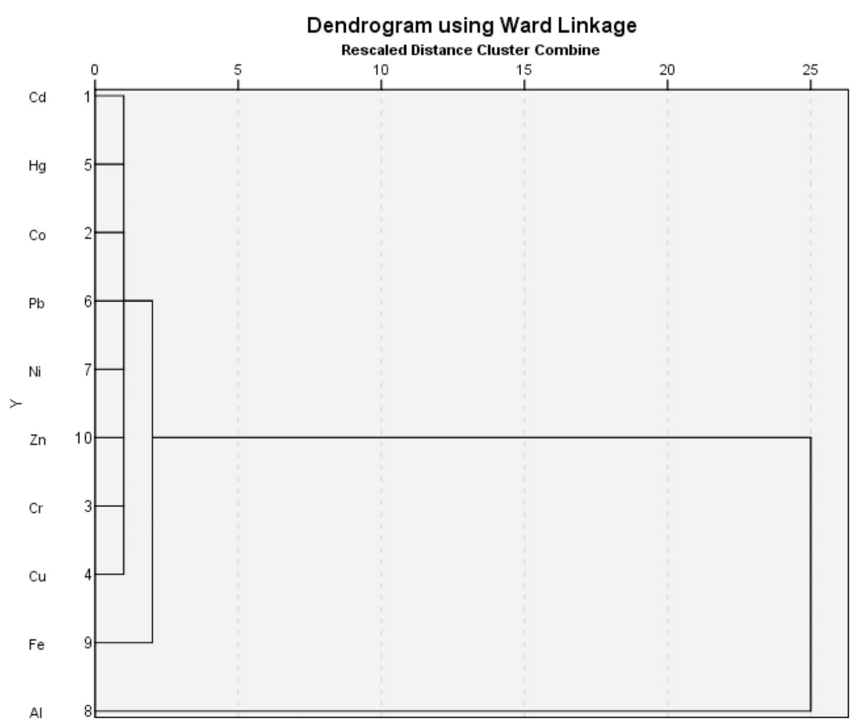

Fig. 6. Dendrogram for hierarchal clusters analyses (HCA) of 10 metals in 30 coastal samples collected along the Red Sea coast, northwest Saudi Arabia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Correlation matrix among analyzed metals.

	Cd	Co	Cr	Cu	Hg	Pb	Ni	Al	Fe	Zn
Cd	1									
Co	−0.140	1								
Cr	−0.090	**0.990**	1							
Cu	**0.765**	−0.460	−0.449	1						
Hg	**0.658**	−0.532	−0.505	**0.922**	1					
Pb	0.066	**0.963**	**0.976**	−0.349	−0.406	1				
Ni	−0.157	**0.970**	**0.975**	−0.583	−0.649	**0.952**	1			
Al	0.186	**0.924**	**0.940**	−0.119	−0.210	**0.952**	**0.861**	1		
Fe	−0.059	**0.976**	**0.983**	−0.473	−0.506	**0.983**	**0.979**	**0.911**	1	
Zn	0.130	**0.939**	**0.956**	−0.334	−0.450	**0.970**	**0.953**	**0.933**	**0.957**	1

Table 7
Principal component loadings and explained variance for the two components with Varimax normalized rotation.

Elements	PC1	PC2
Cd	−0.144	**0.912**
Co	**0.986**	0.056
Cr	**0.989**	0.094
Cu	−0.541	**0.812**
Hg	−0.605	**0.730**
Pb	**0.967**	0.226
Ni	**0.996**	−0.042
Al	**0.893**	0.412
Fe	**0.987**	0.093
Zn	**0.956**	0.237
Percent of variance	72.417	23.253
Cumulative percent	72.417	95.670

Bold values = loadings > 0.5.

those recorded from the Red Sea coast, the Gulf of Aqaba and some Caspian Sea coasts, especially for Zn, Cu, Co, Ni. The distribution pattern of the metals within the studied samples are fluctuated and subdivided into two groups, each has a similar pattern. The first one includes Al, Zn, Pb, Fe, Cr, Co and Ni, while the second one includes Cu, Hg and Cd. Results of enrichment factor indicated extremely severe enriched with Hg, very severe enriched with Cd, severe enriched with Cu and moderately severe enriched with Co, Cr, Ni, Pb and Zn, which suggest anthropogenic sources of these metals, while the enrichment factor of Al and Fe suggests natural sources. The possible sources of anthropogenic pollutants throughout the study area were Duba bulk plant-Saudi Aramco, Duba refinery station, the tourist resorts, the landfilling resulting from new constructions such as the green Duba power plant, Duba port with its ships and shipment operations and the crowded fish boats.

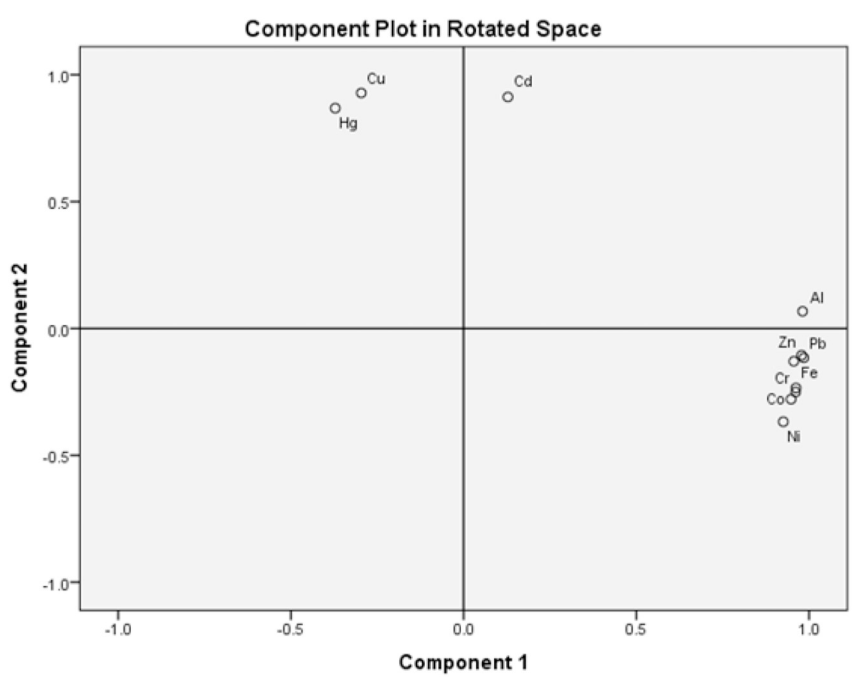

Fig. 7. Factor analysis and concentration of metals in two component plots.

Fig. 8. Possible sources of anthropogenic pollutants in the study area. A. Construction process of the green Duba power plant, site 20; B. Duba Bulk Plant-Saudi Aramco, Duba Refinery station, site 2; C. Cement factory on the coast, site 10; D. Large ship around Duba port; E, Crowded fish boats in site 24. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Acknowledgments

The authors extend their appreciation to the Deanship of Scientific Research at King Saud University for funding this work through the Research Group No. (RG-1438-059). Also, we thank the anonymous reviewers for their valuable suggestions and constructive comments.

References

Akin, B.S., Kırmızıgu, O., 2017. Heavy metal contamination in surface sediments of Gökçekaya Dam Lake, Eskişehir, Turkey. Environ. Earth Sci. 76, 402.
Alahabadia, A., Malvandi, H., 2018. Contamination and ecological risk assessment of heavy metals and metalloids in surface sediments of the Tajan River, Iran. Mar. Pollut. Bull. 133, 741–749.
Alharbi, T., El-Sorogy, A.S., 2017. Assessment of metal contamination in coastal sediments of Al-Khobar area, Arabian Gulf, Saudi Arabia. J. Afr. Earth Sci. 129, 458–468.
Alharbi, T., Alfaifi, H., Almadani, S., El-Sorogy, A.S., 2017a. Spatial distribution and metal contamination in the coastal sediments of Al-Khafji area, Arabian Gulf, Saudi Arabia. Environ. Monit. Assess. 189, 634.
Alharbi, T., Alfaifi, H., El-Sorogy, A.S., 2017b. Metal pollution in Al-Khobar seawater, Arabian Gulf, Saudi Arabia. Mar. Pollut. Bull. 119, 407–415.
Al-Kahtany, Kh., Youssef, M., El-Sorogy, A.S., 2015. Geochemical and foraminiferal analyses of the bottom sediments of Dammam coast, Arabian Gulf, Saudi Arabia. Arab. J. Geosci. 8, 11121–11133.
Al-Kahtany, Kh., El-Sorogy, A.S., Al-Kahtany, F., Youssef, M., 2018. Heavy metals in mangrove sediments of the central Arabian Gulf shoreline, Saudi Arabia. Arab. J. Geosci. 11, 155.
Almasoud, F.I., Usman, A.I., Al-Farraj, A.S., 2015. Heavy metals in the soils of the Arabian Gulf coast affected by industrial activities: analysis and assessment using enrichment factor and multivariate analysis. Arab. J. Geosci. 8 (3), 1691–1703.
Al-Taani, A.A., Batayneh, A., Nazzal, Y., Ghrefat, H., Elawadi, E., Zaman, H., 2014. Status of trace metals in surface seawater of the Gulf of Aqaba, Saudi Arabia. Mar. Pollut. Bull. 86, 582–590.
Birch, G., 2003. A scheme for assessing human impacts on coastal aquatic environments using sediments. In: Woodcoffe, CD, Furness, RA (Eds.), Coastal GIS. 14 Wollongong University Papers in Center for Maritime Policy, Australia.
de Mora, S., Fowler, S.W., Wyse, E., Azemard, S., 2004a. Distribution of heavy metals in marine bivalves, fish and coastal sediments in the Gulf and Gulf of Oman. Mar. Pollut. Bull. 49, 410–424.
de Mora, S., Sheikholeslami, M.R., Wyse, E., Azemard, S., Cassi, R., 2004b. An assessment of metal contamination in coastal sediments of the Caspian Sea. Mar. Pollut. Bull. 48,

61–77.
Diagomanolin, V., Farhang, M., Ghazi-Khansari, M., Jafarzadeh, N., 2004. Heavy metals (Ni, Cr, Cu) in the Karoon waterway river, Iran. Toxicol. Lett. 151, 63–67.
Diaz-de Alba, M., Galindo-Riano, M.D., Casanueva-Marenco, M.J., Garcia-Vargas, M., Kosore, C.M., 2011. Assessment of the metal pollution, potential toxicity and speciation of sediment from Algeciras Bay (south of Spain) using chemometric tools. J. Hazard. Mater. 190, 177–187.
El-Sorogy, A.S., Youssef, M., 2015. Assessment of heavy metal contamination in intertidal gastropod and bivalve shells from central Arabian Gulf coastline, Saudi Arabia. J. Afr. Earth Sci. 111, 41–53.
El-Sorogy, A.S., Youssef, M., Al-Kahtany, Kh., 2016a. Integrated assessment of the Tarut Island coast, Arabian Gulf, Saudi Arabia. Environ. Earth Sci. 75, 1336.
El-Sorogy, A.S., Youssef, M., Al-Kahtany, Kh., Al-Otaibi, N., 2016b. Assessment of arsenic in coastal sediments, seawaters and molluscs in the Tarut Island, Arabian Gulf, Saudi Arabia. J. Afr. Earth Sci. 113, 65–72.
EL-Sorogy, A.S., Tawfik, M., Almadani, S., Attiah, A., 2016c. Assessment of toxic metals in coastal sediments of the Rosetta area, Mediterranean Sea, Egypt. Environ. Earth Sci. 75, 398.
El-Sorogy, A.S., Al-Kahtany, K., Youssef, M., Al-Kahtany, F., Al-Malky, M., 2018. Distribution and metal contamination in the coastal sediments of Dammam Al-Jubail area, Arabian Gulf, Saudi Arabia. Mar. Pollut. Bull. 128, 8–16.
Hökanson, L., 1980. An ecological risk index for aquatic pollution control. A sedimentological approach. Water Res. 14, 975–1001.
ISQG, 1995. Interim Sediment Quality Guidelines. Environment Canada, Ottawa (9 pp).
Jafarabadi, A.R., Bakhtiyari, A.R., Toosi, A.Sh., Jadot, C., 2017. Spatial distribution, ecological and health risk assessment of heavy metals in marine surface sediments and coastal seawaters of fringing coral reefs of the Persian Gulf, Iran. Chemosphere 185, 1090–1111.
Leopold, E.N., Jung, M.C., Auguste, O., Ngatcha, N., Georges, E., Lape, M., 2008. Metals pollution in freshly deposited sediments from River Mingoa, main tributary to the municipal lake of Yaounde, Cameroon. Geosci. J. 12 (4), 337–347.
Lin, C., He, M., Liu, S., Li, Y., 2012. Contents, enrichment, toxicity and baselines of trace elements in the estuarine and coastal sediments of the Daliao River System. Chin. J. Geochem. 46, 371–380.
Liu, Q., Wang, F., Meng, F., Jiang, L., Li, G., Zhou, R., 2018. Assessment of metal contamination in estuarine surface sediments from Dongying City, China: use of a modified ecological risk index. Mar. Pollut. Bull. 126, 293–303.
Long, E.R., MacDonald, D.D., Smith, S.L., Calder, F.D., 1995. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. Environ. Manag. 19, 18–97.
Muller, G., 1979. Heavy metals in the sediment of the Rhine-Changes seity, 1971. Umsch Wiss Tech 79, 778–783.
Müller, G., 1981. The heavy metal pollution of the sediments of neckars and its tributary: a stocktaking. Chemiker Zeitung 105, 157–164.
Naser, H., 2011. Human impacts on marine biodiversity: macro-benthos in Bahrain, Arabian Gulf. In: Lopez-Pujol, J. (Ed.), The Importance of Biological Interactions in the Study of Biodiversity. In Tech Publishing, Croatia, pp. 109–126.
Naser, H., 2012. Metal concentrations in marine sediments influenced by anthropogenic activities in Bahrain, Arabian Gulf. In: Hong-Bo, Shao (Ed.), Metal Contaminations: Sources, Detection and Environmental Impacts. NOVA Science Publishers, Inc., New York, pp. 157–175.
Naser, H.A., 2013. Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: a review. Mar. Pollut. Bull. 72, 6–13.
Nour, H., El-Sorogy, A.S., 2017. Distribution and enrichment of heavy metals in Sabratha coastal sediments, Mediterranean Sea, Libya. J. Afr. Earth Sci. 134, 222–229.
Nour, H., El-Sorogy, A.S., Abdel-Wahab, M., Almadani, S., Alfaifi, H., Youssef, M., 2018. Assessment of sediment quality using different pollution indicators and statistical analyses, Hurghada area, Red Sea coast, Egypt. Mar. Pollut. Bull. 133, 808–813.
Omar, M.B., Mendiguchia, C., Er-Raioui, H., Marhraoui, M., Lafraoui, Gh., Oulad-bdellah, M.k., Garcia-Vargas, M., Moreno, C., 2015. Distribution of heavy metals in marine sediments of Tetouan coast (North of Morocco): natural and anthropogenic sources. Environ. Earth Sci. 74, 4171–4185.
Pan, K., Wang, W.X., 2012. Trace metal contamination in estuarine and coastal environments in China. Sci. Total Environ. 421, 3–16.
Rumisha, C., Elskens, M., Leermakers, M., Kochzius, M., 2012. Trace metal pollution and its influence on the community structure of soft bottom molluscs in intertidal areas of the Dar es Salaam coast, Tanzania. Mar. Pollut. Bull. 64, 521–531.
Sadiq, M., Alam, I., 1989. Metal concentrations in Pearl Oyster, *Pinctada radiata*, collected from Saudi Arabian Coast of the Arabian Gulf. Bull. Environ. Contam. Toxicol. 42, 111–118.
Sinex, S.A., Helz, G.R., 1981. Regional geochemistry of trace elements in Checapeake Bay sediments. Environ. Geol. 3, 315–323.
Taylor, S.R., 1964. Abundance of chemical elements in the continental crust: a new table. Geochim. Cosmochim. Acta 28, 1273–1285.
Turekian, K.K., Wedepohl, K.H., 1961. Distribution of the elements in some major units of the earth's crust. Geol. Soc. Am. 72, 175–192.
Wang, Y., Hu, J., Xiong, K., Huang, X., Duan, S., 2012. Distribution of heavy metals in core sediments from Baihua Lake. Procedia Environ. Sci. 16, 51–58.
Wang, L.M., Zhang, S., Zhao, S.N., Wu, Y., 2014. Spatial distribution characteristics of heavy metals in Ulansuhai Lake. J. Environ. Health 31 (12), 1088–1089.
Wang, Y., Yang, L., Kong, L., Liu, E., Wang, L., Zhu, J., 2015. Spatial distribution, ecological risk assessment and source identification for heavy metals in surface sediments from Dongping Lake, Shandong, East China. Catena 125, 200–205.
Youssef, M., El-Sorogy, A.S., 2016. Environmental assessment of heavy metal contamination in bottom sediments of Al-Kharrar lagoon, Rabigh, Red Sea, Saudi Arabia. Arab. J. Geosci. 9, 474.
Youssef, M., El-Sorogy, A.S., Al-Kahtany, Kh., Al-Otaibi, N., 2015. Environmental assessment of coastal surface sediments Tarut Island, Arabian Gulf (Saudi Arabia). Mar. Pollut. Bull. 96, 424–433.
Youssef, M., El-Sorogy, A.S., Al-Kahtany, Kh., 2016. Distribution of mercury in molluscs, seawaters and coastal sediments of Tarut Island, Arabian Gulf, Saudi Arabia. J. Afr. Earth Sci. 124, 365–370.
Zhang, J., Gao, X., 2015. Heavy metals in surface sediments of the intertidal Laizhou Bay, Bohai sea, China: distributions, sources and contamination assessment. Mar. Pollut. Bull. 98, 320–327.
Zhang, G., Bai, J., Zhao, Q., Lu, Q., Jia, J., Wen, X., 2016. Heavy metals in wetland soils along a wetland-forming chronosequence in the Yellow River delta of China: levels, sources and toxic risks. Ecol. Indic. 69, 331–339.