Journal of African Earth Sciences 129 (2017) 458–468

Contents lists available at ScienceDirect

Journal of African Earth Sciences

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

Assessment of metal contamination in coastal sediments of Al-Khobar area, Arabian Gulf, Saudi Arabia

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A R T I C L E I N F O

Article history:
Received 17 October 2016
Received in revised form
20 January 2017
Accepted 3 February 2017

Keywords:
Assessment
Metals contamination
Al-Khobar
Arabian Gulf
Saudi Arabia

A B S T R A C T

An assessment of marine pollution due to heavy metals was made to coastal sediments collected from Al-Khobar coastline, in the Arabian Gulf, Saudi Arabia by analyzing of Al, V, Cr, Mn, Cu, Zn, Cd, Pb, Hg, Mo, Sr, Se, As, Fe, Co and Ni using Inductively Coupled Plasma-Mass Spectrometer (ICP-MS). The results indicated that the distribution of most metals was largely controlled by inputs of terrigenous material and most strongly associated with distribution of Al in sediments. In general Sr, Cr, Zn, Cu, V, Hg, Mo and Se show severe enrichment factors. Average values of Cu and Hg highly exceed the ERL and the Canadian ISQG values. Average Ni was higher than the ERL and the ERM values. The severe enrichment of some metals in the studied sediment could be partially attributed to anthropogenic activities, notably oil spills from exploration, transportation and from saline water desalination plants in Al-Khobar coast, and other industrial activities in the region.

1. Introduction

Coastal environments are subjected to heavy metal pollutants as a result of industrial development along littoral zones worldwide (El Zrelli et al., 2015). The sources of heavy metals in coastal environments include anthropogenic activities and natural weathering processes (Sadiq and Alam, 1989; El-Sorogy et al., 2012, 2013a, b). Many complex processes of material exchange govern distribution of metals within the aquatic environments. These processes are affected by various anthropogenic activities and industrial wastewaters (Christophoridis et al., 2009).

Most of the anthropogenic metals in a marine coastal area are of terrestrial origin, coming from industrial and urban development, mining, and other human practices near aquatic environments (Carman et al., 2007). Many studies have dealt with assessment of heavy metal pollution worldwide on coastal areas. Most of these studies have used heavy metal analysis in sediments (Adamo et al., 2005; Gonzales-Macias et al., 2006; Carman et al., 2007; Vallius et al., 2007; Abrahim and Parker, 2008; Cevik et al., 2009; Fang et al., 2009; Diaz-de Alba et al., 2011; Hahladakis et al., 2013; Omar et al., 2015; Youssef et al., 2015; El-Sorogy et al., 2016). The more recent studies on the coastal area between Ras Tanura and Ras Abu Aly on the Saudi Arabian Gulf (El-Sorogy and Youssef, 2015; El-Sorogy et al., 2016; Youssef et al., 2015; Almasoud et al., 2015) concluded that these coastal areas were subjected to anthropogenic pollutants in the form of rejected water from desalination, landfills, sewage, oil wastes, as well as the various solid wastes related to new constructions along the coast.

Almasoud et al. (2015) in their study on the relationship between coastal sediments of the Arabian Gulf and industrial activities concluded that Cr values were higher than those of the soil common range as well as the geochemical background in average shale. Their sediment samples were enriched with Zn, Cu, Cr, Pb, of anthropogenic sources and Ni, Co, Mn, Fe originated from the soil parent materials and natural process. In their study on coastal sediments of the Tarut Island on the Arabian Gulf coast, Youssef et al. (2015) indicated these coastal sediments had very high As and high Hg values compared to coastal sediments from the Red Sea and the Gulf of Oman. Their values exceeded the wet threshold safety values (MEC, PEC). They attributed the high values of As and Hg to land filling, dredging, sewage, and oil pollution in the study area.

The primary surveying during this study along the Al-Khobar

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http://dx.doi.org/10.1016/j.jafrearsci.2017.02.007
1464-343X/

coastline indicated human stresses on some localities. These stresses are represented by landfilling, crowded fishing boats, seawater desalination plants, construction of artificial rocky shores and the presence of different solid wastes from human activities. Accordingly, the main objectives of the present study are to: 1) evaluate the levels of heavy metals along Al-Khobar coastal area; 2) assess the impact of human activities on the coastal environment, and 3) compare the rate of pollution in Al-Khobar coastal area with neighboring and worldwide coasts.

2. Material and methods

2.1. Study area

The Al-Khobar coast is located in the south of the Saudi Arabian Gulf between longitudes 49°58′- 50°14′ E and latitudes 25°56′- 26°18′ N (Fig. 1). According to sediment type, the Al-Khobar coast has three major types (Fig. 2): 1) Sandy-dominated shores, composed of a mixture of coarse sand to sandy mud and very few biogenic materials such as samples 11, 12, 13, 14, 20 and 26. Terrigenous matters in these sediments include angular to well-rounded quartz grains. Biogenic materials include bivalves, gastropods, foraminifers, ostracods and sea grass; 2) Biogenic-dominated shores composed mainly of seashells and calcareous sands, such as samples 22, 23, 25, 27, 29 and 30. Seashells are represented by accumulations of gastropods (mostly cerithiids) and bivalves (mostly venerids). Under the microscope, calcareous sands show the presence of foraminiferes (*Peneroplis, Quinqueloculina, Ammonia, Spiroloculina, Triloculina, Sorites and Textularaia* spp.), ostracods, bryozoans, echinoid fragments and embryonic stages of molluscs; 3) Artificial and natural Rocky shores. The artificial rocky shores were constructed from old rock blocks to protect cities and tourist villages from high tides and sea erosion. The natural rocky shores are composed of highly consolidated sands. Sediments beyond the natural rocky shores are composed of calcareous sands and seashells, like samples 24 and 28. Fractures and low biotopes in both artificial and natural rocky shores are inhabited with barnacles, worm tubes and gastropods.

2.2. Sampling and analytical methods

In this study, 29 coastal sediment samples were collected from 29 sites on the littoral zone of the Al-Khobar coastline (Fig. 1). Grain size analysis was determined according to Folk (1974). Samples were sieved to remove stones and shells, homogenized by being ground lightly 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 the filter paper was reweighed. The difference in the two weights is the weight of carbonate and the residue of the non-carbonate fraction (silicate). Samples were analyzed for Al, V, Cr, Mn, Cu, Zn, Cd, Pb, Hg, Mo, Sr, Se, AS, Fe, Co and Ni using ICP-MS: NexION 300D (Perkin Elmer, USA) in the Central Laboratory of the College of Science, King Saud University.

Samples are dried in an oven at 115 °C, mechanically crushed, sieved through a 200 mesh sieve and about 100 mg of samples was put into dry and clean Teflon microwave digestion vessels. 2 ml of HNO_3, 6 ml HCl and 2 ml HF were added to the vessels. Samples are digested using a scientific microwave (Model Milestone Ethos 1600). The resulting solution was transferred to a 15 ml plastic volumetric tube and made up to mark using deionized water. A blank digest is carried out in the same manner.

2.3. Estimation of pollutant indicators

To calculate pollutant indicators of metal pollution in the studied coastal sediments, three factors are taken into consideration:1) Enrichment Factor (EF) to estimate the anthropogenic impact on sediments and to differentiate between the anthropogenic and natural sources of metals (Sinex and Helz, 1981); 2) Geoaccumulation Index (Igeo) to evaluate the trace metal pollution in sediments (Muller, 1979; Leopold et al., 2008); 3) Contamination Factor (CF), which describes the contamination of a given toxic substance in a basin (Hökanson, 1980). In order to establish the relations between trace elements in the Al-Khobar coastal

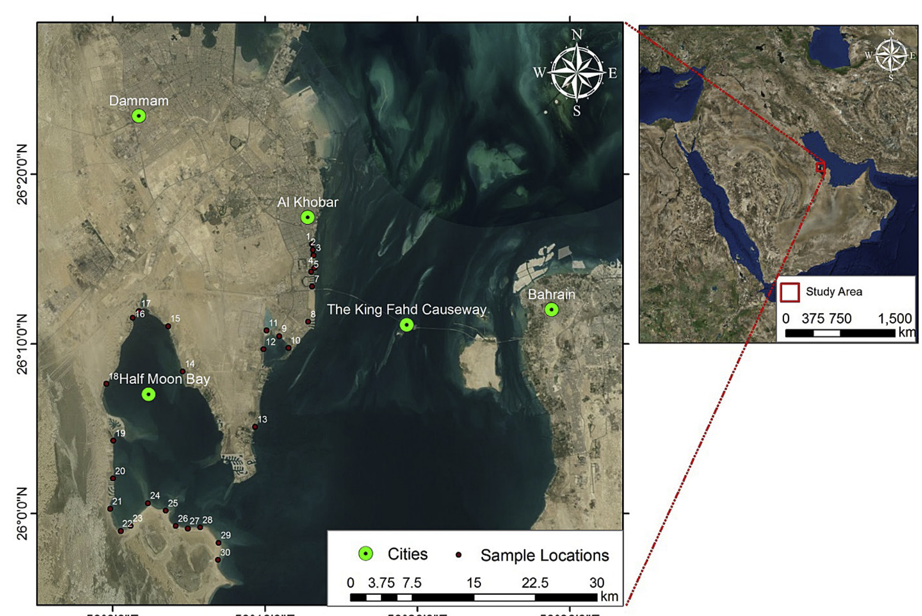

Fig. 1. Location map of Al-Khobar coastline and the locations of sediment samples along the coast.

Fig. 2. A, Example of sandy beaches along Al-Khobar coastline, site 12; B, Accumulation of cerithiid gastropods drifted by tidal currents on the sandy beach of site 5; C, Abundance of venerid bivalves on the sandy beach of site 5; D, Artificial rocky shore of site 4; E, Natural rocky shore of site 27; F, Living molluscs in the depressed areas of the natural rocky shore of site 27.

sediments Pearson's correlation coefficients were calculated with (SPSS program). The cluster analysis (Ward's method) was also performed for the studied samples.

3. Results and discussion

3.1. General characteristics

Sediment characteristics such as carbonate and silicate content and size play an important role in distributing pollutants in coastlines. Fine-grained materials, with larger surface areas, have a greater potential to capture pollutants from a water column. In general terms, coarse sandy sediments with low organic content retain less contaminant than relatively fine mud/silt/clay sediments. Thus, sediments where fines are deposited is likely to exhibit high levels of heavy metals. In general, coastal sediments in the Al-Khobar are ranged from coarse quartz and carbonate sands to very fine mud. The biogenic part of the sediments includes biomorpha and bioclasts of seashells, foraminifers and other invertebrate skeletons.

Table 1 illustrates the concentrations of 16 heavy metals in the 29 surface coastal sediments along the Al-Khobar beach. The average metal levels are in the following order: Fe > Al > Sr > V > Cu > Mn > Ni > Zn > Cr > Mo > Pb > Co > As > Hg > Se > Cd. Accordingly, the studied sediments are divided into four main clusters based on heavy metal content (Fig. 3). Cluster 1 contains samples 10, 15, 16, 17, 18, 19, 20, 21 and 23, which recorded the lowest levels of Mn, Fe, Al, As, Se, Cd, Sr, Hg, Co, Pb and the highest values of V, Cu, and Hg. Cluster 2 includes samples 14, 24, 26, 28 and 30, which recorded lowest levels of Ni, V, Zn, Cr, Cu and Mo. Cluster 3 contains samples 1, 2, 5, 7, 8, 9, 11, 12, 13, 22, 25, 27 and 29 that recorded the average values for the measured trace elements. Cluster 4 includes samples 3 and 4, which recorded the highest values of all trace metals (except V, Cu and Hg). Samples 3 and 4

Table 1
Concentrations of 16 metals in 29 coastal sediments in Al-Khobar coastline.

S. No.	Al	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Sr	Mo	Cd	Hg	Pb
1	2892	236	51	171	10928	6.5	95	134	52	1.6	0.41	2314	9.9	0.24	0.75	5.8
2	2910	251	66	182	12102	7.1	105	145	61	2	0.62	2510	10.8	0.3	0.92	7.1
3	3662	396	83	244	16730	10.4	116	170	86	3.1	1.2	2808	14	0.52	1.4	9.4
4	3224	302	77	202	14368	8.8	111	158	70	2.6	0.84	2614	12.1	0.44	1.2	8.2
5	2931	264	65	190	12205	7.2	108	132	63	2.1	0.6	2490	10.6	0.31	0.94	7.5
7	2805	220	42	158	10310	5.4	86	122	40	1.2	0.24	2109	7.2	0.19	0.61	4.2
8	2843	214	40	160	10112	5.2	89	126	42	1.3	0.26	2120	7	0.17	0.63	4
9	3004	248	68	185	12207	7.3	107	144	60	1.9	0.66	2501	11.4	0.33	0.9	7.3
10	688	386	46	12	664	0.6	44	250	36	0.8	0.18	48	4.2	0.09	0.05	2.1
11	2836	218	38	156	10210	4.9	82	124	41	1.2	0.22	2112	6.9	0.2	0.64	4.4
12	2931	244	61	180	12018	7.5	108	148	63	2	0.62	2498	11.6	0.29	0.89	7.2
13	2882	230	50	172	11044	6.6	93	130	55	1.5	0.44	2320	9.8	0.25	0.72	5.9
14	1366	22	20	85	6950	4.2	41	112	34	1	0.71	1990	3.3	0.19	0.75	5.3
15	855	455	55	18	1108	0.9	50	288	58	1.4	0.26	60	6.6	0.14	0.07	3
16	894	472	60	25	1266	1.3	62	310	68	2	0.39	88	8	0.19	1.31	4.8
17	796	461	57	20	992	1	54	285	56	1.5	0.28	61	6.8	0.12	0.08	3.1
18	880	470	63	24	1250	1.2	62	307	69	1.9	0.38	86	8.1	0.18	1.2	4.5
19	793	459	59	21	1053	0.5	58	286	54	1.4	0.3	69	6.9	0.12	1	3.2
20	924	404	72	28	1439	1.1	66	330	78	2.3	0.51	102	9.5	0.22	1.61	5
21	789	452	60	20	1114	7.2	55	278	54	1.5	0.29	64	6	0.14	0.86	7.1
22	3005	246	64	180	12107	0.6	106	146	60	2.2	0.62	2490	11	0.31	1.12	3.8
23	650	390	49	12	896	3.9	42	261	40	0.7	0.15	50	6.2	0.08	0.88	7.3
24	1237	12	15	70	5220	3.6	32	98	27	0.9	0.6	1742	1.5	0.11	0.44	3.4
25	2982	261	62	184	12212	7.4	108	148	62	2.1	0.64	2510	10.8	0.29	1.11	7.2
26	1198	10	17	75	5110	3.8	35	121	24	0.8	0.56	1690	1.4	0.14	0.46	3.4
27	2798	218	40	156	10192	6	84	115	48	1	0.33	2102	7.5	0.18	0.62	4.3
28	1304	21	23	90	5377	5.1	40	140	35	1.1	0.72	1993	2.7	0.2	0.71	5.1
29	3012	253	68	185	12336	7.3	108	142	62	2.1	0.61	2488	11.1	0.34	0.94	7.4
30	1212	11	14	72	5192	3.8	33	96	25	0.8	0.58	1730	1.3	0.12	0.42	3.6
Min.	650	10	14	12	664	0.5	32	96	24	0.7	0.15	48	1.3	0.08	0.05	2.1
Max.	3662	472	83	244	16730	10.4	116	330	86	3.1	1.2	2808	14	0.52	1.61	9.4
Average	2020	268	51.03	113.97	7552	4.75	75.10	182.97	52.68	1.606	0.502	1568	7.726	0.226	0.803	5.358

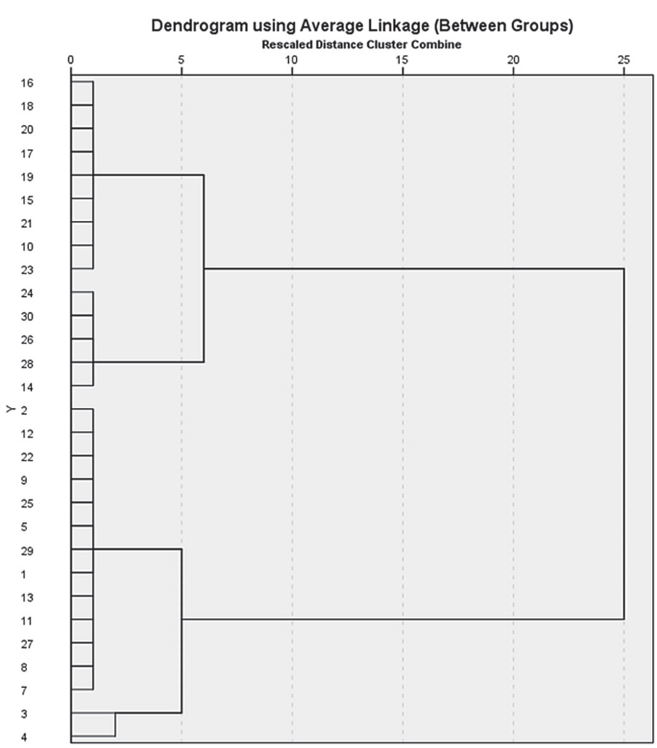

Fig. 3. Dendrogram for hierarchal clusters analyses of 29 studied coastal sediment samples collected from Al-Khobar coastline.

occur in semi-closed lagoons and comprise very fine sands and clays and human activities such landfilling, new building construction and solid rubbish are observed in this region (Fig. 4A).

Fig. 5 illustrates the dendrogram of the concentrations of the 16 elements (using HCA analyses) in the 29 sediment samples. The elements are classified into three different groups: first (Se, Cd, Hg, As, Co, Pb, Mo, Cr, Zn, Ni, Mn, V and Cu), second (Al and Sr) and third (Fe). The higher levels of trace elements are associated with the fine-grained material indicating terrigenous in origin. These results are supported by Pearson's correlation coefficient (Table 2). Strongly positive correlations were observed between Al and each of Mn, Fe, Ni, Sr and Cd ($r = 0.99$, $r = 0.98$, $r = 0.91$, $r = 0.90$, $r = 0.80$ respectively), V and Cu ($r = 0.85$), Cr and each of Zn, Mo and As ($r = 0.94$, $r = 0.90$, $r = 0.86$ respectively), Mn and each of Fe, Ni, Sr and Cd ($r = 1.00$, $r = 0.84$, $r = 0.94$ and 0.82 respectively), Fe and each of Ni, Sr and Cd ($r = 0.85$, $r = 0.95$, $r = 0.83$ respectively), Zn and each of As and Mo ($r = 0.92$ and $r = 0.87$ respectively), Ni and each of Mo and Cd ($r = 0.92$ and 0.84 respectively). Negative relationships were observed between Cu and most of the studied elements and between V and each of Mn, Fe, Co, Se, Sr and Al.

3.2. Spatial distribution of trace elements

3.2.1. Aluminum, iron and strontium

Al, Fe and Sr exhibited a similar distribution pattern (Fig. 6). In general, the majority of Al-Khobar coastal sediments was coarse-grained and have relatively low levels of fine materials. This is reflected in the relatively low values of Al in the sediments; where Al is a good indicator for terrigenous input and Al levels normally increase in fine-grained materials. Al values varied from 650 in sample 23–3662 μg/g in sample 3 (Table 1). The average value of Al (2020 μg/g) was lower than that recorded from the Caspian Sea coast and coasts of Qatar, Bahrain, Oman and Emirates (de Mora et al., 2004a, b). Al values were less than the values of the background shale (Turekian and Wedepohl, 1961) and the earth crust (Taylor, 1964).

Fig. 4. A, Landfilling, construction remains and solid rubbish in the intertidal zone of the site 3, Al-Khobar coastline; B, landfilling by rock blocks of the sand beach of site 11; C, Al-Khobar desalination and power plants, between sites 9 and 10; D, Crowded fishing boats in the intertidal zone of site 5; E, Tourism resorts on sandy beach of site 15; F, Plastic and other solid rubbish due to tourism on the beach of site 7.

The highest value of Fe (16730 μg/g) was recorded in sample 3 and the lowest (664 μg/g) in sample 10 (Table 1). The Al-Khobar coastal sediments exhibited Fe: Al concentration ratio that ranged from 0.97 to 5.09 (average 3.24 μg/g). Average value of Fe is lower than the one recorded from Red Sea, Mediterranean Sea, Caspian Sea and Arabian Gulf coasts. Also, it decreased the data recorded from Gulf of Finland and the background shale and the earth crust (Table 3).

Strontium levels in the sediments ranged from 48 in sample 10 to 2808 in sample 3 (Table 1). Table 3 illustrates that, an average value of Sr is higher than that recorded along the coasts of Azerbaijan (3 folds), Iran (2 folds), Kazakhstan (1.3 folds), Mediterranean coast of Egypt (13.5 folds), as well as the values reported in the background shale (5 folds) and the earth crust (4 folds). EF and CF values (Table 4) suggest that, the coastal sediments of Al-Khobar are very severely enriched and considerably contaminated with Sr ($EF = 25–50$ and $3 \leq Cf < 6$).

3.2.2. Chromium, nickel and zinc

Concentrations of chromium, nickel and zinc displayed some similar spatial distribution and reflected terrigenous input (Fig. 7). The highest values of these metals were recorded in sample 3 (83, 116 and 86 μg/g respectively) and the lowest ones in samples 30, 24 and 26 (14, 32 and 24 μg/g respectively). According to EF (Birch, 2003; Hökanson, 1980), the Al-Khobar sediments are severely enriched with Cr ($EF = 10–25$). Cr exhibited a coincided distribution pattern with Al, reflecting the effect of grain size in determining the metal content. Thus, high levels of Cr in Al-Khobar coastline reflect the deposition of the clay fractions in the sediments. The Cr level exceeds the values recorded from the Red Sea coast (2.5 folds), the Mediterranean coast of Egypt (283.5 folds) and the Arabian Gulf (1.9 folds). It is lower than the values recorded at the coasts of Morocco, Azerbaijan and Iran, as well as the ERL value (Table 3).

Ni displayed a similar pattern to Cr, reflecting the high natural

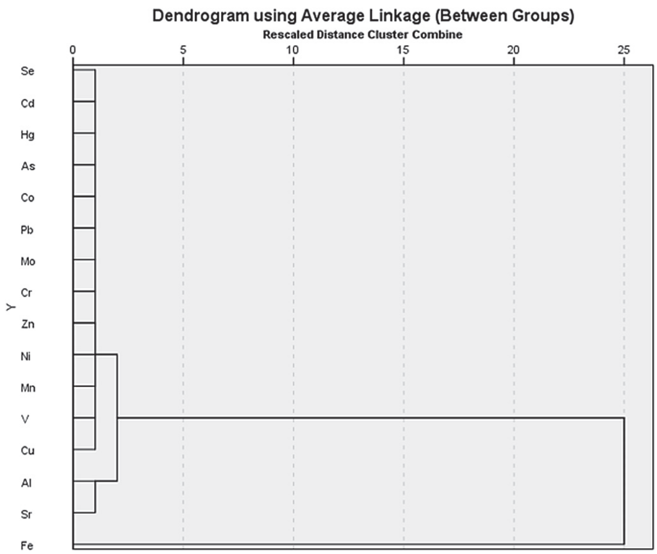

Fig. 5. Dendrogram for hierarchal clusters analyses of 16 metals in coastal sediment samples collected from Al-Khobar coastline.

background. The Al-Khobar sediments are moderately enriched with Ni (EF = 3–5). Average value of Ni (75.10 μg/g) was higher than the 21 μg/g of the ERL, the 52 μg/g of the ERM (Long et al., 1995) and the values ranged from 10.4 to 51.6 μg/g from the Caspian Sea coast, (de Mora et al., 2004b). The present average value decreased the one from the Mediterranean Sea coast (El-Sorogy et al., 2016). The elevated Ni levels reflect a high natural background, but could be augmented through anthropogenic activities as well. EF and CF values suggest severe enrichment and moderate contamination of Al-Khobar samples with Cr (EF = 10–25, $1 \leq Cf < 3$).

The distribution of zinc was similar to that of the fine grained material, again reflecting the importance of terrigenous sources. Values of the enrichment factor suggest a severe enrichment in Zn (EF = 10–25). However, the average concentration (52.68 μg/g) was lower than the 124 μg/g of the Canadian ISQG (ISQG, 1995) and the Mediterranean Sea coast of Egypt and Morocco (El-Sorogy et al., 2016; Omar et al., 2015). It exceeded the values of Kazakhstan and Russia coasts (Table 3).

3.2.3. *Manganese, copper and vanadium*

The distribution of manganese reversed that of copper and vanadium, especially in the central and southern stations of the Al-

Table 2
Correlation matrix among analyzed metals.

Correlations																
	Al	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Sr	Mo	Cd	Hg	Pb
Al	1															
V	-0.220	1														
Cr	0.353	0.747[a]	1													
Mn	0.989[a]	-0.314	0.295	1												
Fe	0.980[a]	-0.340	0.276	0.996[a]	1											
Co	0.745[a]	-0.253	0.236	0.780[a]	0.786[a]	1										
Ni	0.905[a]	0.157	0.695[a]	0.867[a]	0.846[a]	0.634[a]	1									
Cu	-0.656[a]	0.851[a]	0.435[b]	-0.715[a]	-0.732[a]	-0.572[a]	-0.304	1								
Zn	0.341	0.674[a]	0.939[a]	0.296	0.279	0.223	0.656[a]	0.422[b]	1							
As	0.527[a]	0.416[b]	0.859[a]	0.516[a]	0.511[a]	0.387[b]	0.754[a]	0.146	0.924[a]	1						
Se	0.471[a]	-0.326	0.219	0.570[a]	0.605[a]	0.549[a]	0.395[b]	-0.393[b]	0.353	0.607[a]	1					
Sr	0.896[a]	-0.607[a]	-0.002	0.942[a]	0.951[a]	0.742[a]	0.670[a]	-0.887[a]	0.027	0.306	0.619[a]	1				
Mo	0.698[a]	0.460[b]	0.897[a]	0.648[a]	0.628[a]	0.478[a]	0.920[a]	0.048	0.872[a]	0.871[a]	0.360	0.388[b]	1			
Cd	0.796[a]	0.031	0.640[a]	0.818[a]	0.825[a]	0.687[a]	0.840[a]	-0.302	0.681[a]	0.862[a]	0.786[a]	0.688[a]	0.814[a]	1		
Hg	0.297	0.260	0.600[a]	0.298	0.295	0.268	0.484[a]	0.176	0.695[a]	0.730[a]	0.470[b]	0.165	0.611[a]	0.597[a]	1	
Pb	0.563[a]	0.097	0.571[a]	0.592[a]	0.600[a]	0.827[a]	0.644[a]	-0.169	0.557[a]	0.640[a]	0.584[a]	0.477[a]	0.679[a]	0.758[a]	0.611[a]	1

[a] Correlation is significant at the 0.01 level (2-tailed).
[b] Correlation is significant at the 0.05 level (2-tailed).

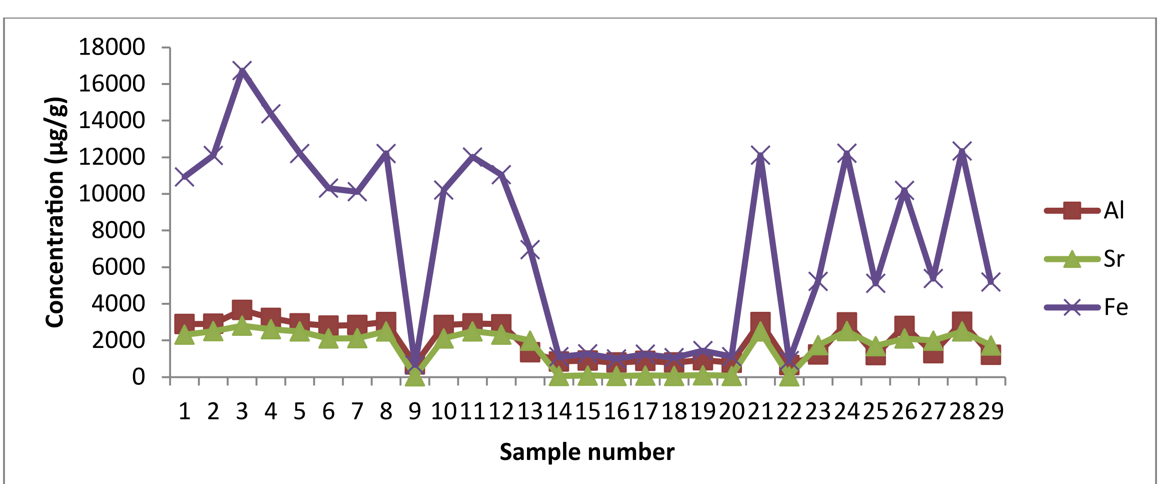

Fig. 6. Spatial distribution of Al, Sr and Fe in the coastal sediment samples of Al-Khobar.

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

Location	Reference	Fe	Mn	Se	V	Cr	Ni	Zn	Cu	Co	Al	Hg	Sr	Mo	Cd	As	Pb
Present study		7552	113.97	0.502	268	51.03	75.10	52.68	182.97	4.75	2020	0.803	1568	7.73	0.226	1.606	5.358
Al-Kharrar lagoon, Red Sea, Saudi Arabia	Youssef and El-Sorogy (2016)	2249.42	102.7			20.62	8.69	39.71	16.00	4.77		0.01		0.51	0.26	1.67	50.87
Rosetta coast, Egypt	El-Sorogy et al. (2016)	109,560	553		374.78	0.18	480.86	183.23	24.57	69.78			114.06		28.88	298.22	384.68
North Morocco	Omar et al. (2015)	33000 –51100	256.6 –651.7			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
Arabian Gulf, Saudi Arabia	Youssef et al. (2015)	3447	75.17	0.36		27.10	–	17.57	5.78	6.35		0.55		2.20	0.66	148	58.68
Qatar	de Mora et al. (2004a)	305–5680	13.2–127		2.7 –32.1	11.5 –40.8	0.7 –20.8	-	1.2–8.2	0.10 –2.2	484 –18000	0.0007 –0.0167		13.2 –127	0.03 –0.09	1.0–6.3	0.4–3.9
UAE		874–29600	32.9–360		4.5 –35.5	17.6–303	2–1010	-	0.6–3.6	0.34 –45.2	534 –26000	0.0009 –0.001		32.9 –360	0.02–11	0.7–9.6	0.7–5.9
Bahrain		471–6475	22.6–84.3		3.5 –28.4	3.4–41.8	2.46 –23.2	6.1–52.2	2.4 –48.3	0.17 –2.43	601 –8954	0.0025 –0.2202		22.6 –84.3	0.04–0.2	3.16 –6.88	0. 7–99
Oman		334–11600	27.8–265		4.7 –44.1	6.5–133	1.8 –77.8	1.6–11.4	0.6–6.7	0.13 –6.92	632 –18300	0.0001 –0.0019		27.8 –256	0.1–0.2	0.74 –5.01	0.3–1.8
Gulf of Aqaba	Al-Taani et al. (2014)	1172–1437	3.9–3.6	0.45 –0.69	–	3. 7–8.0	–	7.0–7.7	7.6 –10.8	0.51 –0.77	1044 –1506	2.36–2.37		0.6–0.7	0.06 –0.07	12.2 –15.1	3.7–6.8
Azerbaijan	de Mora et al. (2004b)	37,100	832	0.30	114	85.3	50.1	83.2	31.9	14.9	69,200	0.15	487		0.14	14.7	19.6
Iran		35,500	815	0.26	116	85.2	51.6	85.3	34.7	15.9	60,500	0.05	693		0.16	12.5	18.0
Kazakhstan		6730	196		20.4	31.4	10.4	11.1	6.4	3.0	17,100	0.01	1220		0.05	4.13	5.75
Russia		5520	200		28.7	32.0	14.0	17.1	8.3	3.8	18,800	0.02	1970		0.06	2.97	4.19
Sediment quality guidelines (Effect range low, ERL)	Long et al., 1995					81	21		34			0.15			1.2	8.2	47
Sediment quality guidelines (Effect range medium, ERM)						370	52		270			0.71			9.6	70	220
Interim sediment quality guideline, Environment Canada (ISQG)	ISQG, 1995					52.3		124	18.7			0.13			0.7	7.24	30.2
Probable effects level, Environment Canada (PEL)						160		271	108			0.7			4.2	41.6	112
Gulf of Finland	Vallius et al. (2007)	–	–		–	45.8 –82.7	–	152–260	42.1 –76.3	10.1 –16.1					0.87–2.7	7.25 –19.1	37.3 –58.9
East China Sea	Fang et al. (2009)	6200 –39700	152–1152		–	–	–	18.2 –114.2	4.3 –41.5	–						–	10–49
Spain	Diaz-de Alba et al. (2011)		227.6 –896.7			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
Salaam coast, Tanzania	Rumisha et al. (2012)	461–5352	17–219		1.1 –13.7	1–9.6	0.4–2.9	2.6–9.3	0.3–2.1	0.21 –2.75					0.01–0.4	0.2–1.3	0.8–2.2
Turkey	Neser et al. (2012)		283–1192			65–264	28–240	86–970	20–703						0.06 –3.94		91.3–751
Background shale	Turekian and Wedepohl (1961)	47200	850	0.6	130	90	68	95	45	19	80000	0.4	300	2.6	0.3	13	20
Background continental crust	Taylor (1964)	56300	950	0.05	135	100	75	70	55	25	82300	0.08	375	1.5	0.2	1.8	12.5
Daliao River System, China	Lin et al. (2012)	–	509–1819		62–83	43–45	18.7 –19.0	43–657	15–20	8.1 –13.2					0.1–4.2	14–34	20–100

Table 4
Values of enrichment factor, geoaccumulation index and contamination factor of the analyzed metals.

Sa No.	Pb			Hg			Se			Mo			Cd			Zn			Cr		
	EF	Igeo	CF	EF	Igeo	CF	EF	Igeo	CF	EF	Geo	CF	EF	Igeo	CF	EF	Iego	CF	EF	Igeo	CF
1	1.25	-0.95	0.29	8.10	0.92	1.88	2.95	-0.09	0.68	16.45	1.62	3.81	3.46	0.06	0.80	2.36	-0.31	0.55	2.45	-0.28	0.57
2	1.38	-0.75	0.36	8.97	1.12	2.30	4.03	0.32	1.03	16.20	1.71	4.15	3.90	0.39	1.00	2.50	-0.16	0.64	2.86	-0.02	0.73
3	1.33	-0.47	0.47	9.87	1.54	3.50	5.64	0.98	2.00	15.19	1.97	5.38	4.89	0.84	1.73	2.55	0.19	0.91	2.60	0.31	0.92
4	1.35	-0.60	0.41	9.86	1.39	3.00	4.60	0.62	1.40	15.39	1.83	4.65	4.82	0.67	1.47	2.42	-0.02	0.74	2.81	0.13	0.86
5	1.45	-0.69	0.38	9.09	1.14	2.35	3.87	0.39	1.00	15.77	1.69	4.08	4.00	0.32	1.03	2.56	-0.12	0.66	2.79	-0.04	0.72
7	0.96	-1.27	0.21	6.98	0.71	1.53	1.83	-0.63	0.40	12.68	1.31	2.77	2.90	-0.17	0.63	1.93	-0.58	0.42	2.14	-0.47	0.47
8	0.93	-1.32	0.20	7.35	0.74	1.58	2.02	-0.55	0.43	12.57	1.28	2.69	2.65	-0.28	0.57	2.06	-0.53	0.44	2.07	-0.52	0.44
9	1.41	-0.72	0.37	8.70	1.10	2.25	4.25	0.38	1.10	16.95	1.77	4.38	4.25	0.38	1.10	2.44	-0.17	0.63	2.92	0.01	0.76
10	7.46	-1.97	0.11	8.89	1.79	0.13	21.33	-0.92	0.30	114.83	0.77	1.62	21.33	-0.92	0.30	26.94	-0.68	0.38	36.33	-0.38	0.51
11	1.02	-1.23	0.22	7.40	0.76	1.60	1.70	-0.72	0.37	12.27	1.26	2.65	3.08	-0.12	0.67	2.00	-0.55	0.43	1.95	-0.57	0.42
12	1.41	-0.73	0.36	8.74	1.09	2.23	4.06	0.32	1.03	17.52	1.78	4.46	3.80	0.25	0.97	2.60	-0.12	0.66	2.66	-0.10	0.68
13	1.26	-0.93	0.30	7.69	0.88	1.80	3.13	-0.02	0.73	16.11	1.61	3.77	3.56	0.11	0.83	2.47	-0.26	0.58	2.37	-0.30	0.56
14	1.80	-1.04	0.27	12.73	0.92	1.88	8.04	0.46	1.18	8.62	0.53	1.27	4.30	-0.17	0.63	2.43	-0.74	0.36	1.51	-1.22	0.22
15	6.39	-1.61	0.15	7.45	1.46	0.18	18.46	-0.55	0.43	108.14	1.22	2.54	19.88	-0.47	0.47	26.01	-0.21	0.61	26.03	-0.20	0.61
16	8.95	-1.14	0.24	122.10	1.47	3.28	24.23	-0.14	0.65	114.72	1.41	3.08	23.61	-0.17	0.63	26.69	-0.05	0.72	24.86	-0.12	0.67
17	7.38	-1.58	0.16	9.52	1.32	0.20	22.20	-0.47	0.47	124.44	1.25	2.62	19.03	-0.63	0.40	28.05	-0.24	0.59	30.13	-0.17	0.63
18	8.50	-1.20	0.23	113.28	1.39	3.00	23.91	-0.17	0.63	117.64	1.42	3.12	22.66	-0.22	0.60	27.43	-0.03	0.73	26.43	-0.07	0.70
19	7.17	-1.54	0.16	112.06	1.20	2.50	22.41	-0.41	0.50	118.96	1.26	2.65	17.93	-0.63	0.40	25.48	-0.28	0.57	29.38	-0.13	0.66
20	8.20	-1.10	0.25	132.02	1.68	4.03	27.88	0.13	0.85	119.85	1.58	3.65	24.05	-0.02	0.73	26.93	0.09	0.82	26.24	0.06	0.80
21	15.04	-0.75	0.36	91.10	1.05	2.15	20.48	-0.44	0.48	97.78	1.12	2.31	19.77	-0.47	0.47	24.08	-0.28	0.57	28.25	-0.12	0.67
22	0.74	-1.37	0.19	10.92	1.32	2.80	4.03	0.32	1.03	16.49	1.73	4.23	4.03	0.32	1.03	2.46	-0.17	0.63	2.77	-0.05	0.71
23	19.23	-0.72	0.37	115.89	1.08	2.20	13.17	-1.10	0.25	125.62	1.16	2.38	14.05	-1.03	0.27	22.18	-0.58	0.42	28.68	-0.32	0.54
24	1.54	-1.48	0.17	9.95	0.38	1.10	9.04	0.29	1.00	5.22	0.26	0.58	3.32	-0.72	0.37	2.57	-0.97	0.28	1.51	-1.50	0.17
25	1.39	-0.73	0.36	10.73	1.31	2.78	4.12	0.35	1.07	16.05	1.71	4.15	3.74	0.25	0.97	2.52	-0.14	0.65	2.66	-0.08	0.69
26	1.57	-1.48	0.17	10.62	0.43	1.15	8.62	0.22	0.93	4.97	0.33	0.54	4.31	-0.47	0.47	2.33	-1.09	0.25	1.74	-1.38	0.19
27	1.00	-1.25	0.22	7.18	0.73	1.55	2.55	-0.31	0.55	13.36	1.35	2.88	2.78	-0.22	0.60	2.34	-0.39	0.51	2.06	-0.52	0.44
28	2.24	-1.08	0.26	15.58	0.86	1.78	10.53	0.47	1.20	9.12	0.33	1.04	5.85	-0.12	0.67	3.23	-0.71	0.37	2.24	-1.08	0.26
29	1.42	-0.71	0.37	8.99	1.14	2.35	3.89	0.30	1.02	16.33	1.74	4.27	4.34	0.41	1.13	2.50	-0.14	0.65	2.89	0.01	0.76
30	1.64	-1.43	0.18	9.55	0.34	1.05	8.79	0.25	0.97	4.55	0.41	0.50	3.64	-0.63	0.40	2.39	-1.05	0.26	1.41	-1.57	0.16
Aver.	4.37	-1.11	0.27	33.56	0.71	2.01	10.37	-0.03	0.84	46.25	1.19	2.97	9.25	-0.12	0.75	10.08	-0.36	0.55	10.98	-0.39	0.57

Sa No.	Ni			Mn			Cu			Fe		Co			Sr			As			V			Al		
	EF	Igeo	CF	EF	Igeo	CF	EF	Igeo	CF	Igeo	CF	EF	Igeo	CF	EF	Iego	CF	EF	Igeo	CF	EF	Igeo	CF	EF	Igeo	CF
1	6.03	0.62	1.40	0.87	-2.90	0.20	12.86	0.99	2.98	-2.70	0.23	1.48	-2.13	0.34	33.32	2.36	7.71	0.53	-3.61	0.12	7.84	0.28	1.82	0.156	-5.37	0.04
2	6.02	0.72	1.54	0.84	-2.81	0.21	12.57	1.10	3.22	-2.55	0.26	1.46	-2.01	0.37	32.63	2.48	8.37	0.60	-3.29	0.15	7.53	0.36	1.93	0.142	-5.37	004
3	4.81	0.82	1.71	0.81	-2.39	0.29	10.66	1.33	3.78	-2.08	0.35	1.54	-1.45	0.55	26.41	2.64	9.36	0.67	-2.65	0.24	8.59	1.02	3.05	0.129	-5.03	0.05
4	5.36	0.78	1.63	0.78	-2.66	0.24	11.53	1.23	3.51	-2.30	0.30	1.52	-1.70	0.46	28.62	2.54	8.71	0.66	-2.91	0.20	7.63	0.63	2.32	0.132	-5.22	0.04
5	6.14	0.75	1.59	0.86	-2.75	0.22	11.34	0.97	2.93	-2.54	0.26	1.47	-1.98	0.38	32.10	2.47	8.30	0.62	-3.22	0.16	7.85	0.44	2.03	0.142	-5.36	0.04
7	5.79	0.52	1.26	0.85	-3.01	0.19	12.41	0.85	2.71	-2.78	0.22	1.30	-2.40	0.28	32.18	2.23	7.03	0.42	-4.02	0.09	7.75	0.17	1.69	0.161	-5.42	0.04
8	6.11	0.56	1.31	0.88	-2.99	0.19	13.07	0.90	2.80	-2.81	0.21	1.28	-2.45	0.27	32.99	2.24	7.07	0.47	-3.91	0.10	7.68	0.13	1.65	0.166	-5.40	0.04
9	6.08	0.74	1.57	0.84	-2.78	0.22	12.37	1.09	3.20	-2.54	0.26	1.49	-1.96	0.38	32.23	2.47	8.34	0.57	-3.36	0.15	7.38	0.35	1.91	0.145	-5.32	0.04
10	46.00	-0.15	0.65	1.00	-6.73	0.01	394.91	1.89	5.56	-6.74	0.01	2.24	-5.57	0.03	11.37	-3.23	0.16	4.37	-4.61	0.06	211.07	0.99	2.97	0.611	-7.45	0.01
11	5.57	0.47	1.21	0.85	-3.03	0.18	12.74	0.88	2.76	-2.79	022	1.19	-2.54	0.26	32.55	2.23	7.04	0.43	-4.02	0.09	7.75	0.16	1.68	0.164	-5.40	0.04
12	6.24	0.75	1.59	0.83	-2.82	0.21	12.92	1.13	3.29	-2.56	0.25	1.55	-1.93	0.39	32.70	2.47	8.33	0.60	-3.29	0.15	7.37	0.32	1.88	0.144	-5.36	0.04
13	5.85	0.60	1.37	0.86	-2.89	0.20	12.35	0.95	2.89	-2.68	0.23	1.48	-2.11	0.35	33.05	2.37	7.73	0.49	-3.70	0.12	7.56	0.24	1.77	0.154	-5.38	0.04
14	4.09	-0.22	0.60	0.68	-3.91	0.10	16.90	0.73	2.49	-3.35	0.15	1.50	-2.76	0.22	45.05	2.14	6.63	0.52	-4.29	0.08	1.15	-3.15	0.17	0.116	-6.46	0.02
15	31.32	-0.02	0.74	0.90	-6.15	0.02	272.64	2.09	6.40	-6.00	0.02	2.02	-4.98	0.05	8.52	-2.91	0.20	4.59	-3.80	0.11	149.10	1.22	3.50	0.455	-7.13	0.01
16	33.99	0.20	0.91	1.10	-5.67	0.03	256.84	2.20	6.89	-5.81	0.03	2.55	-4.45	0.07	10.94	-2.35	0.29	5.74	-3.29	0.15	135.37	1.28	3.63	0.417	-7.07	0.01
17	37.78	0.06	0.79	1.12	-5.99	0.02	301.34	2.08	6.33	-6.16	0.02	2.50	-4.83	0.05	9.67	-2.88	0.20	5.49	-3.70	0.12	168.73	1.24	3.55	0.473	-7.24	0.01
18	34.43	0.20	0.91	1.07	-5.73	0.03	257.61	2.19	6.82	-5.82	0.03	2.38	-4.57	0.06	10.82	-2.39	0.29	5.52	-3.36	0.15	136.52	1.27	3.62	0.415	-7.09	0.01
19	38.23	0.13	0.85	1.11	-5.92	0.02	284.88	2.08	6.36	-6.07	0.02	1.18	-5.83	0.03	10.31	-2.71	0.23	4.83	-3.80	0.11	158.26	1.24	3.53	0.444	-7.24	0.01
20	31.84	0.26	0.97	1.08	-5.51	0.03	240.54	2.29	7.33	-5.62	0.03	1.90	-4.70	0.06	11.15	-2.14	0.34	5.80	-3.08	0.18	101.93	1.05	3.11	0.379	-7.02	0.01
21	34.27	0.08	0.81	1.00	-5.99	0.02	261.75	2.04	6.18	-5.99	0.02	16.06	-1.98	0.38	9.04	-2.81	0.21	4.89	-3.70	0.12	147.32	1.21	3.48	0.418	-7.25	0.01
22	6.08	0.73	1.56	0.83	-2.82	0.21	12.65	1.11	3.24	-2.55	0.26	0.12	-5.57	0.03	32.36	2.47	8.30	0.66	-3.15	0.17	7.38	0.34	1.89	0.146	-5.32	0.04
23	32.54	-0.19	0.62	0.74	-6.73	0.01	305.54	1.95	5.80	-6.30	0.02	10.81	-2.87	0.21	8.78	-3.17	0.17	2.84	-4.80	0.05	158.04	1.00	3.00	0.428	-7.53	0.01
24	4.26	-0.47	0.47	0.74	-4.19	0.08	19.69	0.54	2.18	-3.76	0.11	1.71	-2.98	0.19	52.50	1.95	5.81	0.63	-4.44	0.07	0.83	-4.02	0.09	0.140	-6.60	0.02
25	6.14	0.75	1.59	0.84	-2.79	0.22	12.71	1.13	3.29	-2.54	0.26	1.51	-1.95	0.39	32.34	2.48	8.37	0.62	-3.22	0.16	7.76	0.42	2.01	0.144	-5.33	0.04
26	4.75	-0.38	0.51	0.82	-4.09	0.09	24.84	0.84	2.69	-3.79	0.11	1.85	-2.91	0.20	52.03	1.91	5.63	0.57	-4.61	0.06	0.71	-4.29	0.08	0.138	-6.65	0.01
27	5.72	0.50	1.24	0.85	-3.03	0.18	11.83	0.77	2.56	-2.80	0.22	1.46	-2.25	0.32	32.45	2.22	7.01	0.36	-4.29	0.08	7.77	0.16	1.68	0.162	-5.42	0.03
28	5.16	-0.24	0.59	0.93	-3.82	0.11	27.31	1.05	3.11	-3.72	0.11	2.36	-2.48	0.27	58.32	2.15	6.64	0.74	-4.15	0.08	1.42	-3.22	0.16	0.143	-6.52	0.02
29	6.08	0.75	1.59	0.83	-2.78	0.22	12.07	1.07	3.16	-2.52	0.26	1.47	-1.96	0.38	31.73	2.47	8.29	0.62	-3.22	0.16	7.45	0.38	1.95	0.144	-5.32	0.04
30	4.41	-0.44	0.49	0.77	-4.15	0.08	19.39	0.51	2.13	-3.77	0.11	1.82	-2.91	0.20	52.42	1.91	5.77	0.56	-4.61	0.06	0.77	-4.15	0.08	0.138	-6.63	0.02
Aver.	15.52	0.30	1.10	0.89	-4.07	0.13	105.61	1.32	4.07	-3.88	0.16	2.82	-3.08	0.25	28.88	0.68	5.23	1.99	-3.73	0.12	54.78	-0.19	2.06	0.248	-6.14	0.03

Khobar coast (Fig. 8). It associated with the distribution of aluminum, strontium and iron. The highest values of Mn, Cu and V were recorded in samples 3, 20 and 16 (244, 330 and 472 μg/g respectively) and the lowest ones in samples 30, 24 and 10 (12, 96 and 24 μg/g respectively). Table 3 shows that Mn values exceeded the ones from the Arabian Gulf coast and the Gulf of Aqaba (de Mora et al., 2004a; Al-Taani et al., 2014). The average value was less than those recorded from the Caspian Sea coast and the Mediterranean Sea coast (de Mora et al., 2004b; El-Sorogy et al., 2016; Omar et al., 2015). Present Mn values agree the average value from the Al-Kharrar lagoon, Red Sea coast, Saudi Arabia (Youssef and El-Sorogy, 2016).

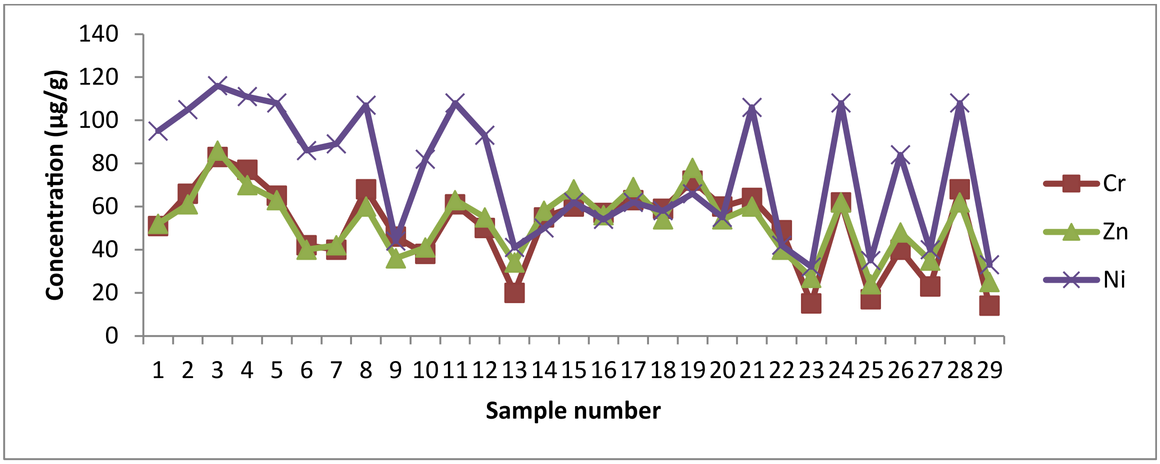

Fig. 7. Spatial distribution of Cr, Zn and Ni in the coastal sediment samples of Al-Khobar.

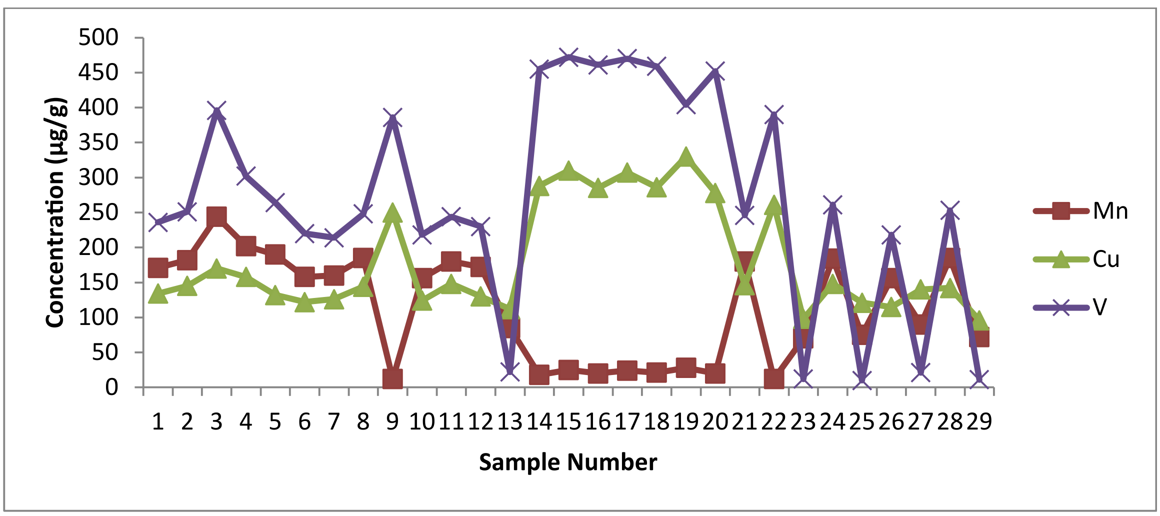

Fig. 8. Spatial distribution of Mn, Cu and V in the coastal sediment samples of Al-Khobar.

The distribution of copper was quite similar to that of vanadium (Fig. 8). The hot spots were observed in samples 15 to 21 of the central area. EF, Igeo and CF values suggested that, the studied sediments are extremely severe enriched, moderately polluted and considerably contaminated with Cu (EF > 50, 1 < Igeo < 2, 3 ≤ Cf < 6). Average Cu value (183 µg/g) is highly exceeded the 34 µg/g of ERL (Long et al., 1995), the 124 µg/g of the Canadian ISQG (ISQG, 1995) and the coasts of the Caspian Sea, the Arabian Gulf, the Red Sea, and the Mediterranean Sea (de Mora et al., 2004a, b; Youssef and El-Sorogy, 2016; El-Sorogy et al., 2016).

The distribution pattern of vanadium is similar to copper. CF values suggest extremely severe enriched and moderate contaminated with V (EF > 50, 1 ≤ Cf < 3). V values (average 268 µg/g) exceeded the one from the Caspian Sea (de Mora et al., 2004b), the Red Sea (Youssef and El-Sorogy, 2016; de Mora et al., 2004a), the background shale (Turekian and Wedepohl, 1961) and the earth crust (Taylor, 1964). Present levels of vanadium decreased the ones from Rosetta coast, the Mediterranean Sea (El-Sorogy et al., 2016). In general, the Al-Khobar coastline is being fairly remote from the Industrial City of Al-Jubail to the north and it characterized by low population, therefore, the high V levels are related to the oil spills off the Arabian Gulf, as the corresponding concentration of V, a metal sometimes used as a marker for oil (de Mora et al., 2004a).

3.2.4. Mercury and arsenic

The distribution pattern of Hg and As were very poorly associated with the Al distribution and consequently the percentage of fine-grained material, and the carbonate content of the Al-Khobar sediments (Fig. 9). Thus, the sources of Hg and As must be attributing to other than the main terrigenous and biogenic inputs. EF and CF values of Hg suggest very severe enriched and moderately contaminated with Hg (EF = 25–50, 1 ≤ Cf < 3). The concentrations of Hg were relatively high, ranged from 0.05 to 1.61 µg/g, with an

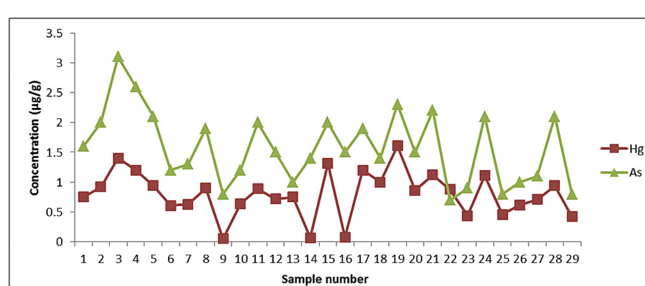

Fig. 9. Spatial distribution of Hg and As in the coastal sediment samples of Al-Khobar.

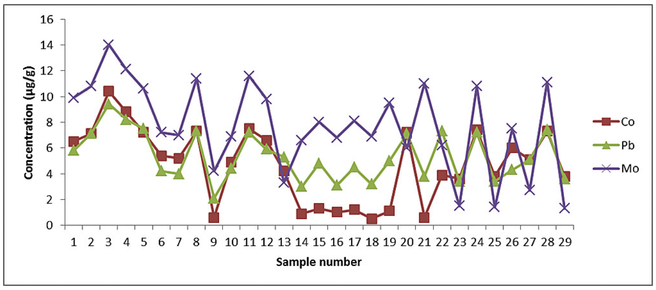

Fig. 10. Spatial distribution of Co, Pb and Mo in the coastal sediment samples of Al-Khobar.

average value of 0.803 µg/g. The levels exceed the ERL value of 0.15 µg/g (Long et al., 1995), the Canadian ISQG value of 0.13 µg/g (ISQG, 1995), the values of the Caspian Sea (de Mora et al., 2004b), the Arabian Gulf (Youssef et al., 2015; de Mora et al., 2004a), the background shale (Turekian and Wedepohl, 1961) and the earth crust (Taylor, 1964). Al-Khobar values are lower than the ones ranged from 0.064 to 30.38 µg/g (average 5.04 µg/g) from the Gulf of Trieste, as a result of the historic cinnabar mining in the catchment (Covelli et al., 2001).

Concentrations of As were low in coarse sediment samples or that composed of carbonates. Higher concentrations of As were recorded in the northern and southern sectors in comparison to the central one of Al-Khobar coast (Table 2). As values ranged from 0.7 to 3.10 µg/g, with an average value of 1.61 µg/g. The levels were lower than the ERL value of 8.2 µg/g (Long et al., 1995), the ones from the Gulf of Finland (Vallius and Lehto, 1998), the Interim sediment quality guideline of Canada (ISQG), the Red Sea, the Caspian Sea, the Arabian Gulf and the Mediterranean coasts; and the background shale and the earth crust (Table 3). Also, Al-Khobar levels decrease the extremely As-contaminated sediments of 137 µg/g, in the North Sea off the English coast (Whalley et al., 1999) and the 20 µg/g in surface sediments of the South Caspian Sea (de Mora et al., 2004a; b). Accordingly, the recorded As levels are quite low based on global standards, and generally not of environmental concern.

3.2.5. Cobalt, lead and molybdenum

Co, Pb and Mo exhibited some similar spatial distribution patterns coinciding with the distribution of Al, indicating a terrigenous input (Fig. 10). The highest values of these heavy metals were recorded in sample 3 (10.4, 9.4 and 14 µg/g respectively) and the lowest ones were recorded in samples 19, 10 and 30 (0.5, 2.1 and 1.3 µg/g respectively). The average value of Co (4.75 µg/g) is lower than the ones from the Mediterranean coast, the Azerbaijan and Iran coasts, the Gulf of Finland and the background shale and the earth crust (Table 3). EF values suggest a minor enrichment with Co (EF < 3).

Similarly, the lead concentrations were low for sites investigated in the Al-Khobar coast (average 5.38 µg/g). It never exceeds the ERL value of 47 µg/g. The average value was lower than the Interim sediment quality guideline, the ISQG and the data recorded from the Red Sea, the Arabian Gulf, the Mediterranean coast, Azerbaijan and Iran coasts, the Gulf of Finland and the background shale and earth crust (Table 3). Like Co, EF values suggest moderate enrichment with Pb (EF = 3–5). The average value of molybdenum (7.73 µg/g) exceeds the ones from the Arabian Gulf coast and the Red Sea coast. Also, it exceeds those of the background shale (Turekian and Wedepohl, 1961) and the earth crust (Taylor, 1964). EF, Igeo and CF values suggest that the Al-Khobar coastal sediments are very severe enriched, moderately polluted and contaminated with Mo (EF = 25–50, 1 < Igeo<2, 1 ≤ Cf < 3).

3.2.6. Cadmium and selenium

Cd exhibited a distribution pattern similar to Se (Fig. 11). The highest values of Cd and Se were recorded in sample 3 (0.52 and 1.2 µg/g respectively) and the lowest ones were recorded in sample 23 (0.08 and 0.15 µg/g respectively). According to Hökanson classification, the Al-Khobar sediments are moderately severe enriched with Cd (EF = 5–10) and severe enrichment with Se (EF = 10–25). Although the Cd levels were higher in the northern and southern sectors than the central one, the average value (0.23 µg/g) decreased the ERL value of 1.2 µg/g (Long et al., 1995), the Canadian ISQG value of 0.7 µg/g (ISQG, 1995) and the black sand sediments of 28.88 on Rosetta beach, Egypt (El-Sorogy et al., 2016). Average Se value (0.50 µg/g) increased the average value from the Arabian Gulf coast (Youssef et al., 2015) and Azerbaijan and Iran coasts (de Mora et al., 2004b).

4. Conclusions

The analyses of 16 heavy metals from 29 coastal sediments along the Al-Khobar coastline indicated the following order of averages: Fe > Al > Sr > V > Cu > Mn > Ni > Zn > Cr > Mo > Pb > Co > As > Hg > Se > Cd. Most of the heavy metals are strongly associated with Al, a good proxy for terrigenous

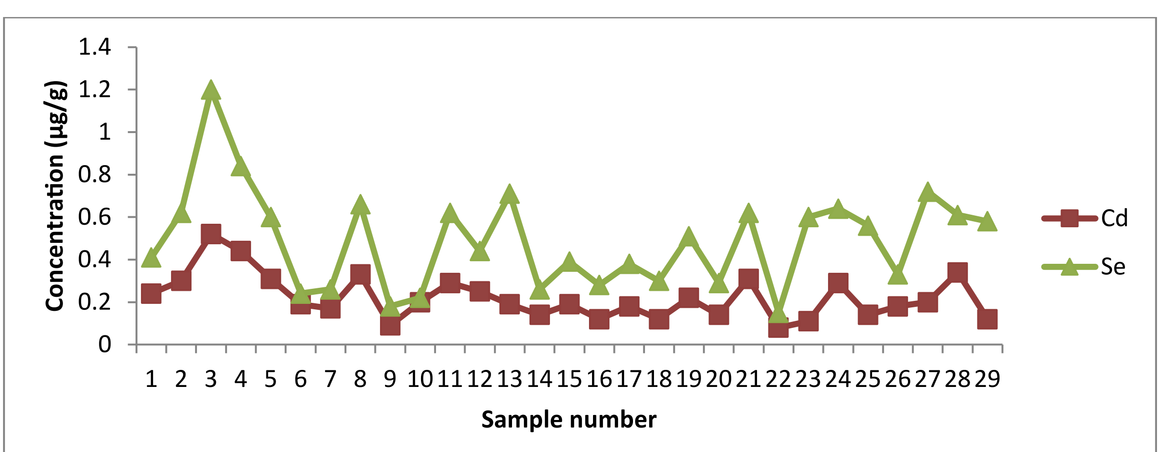

Fig. 11. Spatial distribution of Cd and Se in the coastal sediment samples of Al-Khobar.

material. Notable exceptions to this behavior are V and Cu, which have a negative correlation with Al. Coastal sediments in the Al-Khobar coast recorded extremely severe enrichment with Cu and V, very severe enrichment with Sr, and severe enrichment with Cr, Zn, Hg, Mo and Se. Anthropogenic activities, notably oil spills from exploration and transportation, saline water desalination plants in the Al-Khobar coast and the industrial activities in Al-Jubail Industrial City to the north may have further enhanced the metal burdens in the studied sediments. Other determined heavy metals like Al, Mn, Cd, Pb, and As exhibited relatively low levels to the corresponding consensus-based ERL, ERM and ISQG levels, as well as their enrichment factors <2, indicating no environmental concerns and are most likely natural and reflect the local mineralogy rather than contamination.

Acknowledgments

This project was financially supported by King Saud University, Vice Deanship of Research chairs. Also, we would like to thank the two reviewers for their valuable and constructive comments.

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