




Factors influencing heavy metal concentrations in the bottom sediments of the Al-Kharrar Lagoon and Salman Bay, eastern Red Sea coast, Saudi Arabia

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Abstract

The Al-Kharrar Lagoon (KL) and Salman Bay (SB) are located on the eastern Red Sea coast, Saudi Arabia. The concentrations of heavy metals such as Fe, Mn, Zn, Cu, Ni, Pb, Co, and Cd in their bottom sediments were measured and correlated with the surface water temperature, salinity, pH and dissolved oxygen (DO), organic carbon (OC), carbonates, and sediment grain size. The highest concentration of metals in the KL is mostly attributed to influx of siliciclastics from wadies to the center and south-eastern parts of the lagoon where metals were directly correlated with salinity, pH, and mud. At the inlet stations, the metals were the lowest indicating that the KL acts as a buffer zone, preventing metals from dispersion into the Red Sea waters. But also, the enrichment factor (EF), there, for Mn, Zn, Cu, Co, and Ni, was the highest due likely to the effectiveness of biosorption by mucus algae that proliferate on coral debris and sand grains. The metals had no relationships with the OC, but with mud and Fe-Mn oxides due possibly to the presence of high DO. The brine waters of SB showed inverse relationships with the metals that ascribed probably to the occurrence of many soluble salts preventing precipitation of heavy metals into the sediments. Normalizing the heavy metals with Fe and the world average shale indicated that the bottom sediments of the KL and SB were uncontaminated and mainly influenced by natural sources.

Keywords Fe-Mn oxides · Brine · Lagoon · PCA · Heavy metals · Organic carbon

Introduction

Heavy metals (commonly of Fe, Mn, Al, Cu, Zn, Cd, Ni, Cr, Co, Pb, Ag, and As) in the shallow water sediments of the eastern Red Sea coast have been studied by many authors in order to evaluate their natural background levels against the effect of anthropogenic activities (El Sayed and Basaham 2004; Turki 2007; Badr et al. 2009; Pan et al. 2011; Abu-Zied et al. 2013; Ghandour et al. 2014; Basaham et al. 2015; Abu-Zied et al. 2016; Youssef and El-Sorogy 2016; Abu-Zied and Hariri 2016; Al-Mur et al. 2017). Some of these studies

have showed that the shallow water sediments of the Red Sea that are far away from cities are not polluted and have natural heavy metal accumulations except, for example, those of the coastal area of Jeddah City that has been highly affected by human and industrial pollutions leading to occurrence of high concentration of heavy metals in their sediments (Abu-Zied and Hariri 2016; Al-Mur et al. 2017). In the un-polluted areas, the nearshore sediments of the Red Sea were mainly composed of biogenic sands with very low metal concentrations which primarily originated from the influx of wadies that are numerous in the eastern coastal plain of the Red Sea (Abu-Zied and Hariri 2016). These wadies are active for a short period during winter and originate from the escarpment of the Al-Hejaz and Asir mountains; they end with mouths (such as bays, lagoons and sharms) or disappear in the alluvium of the eastern coastal plain of the Red Sea.

Few studies have dealt with the factors that control the concentrations of heavy metals in nearshore sediments of the Red Sea. Among of these studies, Abu-Zied et al. (2013, 2016) and Abu-Zied and Hariri (2016) have showed that the distribution and accumulations of heavy metals (e.g., Fe, Mn,

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Cu, Zn, Cd, Ni, Cr, Co, and Pb) in the surficial bottom sediments of the eastern coast of the Red Sea have been affected by factors such as temperature, salinity, pH, dissolved oxygen, organic carbon, carbonates, sediment grain size, closeness to natural or pollution point-source, and redox potential. Also, the degree of bioavailability, mobility, and toxicity of heavy metals in the environment depend strongly on their specific chemical forms (Yu et al. 2010; Tamunobereton-ari et al. 2011). Pan et al. (2011) studied the speciation of heavy metals (Cd, Zn, Ag, Cu, Pb, As, and Hg) in the sediments of eastern coast of the Red Sea and concluded that the sequential extraction indicated that the anthropogenic input of metals was not significant in the studied areas except in the local fish market of Jeddah City. They also mentioned that the metals of the exchangeable phase which is an indication of the anthropogenic origin and of high potential bioavailability were low in all studied sites, whereas those of Fe-Mn oxides and organic phases were high in the sediments of the local fish market of Jeddah City. This is because of Fe-Mn oxides and organic matters are important metal scavengers in sediments through various mechanisms including coprecipitation, adsorption, surface complex formation, and ion exchange.

In addition, bacteria play a role in metal distributions, relationships, and Fe-Al complexation in metal-polluted lake sediment due to having mineral coatings of varying composition and texture formed by adsorption of detrital clay and precipitation of authigenic oxides and clay (Jackson et al. 2011). They also reported that some bacteria mobilize metals by releasing water-soluble chelating agents, while others immobilize them by producing H₂S. Also, algae, specially the brown seaweed *Sargassum* sp., can mediate and change the concentration of heavy metals in seawaters and hence in sediments due to having high potentials for the accumulation of heavy metals, as compared to other algal genera (Da Costa et al. 2001; Bina et al. 2006). They also mentioned that this seaweed is mainly constituted by the polysaccharide alginic acid (usually calcium, magnesium, sodium, and potassium salts) produced due to the interaction between alginic acid and alkaline and alkaline-earth elements from seawater, then acting as efficient ion-exchangers (biosorbents) for heavy metals present in solution.

The heavy metals in seawaters and sediments have a two-fold of importance. They are essential nutrients for marine organisms and become very toxic if its concentrations exceed the requirements of metabolic processes of these organisms which are being used as good food sources for human (Du Laing et al. 2009; Tamunobereton-ari et al. 2011; Oves et al. 2016). Also, Tchounwou et al. (2012) reported that metals such as Co, Cu, Cr, Fe, Mg, Mn, Mo, Ni, Se, and Zn are essential nutrients that are required for various biochemical and physiological functions, but inadequate supply of these micronutrients results in a variety of deficiency diseases or syndromes.

The Saudi Red Sea lagoons and bays and its natural resources that are close to coastal cities are at risk due to

pollution from domestic and industrial wastes and their use as fish farms (Abu-Zied et al. 2013; Al-Mur et al. 2017). Such anthropogenic activities are, at present, growing rapidly and could lead to increase of heavy metal concentrations above the permissible limits and change the water quality of these aquatic environments (Badr et al. 2009), especially the ones (Al-Kharrar and Salman lagoons) that are under the concern of this study.

Therefore, this study aims to determine the concentrations of the heavy metals such as iron (Fe), manganese (Mn), nickel (Ni), zinc (Zn), copper (Cu), cobalt (Co), cadmium (Cd), and lead (Pb) in the surficial bottom sediments of Al-Kharrar (hypersaline) and Salman (brine pool) lagoons in order to compare them with the natural background level and make distinction between the heavy metal inventory of these lagoons. Also, the heavy metal concentrations in the studied sediments will be correlated with the hydrogeochemical parameters (temperature, salinity, pH, dissolved oxygen, and organic carbon and carbonates) and sediment grain size to shed light on the factors affecting their concentrations and distribution.

The study area

Al-Kharrar Lagoon

Al-Kharrar Lagoon (KL) is located 9 and 140 km north of Rabigh and Jeddah cities, respectively. It occurs in the center of the eastern coast of Red Sea, Saudi Arabia, between latitudes 22.84° and 23.00° N and longitudes 38.83° and 38.98° E (Fig. 1). The KL is a normal to hypersaline water body with a salinity ranging from 38.8 to 41.5‰, during winter (this study). It has an elongated shape parallel to the Red Sea with a total area of 82 km² and elongated small islets at its northern and center of its southern parts (Fig. 1). Mangrove shrubs grow abundantly around the islets and at the northern and southern shorelines (Fig. 1). It is only connected with the Red Sea water via a narrow (120 m wide) and deep (14 m) inlet located at its northwestern corner (Al-Dubai et al. 2017). The eastern side of the KL is connected with several dry wadies (such as: Rabigh, Rahab, Murayyikh and Al-Khariq) originating from the escarpment of the Al-Hejaz mountains (Fig. 1). These wadies feed the KL with an irregular influx of freshwaters only during winter for a short period. The influx of freshwaters via the Wadi Rabigh is no longer reaching the KL since 2009 due to the construction of Rabigh Dam about 35 km east of Rabigh City.

Salman Bay

Salman bay (SB) is located north of Jeddah City, center of the eastern coast of Red Sea, Saudi Arabia (Fig. 1). It occurs



Fig. 1 Location map of the study areas. **a** Al-Kharrar Lagoon; **b** Salman Bay. The station sites indicated by red circles

between latitudes 21.84° and 21.95° N and longitudes 38.96° and 39.04° E (Fig. 1). The SB has an elongated shape parallel to the Red Sea with a total area of 32 km^2 (Fig. 1). It is only connected with the Red Sea water via a very narrow, shallow inlet located at its northwestern corner. It is a brine water body with a salinity ranging from 70 to 80‰, during winter (this study). Owing to shallowness of SB and restriction of water exchange between it and Red Sea, its water quality is deteriorated. Field work indicated that the SB is not connected either to wadies of the catchment area or to industrial effluents, but layer of black sludge was noticed on its eastern shoreline. The brine waters of the SB are used for salt extraction by the SASA salt company located at the eastern coast of the bay (Fig. 1).

Materials and methods

Field work Twenty five and Thirteen surficial (upper 2 cm) bottom sediments were collected from the Al-Kharrar Lagoon (KL) and Salman Bay (SB) during December 2016, respectively. The KL' samples were collected on board using the Van Veen grab sampler and those of the SB were collected from close to shoreline using a stainless steel knife. Immediately after collection, the substrate types were described, and the upper 2 cm was cut off and placed in plastic bags, then transported to laboratory for geochemical and heavy metal analyses. At each station of the sediment samples, the hydrochemical

parameters such as water depth (measured by Eco-sounder UWTEC), temperature, salinity, pH, and dissolved oxygen (DO) were, in situ, measured by YSI 556 MPS Meter. At some stations of the KL (KH3, KH8, and KH10), vertical profiles for water column temperature, salinity, and DO were undertaken. The coordinates of sediment samples at each station were determined by Garmin II GPS and listed with substrate types and hydrochemical parameters in Table 1.

Granulometry Sediment grain size variations were determined by wet sieving method; this is because the collected sediment samples are small and consist mainly of bioclastics grains that when dried, they get solidified. So, it is better to disintegrate them by wet sieving. A known dry weight of the sediment sample was passed through > 2 and 0.063 mm sieve openings using a shower of tape water until all mud grains passed through the 0.063 mm sieve opening. The fractions that were retained in the sieves were dried in an oven at 60°C for 72 h. After that, the dried fractions in each sieve were weighed to determine the percentages of the gravel ($> 2 \text{ mm}$) and sand ($0.063\text{--}2 \text{ mm}$) fractions. Mud fraction was determined by subtracting the total gravel and sand fraction from the total dry weight of sediments.

Geochemical analysis It was performed on bulk sediment dry weight, because it is a good representation for all metals since

Table 1 Station coordinates, water depths (m), substrate types, and hydrochemical parameters (temperature °C, salinity ‰, dissolved oxygen (mg/l), and pH) of the Al-Kharrar Lagoon and Salman Bay during December 2016

Area/S. No.	Latitude (N)	Longitude (E)	Depth (m)	Substrate type	Sur. temp.	Bot. temp.	Sur. salinity	Bot. salinity	Sur. DO	Bot. DO	Surface pH	Bottom pH
Al-Kharrar Lagoon												
KH1	22° 58' 08.76"	38° 50' 04.74"	14.80	Brown gravelly sediments	29.05	28.55	38.82	39.19	6.15	6.26	8.96	8.69
KH2	22° 58' 15.13"	38° 50' 15.76"	13.30	Brown gravelly sediments	29.00	28.91	38.84	38.90	6.00	5.97	8.81	8.84
KH3	22° 58' 13.87"	38° 50' 33.58"	15.00	Brown gravelly sediments	28.80	28.02	38.97	39.45	5.93	5.90	8.78	8.76
KH4	22° 57' 50.90"	38° 51' 10.69"	7.50	Sandy gravels; red algae	28.69	26.91	39.06	40.35	6.41	6.50	8.89	8.86
KH5	22° 57' 39.89"	38° 52' 02.35"	8.20	Gray mud; sea-grasses	27.95	26.57	39.56	40.60	6.14	6.59	8.82	8.83
KH6	22° 56' 51.58"	38° 53' 07.58"	8.80	Gray mud; sea-grasses	27.47	26.04	39.87	41.19	6.42	6.59	8.83	8.84
KH7	22° 55' 41.84"	38° 54' 00.14"	8.10	Black mud; sea-grasses	26.68	25.91	40.48	41.46	6.86	5.97	8.84	8.84
KH8	22° 54' 19.70"	38° 54' 40.22"	7.60	Black mud; sea-grasses	26.43	25.96	40.73	41.47	6.97	6.24	8.92	8.89
KH9	22° 53' 01.28"	38° 55' 22.19"	7.00	Black mud; sea-grasses	26.57	26.54	40.93	41.14	6.59	6.50	8.92	8.88
KH10	22° 52' 25.63"	38° 55' 45.61"	6.50	Black mud	26.47	26.30	41.13	41.41	6.63	6.10	8.87	8.86
KH11	22° 52' 02.28"	38° 55' 58.38"	4.40	Black mud	26.45	26.46	41.21	41.21	6.50	6.56	8.91	8.89
KH12	22° 51' 42.07"	38° 55' 53.30"	2.90	Black mud; sea-grasses	26.65	26.64	41.15	41.19	6.51	6.38	8.89	8.87
KH13	22° 51' 34.13"	38° 55' 44.19"	1.20	Black mud	27.63	27.71	41.53	41.59	6.59	6.65	8.85	8.85
KH14	22° 51' 29.56"	38° 55' 32.80"	1.70	Black mud	26.94	26.97	41.51	41.48	6.15	6.15	8.84	8.85
KH15	22° 51' 27.15"	38° 55' 20.34"	1.30	Black mud; sea-grasses	26.95	26.95	41.48	41.48	6.16	6.18	8.85	8.84
KH16	22° 51' 26.39"	38° 55' 09.80"	0.40	Black sandy mud	27.24	27.24	41.56	41.55	6.53	6.56	8.97	9.06
KH17	22° 51' 45.53"	38° 56' 21.60"	2.00	Black mud; sea-grasses	26.59	26.58	41.21	41.22	6.61	6.68	8.85	8.86
KH18	22° 51' 29.99"	38° 56' 25.85"	2.90	Black mud; sea-grasses	26.59	26.62	41.30	41.28	6.17	6.17	8.83	8.82
KH19	22° 51' 14.19"	38° 56' 28.60"	0.50	Black sandy mud	27.03	27.04	41.34	41.29	6.66	6.71	8.89	8.96
KH20	22° 51' 38.47"	38° 56' 45.73"	3.50	Black mud	26.65	26.69	41.24	41.23	6.31	6.29	8.88	8.86
KH21	22° 51' 39.05"	38° 57' 04.49"	2.70	Gray blackish mud, sea-grasses	26.76	26.80	41.17	41.21	6.48	6.46	8.86	8.85
KH22	22° 51' 39.92"	38° 57' 23.24"	2.10	Gray blackish mud	26.83	26.88	41.29	41.27	6.45	6.48	8.86	8.88
KH23	22° 51' 44.02"	38° 57' 39.46"	1.70	Gray blackish mud	27.63	27.68	41.24	41.74	6.24	6.30	8.86	8.85
KH24	22° 51' 49.00"	38° 57' 51.22"	1.60	Gray blackish mud	27.50	27.68	41.80	41.70	6.41	6.36	8.86	8.87
KH25	22° 51' 54.76"	38° 57' 59.62"	1.20	Gray blackish mud	28.01	28.09	42.11	42.07	6.23	6.26	8.86	8.82
Min.					26.43	25.91	38.82	38.90	5.93	5.90	8.78	8.69
Max.					29.05	28.91	42.11	42.07	6.97	6.71	8.97	9.06
Average					27.30	27.03	40.78	41.07	6.40	6.35	8.87	8.86
STDEV					0.85	0.78	0.99	0.79	0.26	0.23	0.04	0.06
Salman Bay												
SA1	21° 50' 43.30"	39° 01' 32.60"	0.10	Brown, black algal mat, salt layer	23.98		82.19		3.47		8.29	
SA2	21° 51' 12.42"	39° 01' 46.06"	0.20	Brown, black algal mat, salt layer	23.68		75.75		5.05		8.72	
SA3	21° 51' 43.56"	39° 01' 49.33"	0.40	Salt layer, black organic matters	24.65		75.64		3.57		8.80	
SA4	21° 52' 14.88"	39° 01' 37.56"	0.50	Black algal mat, slippery	24.36		73.97		4.03		8.80	

Table 1 (continued)

Area/S. No.	Latitude (N)	Longitude (E)	Depth (m)	Substrate type	Sur. temp.	Bot. temp.	Sur. salinity	Bot. salinity	Sur. DO	Bot. DO	Surface pH	Bottom pH
SA5	21° 52' 48.25"	39° 01' 13.73"	0.40	Slippery algal mat, black	24.61		68.12		4.73		8.69	
SA6	21° 53' 16.26"	39° 01' 19.02"	0.10	Black algal mat, bad smell	28.12		70.28		3.90		8.53	
SA7	21° 54' 08.24"	39° 00' 44.40"	0.10	Black layer, sludge	28.83		68.32		3.52		8.48	
SA8	21° 54' 35.28"	39° 00' 17.71"	0.15	Hard, slippery	26.09		66.29		5.46		8.66	
SA9	21° 54' 59.11"	39° 01' 00.80"	0.20	Black whitish sludge, bad smell	28.17		69.91		3.87		8.60	
SA10	21° 55' 27.52"	39° 00' 46.37"	0.30	Firm black substrates, slippery	28.22		68.97		5.49		8.52	
SA11	21° 55' 46.70"	39° 00' 20.20"	0.30	Slippery algal mat	28.05		70.85		5.49		8.59	
SA12	21° 56' 12.91"	39° 00' 08.39"	0.30	Slippery algal mat	26.71		71.68		5.26		8.61	
SA13	21° 56' 39.62"	39° 00' 09.68"	0.20	Slippery algal mat	27.62		71.82		5.03		8.65	
Min.					23.68		66.29		3.47		8.29	
Max.					28.83		82.19		5.49		8.80	
Average					26.39		71.83		4.53		8.61	
STDEV					1.90		4.22		0.82		0.14	

some samples contain insignificant amounts of fine-grained sediments and simplifies sample processing and potential artifacts that might change the original composition (Herut and Sandler 2006). Sediment samples were dried on room temperature. Total organic carbon (OC) was determined by the loss on ignition (LOI) technique (Heiri et al. 2001; Abu-Zied et al. 2011). Total carbonate (CaCO₃) was determined by etching 0.5 g of the dry weight sediment sample in 50 ml of 1 M HCl solution at room temperature for 24 h. After that, the residue was filtered, oven dried, and weighed. Then, the CaCO₃ in the sediment sample was determined by the loss in weight.

Concentration of heavy metals (Fe, Mn, Zn, Cu, Ni, Pb, Co, and Cd) in bulk, dry weight sediment samples was measured by the atomic absorption spectrophotometer (AAS), GBC-93, Australian Model at the National Institute of Oceanography and Fisheries, Hurghada, Egypt. Approximately, 0.5 g of each pre-powdered samples was digested with a mixture of concentrated HF, HNO₃, and HClO₃ acids (5:3:1). The digested solution was evaporated to near dryness. The digested samples were filtered and diluted with de-ionized water (Chester et al. 1994). After that, measurement of heavy metal concentrations was undertaken by the AAS, GBC-932. To insure that maximum accuracies have been obtained, the AAS was adjusted to provide mean value of triplicate measurements of each metal with precision of < 3% and detection limit of 0.01 mg/kg; the obtained results were expressed in mg/kg (Table 2). The zero level of the AAS was adjusted by blanks and the quality control tools were adopted to avoid possible contamination. Meanwhile, the chemical reagents are of high analytical grade and all of glassware were washed with diluted acid and later rinsed with double-distilled water before use.

Enrichment and pollution factors were applied in this study to normalize and compare the metal concentrations of the studied sediments between different parts of the lagoons and between lagoons itself and to see the degree of metal enrichment in the studied sediment samples relating this enrichment either to natural or anthropogenic sources. Armstrong-Altrin and Machain-Castillo (2016) reported that the enrichment factor (EF) is a useful tool to evaluate the heavy metal contamination in sediments against their natural background. In this study, the enrichment factor (EF) of the recorded metal concentrations was applied using the Fe as normalizer to correct for difference in sediment grain size (Loring 1991; Acevedo-Figueroa et al. 2006). This is also because Fe showed a perfect correlation (*r* values were higher than 0.9) with all metals. The EF was calculated using this equation: $EF = (M/Fe)_{\text{sediment}} / (M/Fe)_{\text{background}}$ (Abraham and Parker 2008; Ghandour et al. 2014; Nowrouzi and Pourkhabbaz 2014; Youssef and El-Sorogy 2016). The $(M/Fe)_{\text{sediment}}$ represents the metal concentrations in the studied sediments and the $(M/Fe)_{\text{background}}$ represents the metal concentrations in the average shale background (Turekian and Wedepohl 1961). The $EF < 1.5$ indicates that the metals are originated from natural sources, whereas the $EF > 1.5$ means

Table 2 Percentages of sediment grain sizes, organic carbon (OC), CaCO₃, and concentrations (mg/kg) of heavy metals Fe, Mn, Zn, Cu, Ni, Co, Cd, and Pb in the bulk surficial bottom sediments (dry weight) of Al-Kharrar Lagoon and Salman bay during December 2016

Area/S. No.	% Gravel	% Sand	% Mud	%OC	% CaCO ₃	Fe	Mn	Zn	Cu	Ni	Pb	Co	Cd
Al-Kharrar Lagoon													
KH1	28.20	68.12	3.68	5.13	97.17	1585.7	77.7	3.42	5.76	1.60	ND	4.72	0.00
KH2	1.59	95.95	2.46	4.70	96.80	1797.3	120.3	0.19	4.78	8.71	0.00	0.84	0.00
KH3	2.47	94.50	3.02	5.36	90.08	1899.7	111.1	1.06	4.26	5.36	0.00	8.33	0.00
KH4	14.44	75.13	10.43	5.43	93.75	4658.6	155.6	2.71	6.37	2.84	0.00	3.19	0.00
KH5	7.36	41.05	51.59	5.88	79.26	9307.1	211.3	10.53	12.79	15.87	0.00	8.89	0.00
KH6	7.62	76.14	16.24	3.74	77.78	14,535.1	348.4	19.24	18.13	24.51	0.00	5.08	0.00
KH7	3.70	20.98	75.33	5.81	59.72	20,423.9	382.4	25.10	23.61	27.92	0.00	7.44	0.00
KH8	1.94	14.98	83.08	11.25	60.38	19,305.8	397.4	21.30	20.81	24.75	0.00	11.30	0.00
KH9	4.61	29.70	65.69	9.89	68.91	30,021.9	470.0	36.62	36.17	45.99	0.00	14.46	0.00
KH10	0.75	4.82	94.42	14.56	30.47	25,986.8	422.7	29.97	29.71	39.09	0.00	15.41	0.00
KH11	0.20	4.15	95.66	11.39	48.04	19,989.9	373.1	26.24	21.69	19.15	0.00	9.02	0.00
KH12	2.57	11.32	86.11	12.77	64.00	9927.0	208.3	12.83	13.58	12.06	0.00	7.30	0.00
KH13	1.02	25.58	73.39	9.41	76.67	14,703.7	270.1	16.51	17.55	19.25	0.00	7.23	0.00
KH14	0.85	5.64	93.51	11.39	68.03	17,256.2	319.2	21.41	22.18	25.22	0.00	6.53	0.00
KH15	1.30	3.59	95.12	13.85	62.93	4101.0	116.8	4.16	8.95	0.00	1.27	4.10	7.83
KH16	3.05	53.88	43.07	5.48	83.19	22,108.1	390.5	25.82	25.40	32.16	0.00	10.53	0.00
KH17	4.22	13.80	81.98	15.20	53.44	22,025.7	364.4	25.48	24.89	31.53	0.00	9.08	0.00
KH18	2.42	6.55	91.04	8.00	53.00	6713.0	149.1	7.93	11.29	8.17	0.00	0.00	0.00
KH19	4.01	85.61	10.38	6.67	94.66	31,363.2	472.4	38.94	36.37	42.39	0.00	15.10	0.00
KH20	0.44	2.53	97.03	13.27	33.06	32,501.9	456.7	43.37	43.06	56.76	0.00	13.07	0.00
KH21	0.71	3.40	95.89	9.76	28.36	31,823.9	477.9	43.43	35.56	45.08	0.00	14.41	0.00
KH22	1.71	4.04	94.25	6.33	22.86	31,061.1	510.1	43.34	31.69	45.52	0.00	12.11	0.00
KH23	0.37	2.67	96.95	5.26	20.31	32,332.4	495.9	46.28	37.54	47.19	0.00	13.80	0.00
KH24	0.57	4.19	95.24	4.59	14.81	31,520.8	490.1	41.10	33.96	43.63	0.00	13.57	0.00
KH25	0.00	6.45	93.55	4.39	3.31	31,386.8	432.2	43.29	34.44	46.60	0.00	13.93	0.00
Min.	0.00	2.53	2.46	3.74	3.31	1585.7	77.7	0.19	4.26	0.00	0.00	0.00	0.00
Max.	28.20	95.95	97.03	15.20	97.17	32,501.9	510.1	46.28	43.06	56.76	1.27	15.41	7.83
Average	3.84	30.19	65.96	8.38	59.24	18,733.5	328.9	23.61	22.42	26.85	0.05	9.18	0.31
STDEV	5.98	32.98	36.24	3.66	27.90	11,201.6	143.4	15.46	11.80	17.09	0.25	4.53	1.57
Salman Bay													
SA1	14.02	57.03	28.95	13.51	49.21	5423.1	96.9	14.09	4.95	0.00	0.00	0.00	0.00
SA2	9.38	80.27	10.35	3.30	90.38	4947.1	100.0	12.98	4.25	2.73	0.00	2.06	0.00
SA3	5.28	35.11	59.61	14.81	63.48	4449.0	43.0	6.36	6.72	0.00	0.00	0.00	0.00
SA4	2.42	58.28	39.29	7.08	84.26	4329.4	65.1	5.07	4.08	1.10	1.80	1.87	2.96
SA5	21.62	65.26	13.13	5.56	69.85	3888.8	54.9	4.96	3.67	0.26	0.00	0.00	0.00
SA6	18.93	43.65	37.42	11.85	79.82	10,402.8	139.9	9.03	18.32	0.00	0.00	0.00	0.00
SA7	5.23	49.47	45.31	23.19	57.00	7725.7	94.3	12.41	10.38	4.06	0.00	0.00	0.00
SA8	14.35	65.85	19.80	13.85	66.88	7261.7	91.8	10.29	9.07	2.51	0.00	2.63	0.00
SA9	0.00	66.93	33.07	6.86	60.00	9517.9	153.3	9.41	7.65	10.26	0.00	1.29	0.00
SA10	3.57	60.59	35.84	8.13	69.23	8197.4	143.2	10.60	8.08	7.32	0.00	3.73	0.48
SA11	14.50	44.19	41.31	10.59	83.19	7380.2	139.7	10.23	7.63	7.09	0.00	0.00	0.00
SA12	9.78	69.92	20.30	8.93	58.62	3141.0	48.0	7.78	9.25	0.00	0.00	0.00	0.00
SA13	7.05	74.99	17.96	5.11	86.55	3268.5	53.3	2.51	2.79	0.00	0.00	0.69	0.00
Min.	0.00	35.11	10.35	3.30	49.21	3141.0	43.0	2.51	2.79	0.00	0.00	0.00	0.00
Max.	21.62	80.27	59.61	23.19	90.38	10,402.8	153.3	14.09	18.32	10.26	1.80	3.73	2.96
Average	9.70	59.35	30.95	10.21	70.65	6148.7	94.1	8.90	7.45	2.72	0.14	0.94	0.26
STDEV	6.59	13.22	14.22	5.32	13.04	2406.7	39.7	3.43	4.06	3.47	0.50	1.26	0.82

that the metals are relatively higher than the natural background due to contribution from natural and/or anthropogenic sources (Zhang and Liu 2002; Xu et al. 2015; Al-Mur et al. 2017).

Contamination factor (CF) was applied to determine the degree of anthropogenic contamination to the studied sediment samples. It was calculated using this equation: $CF = M_{\text{sediment}}/M_{\text{background}}$. When $CF < 1$, this indicates that the heavy metal concentrations in sediments are uncontaminated,

whereas $CF > 1$ means that the sediments are contaminated (Hakanson 1980; Tomlinson et al. 1980).

Pollution load index (PLI) was calculated using this equation: $PLI = (CF_1 \times CF_2 \times CF_3 \dots CF_n)^{(1/n)}$. When $PLI < 1$ indicates there is no pollution and $PLI > 1$ indicates there is a pollution (Tomlinson et al. 1980; Al-Mur et al. 2017).

Index of geoaccumulation (Igeo) was calculated using this equation: $Igeo = \log_2 (Cn/(1.5 \times Bn))$ following Muller

(1969). The C_n is the measured concentration of metal (n), and B_n the metal's concentration in the average shale (Turekian and Wedepohl 1961). The factor 1.5 is introduced to include possible variations of the background values due to lithogenic effects. Value < 0.0 indicates the sediments uncontaminated, and 0–1 indicates that the sediments are uncontaminated to moderately contaminated.

Statistical analysis The relationships and structures that may exist between the recorded heavy metals, hydrogeochemical parameters, and sediment grain size were best obtained by the correlation matrix of the principal component analysis (PCA) and by the correlation similarity index of the R-mode hierarchical clustering (UPGMA algorithm), using the PAST software (Hammer et al. 2001). Also, the Bray-Curtis similarity index of the Q-mode hierarchical clustering (UPGMA algorithm) was performed for the data of Salman Bay.

Results

Al-Kharrar Lagoon

Hydrogeochemical parameters

Bathymetry of the Al-Kharrar Lagoon (KL) shows a gradual increase in the depth towards its opening (inlet) with the Red Sea, reaching a maximum water depth of 15 m at station 1 (Table 1). In the center of the lagoon water depth stabilizes around 8 m. In the upper lagoon (southern part), water depth averages 4 m which rapidly decreases to 0.5–1 m near-shore of the southern stations (Table 1).

Surface water temperature of the KL averaged 27.3 ± 0.8 °C during December 2016 (Fig. 2). It showed maximum values up to 29 °C at the inner inlet stations KH1–4, but at the rest of the studied stations, it decreased to an average value of 26.5 °C (Fig. 2). The bottom water temperature showed the same pattern as those of the surface water temperature, but with a subtle decrease in its mean value of 27 ± 0.8 °C (Table 1).

Surface water salinity of the KL averaged $40.8 \pm 1\%$ during December 2016 (Fig. 2). It showed the lowest values 38.8‰ at the inner inlet stations KH1–4. It increased to 41.5‰ at the stations of the southern part, the upper lagoon (Fig. 2). Bottom water salinity of the KL showed the same pattern as those of the surface water salinity, displaying an average of $41.1 \pm 0.8\%$ (Table 1). At the stations KH1–10, the bottom water salinity increased from those of the surface water by about 0.5‰, whereas at the rest of the stations (southern stations), the surface and bottom salinities are more or less similar, but with a subtle surface salinity increase of about 0.1‰ (Fig. 3, Table 1).

The surface and bottom water pH were very similar in all stations, displaying average values 8.87 and 8.86, respectively (Fig. 2, Table 1). The surface and bottom water dissolved oxygen (DO) were also the same in all stations, displaying a mean value of 6.4 mg/l (Fig. 2, Table 1). In all the studied stations (except stations KH7–10), the surface DO was a slightly higher than those of the bottom DO with a mean difference of 0.1 mg/l (Table 1). At the stations KH7–10 (center of the lagoon, 8 m water depth), the bottom water DO decreased from the overlying surface DO by a value of 0.5 mg/l (Fig. 3).

The vertical profiles of temperature, salinity, and dissolved oxygen in the water column of the KL showed that the water column consists of surface and bottom layers (Fig. 3) (Al-Dubai et al. 2017). The surface layer was less saline, warm with high DO, whereas the bottom layer was more saline, colder with slightly low DO (Fig. 3).

The total LOI organic carbon (OC) in the surficial bottom sediments of Al-Kharrar Lagoon (KL) averaged $8.4 \pm 4\%$. It was the lowest near the inner inlet stations (KH1–7) and at the south-eastern stations of the lagoon, displaying value of 5% (Fig. 4). In the center of the lagoon, the OC was the highest displaying a value of 12% (Fig. 4). The CaCO_3 in the surficial bottom sediments of KL averaged $59.24\% \pm 28$. It was the highest near the inner inlet stations (KH1–4), displaying value of 95% (Fig. 4). In the center of the lagoon, it decreased to 50%. At the south-eastern stations of the lagoon, the CaCO_3 decreased to the lowest value of 25% (Fig. 4).

Sediment grain size

The gravel fraction (> 2 mm) represents about 5 to 10% of the total bottom sediments (dry wt) at the inlet stations of the KL (Fig. 4). At these stations, it consists of rounded, yellow to brown-coated coral debris, small bivalves, and gastropods. In the rest of the lagoon, it is very low or absent, consisting only of small bivalves and gastropods, echinoid fragments, and the larger benthic foraminifera *Sorites*.

The sand fraction (0.063–2 mm) is the highest at the inlet stations of the lagoon, representing about 80% of the total bottom sediments (Fig. 4). It is composed of the same bio-clastics of the gravel fraction, but with a plenty of benthic foraminifera. In the rest of the lagoon, it is very low (15%), enriched with small bivalves and benthic foraminifera and with small components of small gastropods, echinoid fragments/spines, and ostracod shells. At the south-eastern stations, the above components are dominated by the mica flakes.

Mud fraction (> 0.063 mm) is very low (14%) at the inlet stations of the KL (Fig. 4), whereas, in the rest of the stations, it is the highest reaching 90% of the total bottom sediments (dry wt) of the KL.

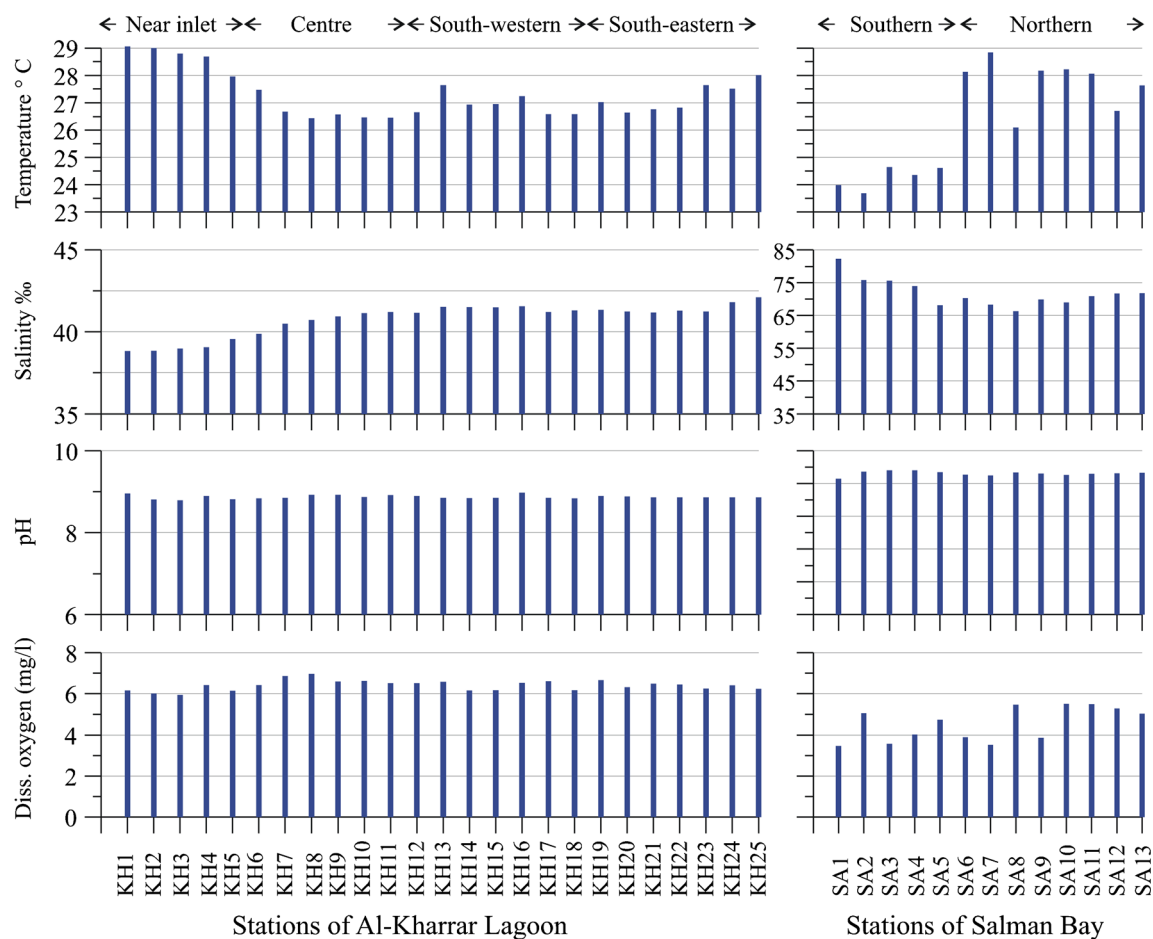


Fig. 2 Distribution of the hydrochemical parameters such as temperature °C, salinity %, pH, and dissolved oxygen (mg/l) in the Al-Kharrar Lagoon and Salman Bay, December 2016

Heavy metals

Fe concentration in the surficial bottom sediments of Al-Kharrar Lagoon (KL) averaged $18,500 \pm 11,200$ mg/kg (Fig. 4). It was the lowest at the northern stations, near the inlet stations, displaying values around 1500 mg/kg. After that, Fe concentration increased gradually as it moves through the lagoon's center and towards the south, reaching concentrations up to 30,000 mg/kg (Fig. 4). At the south-western stations, it showed low values around 10,000 mg/kg, whereas, at the south-eastern stations of the lagoon, highest concentrations of Fe were recorded with values up to 30,000 mg/kg (Fig. 4).

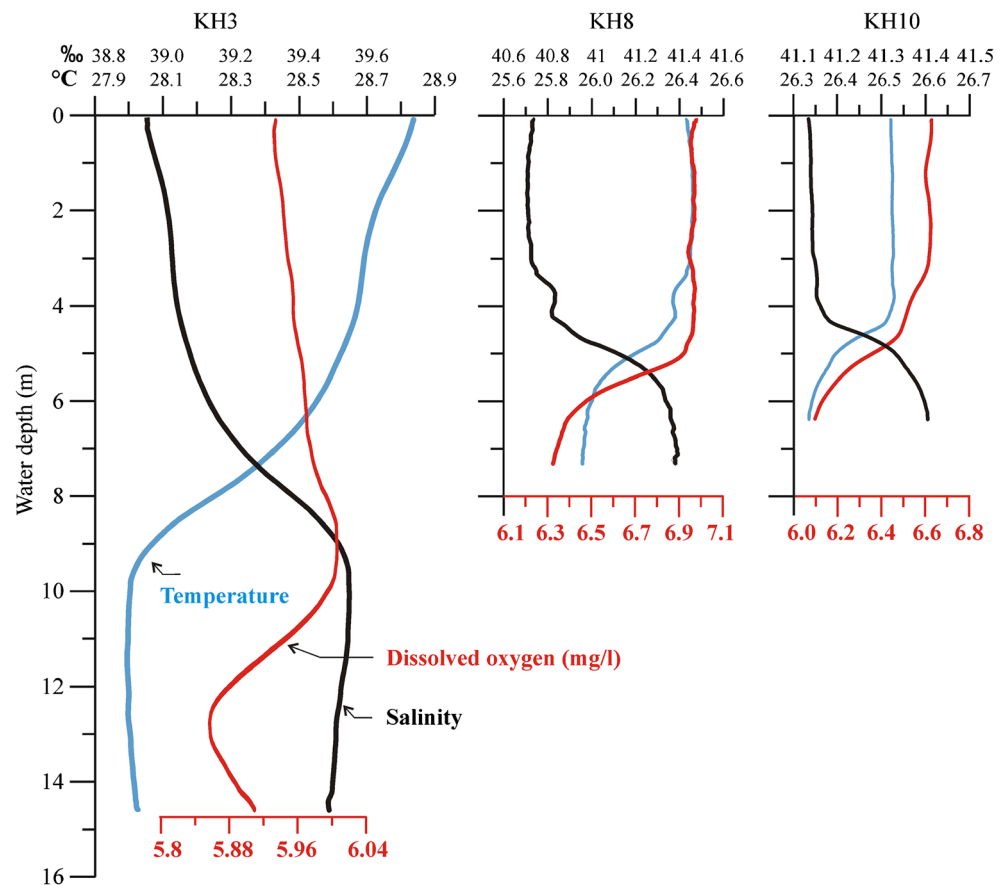
The spatial concentration distribution patterns of the rest of metals (Mn, Zn, Ni, Cu, and Co) in the surficial bottom sediments of KL are very similar to those of the Fe. The concentration of Mn averaged 330 ± 140 mg/kg (Fig. 4). It was the lowest at the northern stations, near the inlet stations, displaying values around 100 mg/kg. After that, Mn concentration increased gradually as it moves through the lagoon's center and towards the south, reaching concentrations up to 400 mg/kg (Fig. 4). At the south-western stations, it showed

low values around 200 mg/kg, whereas, at the south-eastern stations of the lagoon, highest concentrations of Mn were recorded with values up to 500 mg/kg (Fig. 4).

Zn concentration in the surficial bottom sediments of KL averaged 23 ± 15 mg/kg (Fig. 4). It was undetectable at the northern stations, near the inlet stations. After that, Zn concentration increased gradually as it moves towards the lagoon's center, reaching concentrations up to 30 mg/kg (Fig. 4). At the south-western stations, it showed low values around 15 mg/kg, whereas, at the south-eastern stations of the lagoon, highest concentrations of Zn were recorded with values up to 45 mg/kg (Fig. 4).

Ni, Cu, and Co concentrations in the surficial bottom sediments of KL averaged 26 ± 17 , 22 ± 11 and 9 ± 4 mg/kg, respectively (Fig. 4). They were the lowest at the northern stations, near the inlet stations, displaying values around 5 mg/kg. After that, their concentrations increased gradually as it moves through the lagoon's center and towards the south, showing concentrations up to 30, 30, and 14 mg/kg, respectively (Fig. 4). At the south-western stations, they showed low values around 20, 20, and 6 mg/kg, respectively, whereas, at the south-eastern stations of the lagoon, highest concentrations

Fig. 3 Vertical profiles of temperature °C, salinity ‰, and dissolved oxygen (mg/l) in the water column of the Al-Kharrar Lagoon at the stations KH3, KH8, and KH10, December 2016



of Ni, Cu, and Co were recorded with values up to 45, 35, and 14 mg/kg, respectively (Fig. 4).

Pb and Cd were undetected in the surficial sediments of the KL except at station KH15 of the south-western corner of the lagoon; they showed values of 1.3 and 7.8 mg/kg, respectively (Table 2).

Correlation of heavy metals with the hydrogeochemical parameters and sediment grain size

In the ordination plot of the PCA, the components 1 and 2 explain 47 and 16% of the variance, respectively (Fig. 5a). There is a close similarity correlation between the heavy metals Co, Ni, Zn, Mn, Fe, and Cu, and the sediment samples of the south-eastern stations of the KL (Fig. 5a). These heavy metals showed also direct relationships with the hydrochemical parameters such as salinity, dissolved oxygen, and pH. On the other hand, they were inversely correlated with the water temperature and carbonate (CaCO_3), and they showed no correlation with the OC (Fig. 5a).

The heavy metals Pb and Cd showed no relationships with the other heavy metals and hydrogeochemical parameters (Fig. 5a).

The water temperature and carbonates (CaCO_3) showed a close kinship correlation with the sediment samples of the

near inner inlet stations KH1–6 (Fig. 5a). This correlation was also indicated by the R-mode hierarchical cluster analysis (Fig. 5b) and by the matrix of Pearson correlation coefficients (r) (Table 3).

Salman Bay

Hydrogeochemical parameters

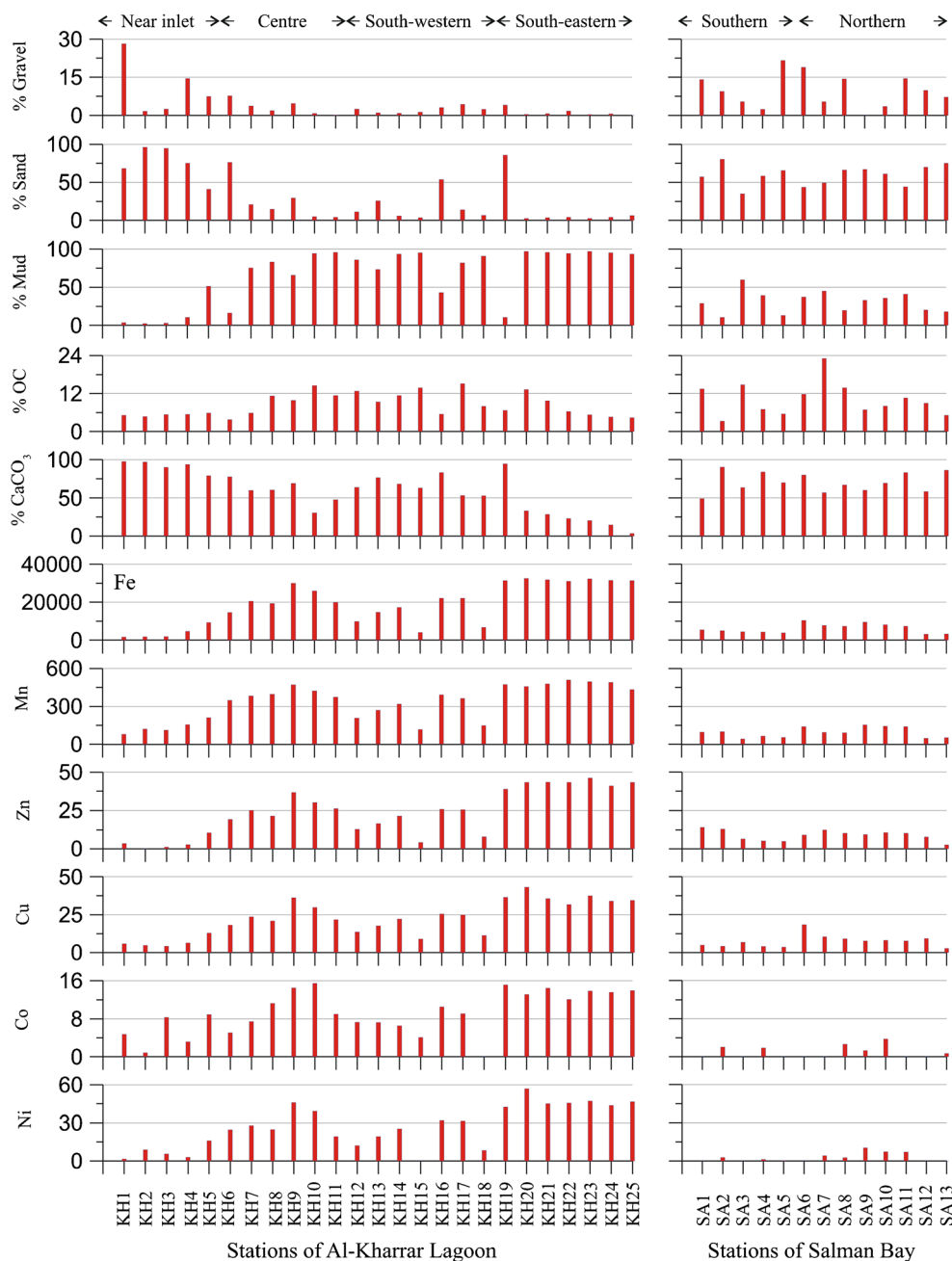
The studied stations of Salman Bay were collected from close to the shoreline at water depths not more than 0.5 m (Table 1). The water temperature averaged 26.4 ± 2 °C during December 2016 (Fig. 2). It was the lowest (24 °C) in southern part of the bay, stations SA1–5, but at the rest of the stations, it was the highest, up to 28 °C.

The water salinity was averaged 71.8 ± 4.2 ‰. Its highest values up to 80 ‰ were recorded in southern part of the bay, stations SA1–4, but at the rest of the stations, the salinity was around 70 ‰ (Fig. 2).

The water pH of the Salman Bay during December 2016 averaged 8.6 ± 0.2 (Fig. 2). It was the highest up to 8.8 at southern stations SA2–5, but at the rest of the stations, it was low displaying a value of 8.55 (Fig. 2).

The dissolved oxygen was low in the Salman Bay showing a mean value of 4.5 ± 0.8 mg/l (Fig. 2). It was, more or less,

Fig. 4 Distribution of % sediment grain sizes (gravel, sand, and mud) % organic carbon (OC), % CaCO₃, and concentrations (mg/kg) of the heavy metals Fe, Mn, Zn, Ni, Cu, Co, Cd, and Pb in the bottom sediments of the Al-Kharrar Lagoon and Salman Bay



the lowest at the southern stations, showing values of 3.5 mg/l, but at northern stations, it increased to 5 mg/l (Fig. 2).

The total LOI organic carbon (OC) and CaCO₃ in the surficial bottom sediments of Salman Bay averaged 10.2 ± 5.3 and $70.7 \pm 13\%$, respectively (Fig. 4). They did not show significant changes between the southern and northern part of the bay (Fig. 4).

Sediment grain size

The gravel fraction (> 2 mm) represents about 10% of the total bottom sediments (dry wt) at the studied stations of the

Salman Bay (Fig. 4). It consists of blackish to white, solidified sediments, with a plenty of small gastropods, mainly of *Cerithium* sp., but the small bivalves are low and restricted to the *Mytilus* sp. At the southern stations, the above components are dominated by evaporitic crystals of gypsum.

The sand fraction (0.063–2 mm) represents about 60% of the total dry wt sediments of the studied stations of the SB (Fig. 4). It is composed of the same materials of the gravel fraction, but with a plenty of reworked benthic foraminifera.

Mud fraction (> 0.063 mm) shows 30% of the total dry wt sediments of the studied stations of the SB (Fig. 4).

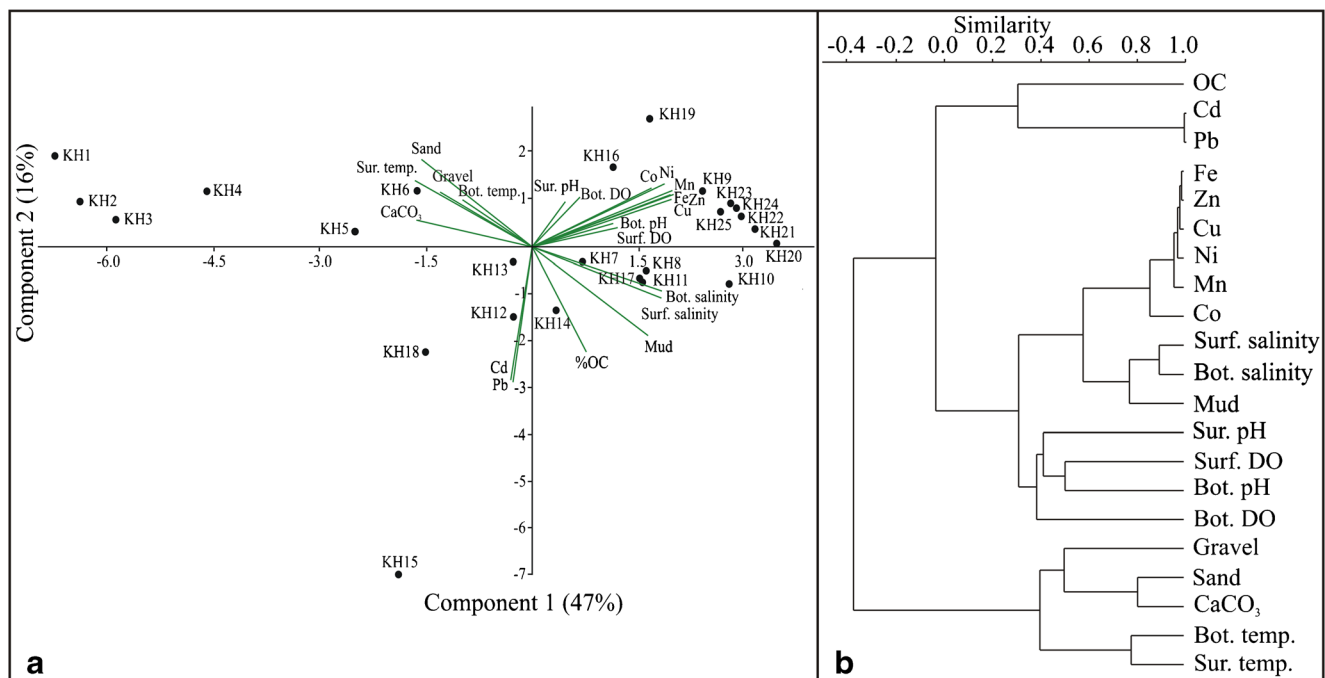


Fig. 5 Plots of the principal component analysis (PCA) (a) and R-mode hierarchical cluster (b) based on the hydrogeochemical parameters, sediment grain sizes, and concentrations of heavy metals of the Al-Kharrar Lagoon

Heavy metals

The distribution of heavy metals in the Salman Bay (SB) divided the bay into southern and northern parts. Fe concentration in the surficial bottom sediments of Salman Bay (SB) averaged 6150 ± 2400 mg/kg (Fig. 4). It was the lowest at the southern stations (stations SA1–5), displaying values around 4000 mg/kg. In the southern part of the SB, Fe concentration increased to 8000 mg/kg, except at the stations 12–13 that showed a value of 2500 mg/kg (Fig. 4).

The concentration distribution patterns of the rest of metals (Mn, Zn, Ni, Cu, and Co) in the surficial bottom sediments of SB are very similar to those of Fe. The concentration of Mn averaged 94 ± 40 mg/kg (Fig. 4). It was the lowest (60 mg/kg) in the surficial sediments of the southern part of the SB, displaying values around 60 mg/kg. In the northern part of the SB, Mn concentration increased to 140 mg/kg, except at the stations SA12–13 that showed value of 40 mg/kg (Fig. 4).

Zn concentration distribution in the surficial bottom sediments of SB averaged 9 ± 3 mg/kg (Fig. 4). It was, more or less, low (5 mg/kg) in surficial sediments of the southern part of the bay, except at the stations SA1–2, the highest concentration 14 mg/kg was recorded. In the northern part of the SB, Zn concentration increased to 10 mg/kg, except at the station SA13 a value of 2 mg/kg was recorded (Fig. 4).

Cu concentration distribution in the surficial bottom sediments of SB averaged 7 ± 4 mg/kg (Fig. 4). It was the lowest at the southern part of the bay, displaying values around 4 mg/kg. In the northern part of the SB, Cu concentration

increased to 8 mg/kg, except at the station SA13 a value of 2 mg/kg was recorded (Fig. 4).

Ni and Co concentrations in the surficial bottom sediments of the southern part of SB were undetectable (Fig. 4). In the northern part of the SB, they increased to the highest values of 8 and 3 mg/kg, respectively (Fig. 4).

Pb and Cd were undetected in the surficial sediments of the SB except at station SA4 of the southern part of the bay, they showed values of 1.8 and 3 mg/kg, respectively (Table 2).

Correlation of heavy metals with the hydrogeochemical parameters and sediment grain size

In the ordination plot of the PCA, the components 1 and 2 explain 29 and 19% of the variance, respectively (Fig. 6a). It shows that the Fe, Mn, Ni, Cu, and Zn have direct relationships with the water temperature, but their relationships with the OC are weak. On the other hand, they are inversely correlated with the water salinity, pH, and CaCO₃ (Fig. 6a). The concentrations of Pb, Cd, and Co were very low or undetectable in the surficial sediments of Salman Bay, but they showed direct relationships with pH, CaCO₃, and DO. On the other hand, they are inversely correlated (or no correlation) with the water salinity, temperature, and the other heavy metals (Fig. 6a). The abovementioned relationships were also indicated by the correlation similarity index of the R-mode hierarchical cluster (Fig. 6b) and by the matrix of Pearson correlation coefficients (*r*) (Table 3).

Table 3 Linear Pearson correlation coefficients (*r*) showing the relationships between the hydrogeochemical parameters (% organic carbon (OC), % CaCO₃, temperature °C, salinity ‰, pH, and dissolved oxygen (DO, mg/l), sediment grain sizes, and the concentration (mg/kg) of heavy metals Fe, Mn, Zn, Ni, Cu, Co, Cd, and Pb in the Al-Kharrar Lagoon and Salman bay. Significant values are indicated by bold

Al-Kharrar	Sur. temp.	Bot. temp.	Sur. salinity	Bot. salinity	Sur. DO	Bot. DO	Sur. pH	Bot. pH	% Gravel	% Sand	% Mud	% OC	% CaCO ₃	Fe	Mn	Zn	Cu	Ni	Pb	Co	Cd	
Sur. temp.	1.00																					
Bot. temp.	0.78	1.00																				
Sur. Salinity	-0.26	1.00																				
Bot. Salinity	-0.51	0.90	1.00																			
Sur. DO	-0.62	0.36	0.51	1.00																		
Bot. DO	-0.21	0.26	0.32	0.36	1.00																	
Surface pH	-0.18	-0.09	0.17	0.13	0.45	0.36	1.00															
Bottom pH	-0.47	-0.33	0.50	0.50	0.51	0.46	0.39	1.00														
% Gravel	0.53	0.21	-0.64	-0.57	-0.14	0.10	0.38	-0.46	1.00													
% Sand	0.70	0.39	-0.76	-0.73	-0.26	-0.01	-0.06	-0.09	0.48	1.00												
% Mud	-0.73	-0.39	0.80	0.75	0.26	-0.01	-0.01	0.15	-0.60	-0.99	1.00											
% OC	-0.67	-0.46	0.40	0.29	0.30	0.04	0.10	0.11	-0.31	-0.55	0.55	1.00										
% CaCO ₃	0.44	-0.14	-0.67	-0.64	-0.12	0.06	0.08	-0.04	0.52	0.81	-0.82	-0.18	1.00									
Fe	-0.53	-0.24	0.69	0.68	0.46	0.32	0.22	0.46	-0.46	-0.50	0.53	0.11	-0.70	1.00								
Mn	-0.56	-0.34	0.64	0.68	0.55	0.34	0.22	0.52	-0.47	-0.46	0.50	0.08	-0.65	0.98	1.00							
Zn	-0.49	-0.19	0.67	0.66	0.39	0.30	0.20	0.40	-0.44	-0.52	0.54	0.06	-0.74	0.99	0.96	1.00						
Cu	-0.54	-0.24	0.68	0.66	0.41	0.29	0.22	0.44	-0.45	-0.50	0.53	0.15	-0.68	0.99	0.95	0.98	1.00					
Ni	-0.45	-0.18	0.60	0.58	0.36	0.25	0.14	0.41	-0.45	-0.43	0.46	0.06	-0.67	0.98	0.95	0.97	0.98	1.00				
Pb	-0.09	-0.02	0.15	0.11	-0.20	-0.15	-0.10	-0.07	-0.09	-0.17	0.17	0.31	0.03	-0.27	-0.31	-0.26	-0.24	-0.33	1.00			
Co	-0.38	-0.16	0.51	0.50	0.41	0.26	0.26	0.36	-0.35	-0.35	0.38	0.14	-0.57	0.88	0.85	0.86	0.86	0.86	0.86	-0.23	1.00	
Cd	-0.09	-0.02	0.15	0.11	-0.20	-0.15	-0.10	-0.07	-0.09	-0.17	0.17	0.31	0.03	-0.27	-0.31	-0.26	-0.24	-0.33	1.00	-0.23	1.00	
Salman Bay																						
Temp.	1.00																					
Salinity	-0.62	1.00																				
DO	0.14	-0.42	1.00																			
pH	-0.33	-0.21	0.21	1.00																		
% Gravel	-0.19	-0.08	0.19	-0.19	1.00																	
% Sand	-0.19	-0.06	0.48	0.10	-0.09	1.00																
% Mud	0.26	0.09	-0.53	-0.01	-0.38	0.89	1.00															
% OC	0.29	-0.08	-0.47	-0.40	0.00	-0.65	0.60	1.00														
% CaCO ₃	-0.06	-0.11	0.43	0.54	0.08	0.21	-0.23	-0.57	1.00													
Fe	0.62	-0.37	-0.16	-0.40	-0.02	-0.36	0.34	0.32	-0.10	1.00												
Mn	0.53	-0.20	0.06	-0.46	-0.05	-0.14	0.15	0.02	0.04	0.89	1.00											
Zn	0.03	0.23	-0.11	-0.63	0.05	-0.07	0.04	0.40	-0.36	0.48	0.57	1.00										
Cu	0.56	-0.36	-0.15	-0.30	0.23	-0.47	0.33	0.46	-0.14	0.72	0.47	0.28	1.00									
Ni	0.54	-0.36	0.18	-0.15	-0.45	0.02	0.19	-0.04	-0.05	0.61	0.76	0.35	0.06	1.00								
Pb	-0.32	0.15	-0.18	0.40	-0.33	-0.02	0.18	-0.18	0.31	-0.23	-0.22	-0.34	-0.25	-0.14	1.00							
Co	-0.01	-0.24	0.46	0.18	-0.39	0.42	-0.20	-0.32	0.24	0.19	0.30	0.14	-0.15	0.41	0.22	1.00						
Cd	-0.27	0.12	-0.13	0.37	-0.38	-0.02	0.19	-0.20	0.31	-0.19	-0.16	-0.31	-0.24	-0.08	0.99	0.33	1.00					

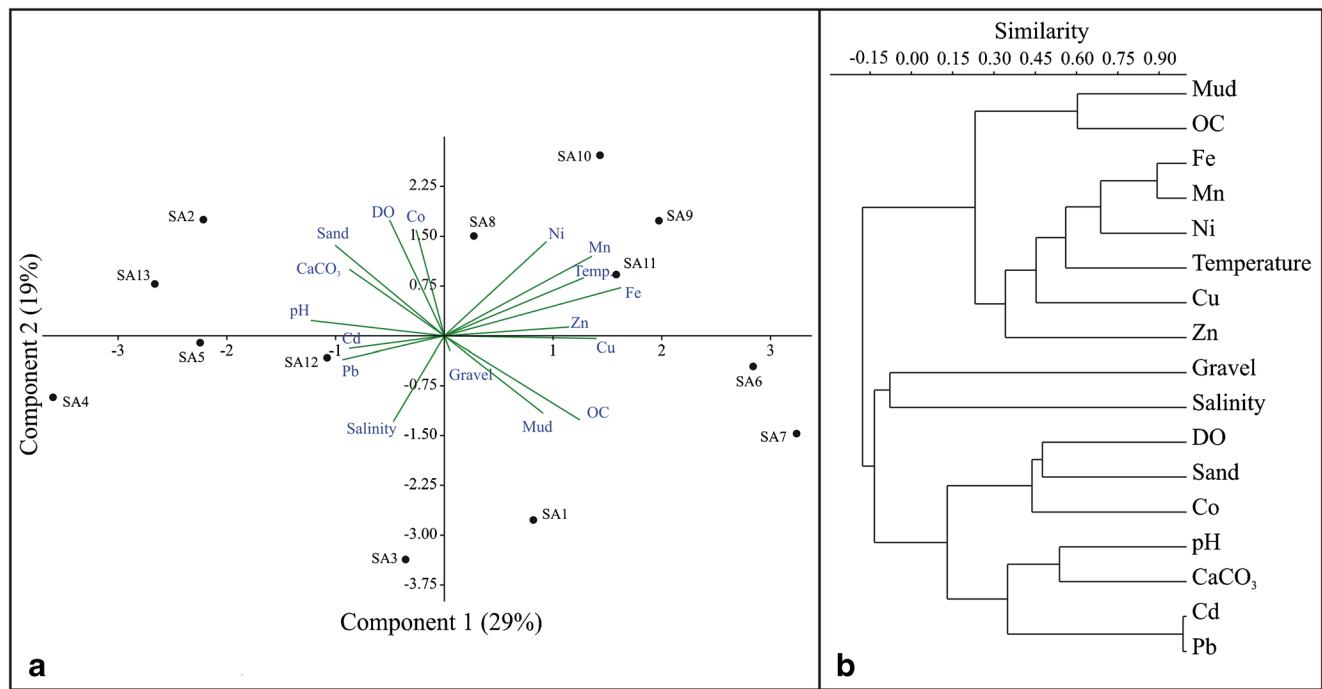


Fig. 6 Plots of the principal component analysis (PCA) (a) and R-mode hierarchical cluster (b) based on the hydrogeochemical parameters, sediment grain sizes, and concentrations of heavy metals of the Salman Bay

Comparison of Al-Kharrar and Salman Lagoons

The Salman Bay (SB) is very shallow water body, whereas the KL has a maximum water depth of 9 m. The water temperature of the SB was lower than of the KL, although its salinity was 72‰. The water salinity of the KL was 41‰. The pH of both of the SB and KL was similar, whereas the DO of the SB was lower than of the KL. The total OC and CaCO₃ of the SB were higher than those of the KL.

The concentrations of Fe, Mn, Zn, and Cu in the surficial sediments of the KL are threefold higher than those of the SB, whereas Ni and Co of KL were 10 times higher than those of the SB. The concentrations of Pb and Cd in the sediments of the SB and KL were very low or undetectable (Table 4).

In Table 4, the heavy metal concentrations (Fe, Mn, Zn, Cu, Ni, Pb, Co, and Cd) in the bottom sediments of the KL are more or less similar to those of lagoonal conditions such as Al-Arbaeen and Al-Shabab inlets (Abu-Zied et al. 2013), Shuaiba and Al-Mejarma lagoons (Basaham et al. 2015), and Sharm Obhur (Ghandour et al. 2014). They showed also a similarity to those of Gulf of Aqaba (Abu-Hilal et al. 1988) and Jizan Shelf (Basaham 2009). In other hand, these concentrations are lower than those recorded for the same area by Basaham et al. (2015) and the world average shale (Turekian and Wedepohl 1961).

The heavy metal concentrations in the shoreline sediments of SB showed, more or less, a similarity to those of the Red Sea coast (Badr et al. 2009; Abu-Zied et al. 2013; Abu-Zied and Hariri 2016; Al-Mur et al. 2017), but they are very low in

comparison with the lagoons of the Red Sea and the world average shale (Table 4).

Heavy metal enrichment/pollution factors

The enrichment factors (EFs) of heavy metals (Mn, Cu, Co, and Ni) in the studied bottom sediment samples of the KL were slightly below 1.5 except at the near-inlet samples (located in the channel of bottom water outflow), they exhibited higher values than the threshold 1.5 value (Fig. 7). In the near-inlet sediment samples, their EFs were the highest showing 3.5, 3.5, > 4, and 6, respectively (Fig. 7). The EF of Zn was around 0.5 in all stations except at the inlet, it increased to 1. The average EFs indicated that the concentration behavior of heavy metals relative to the world average shale in the KL follows this order: Co > Cu > Ni > Mn > Zn (Table 5).

The PLI of the studied bottom sediment samples of the KL was around 0.5, except, at the near-inlet samples, it decreased to 0.0 (Fig. 7).

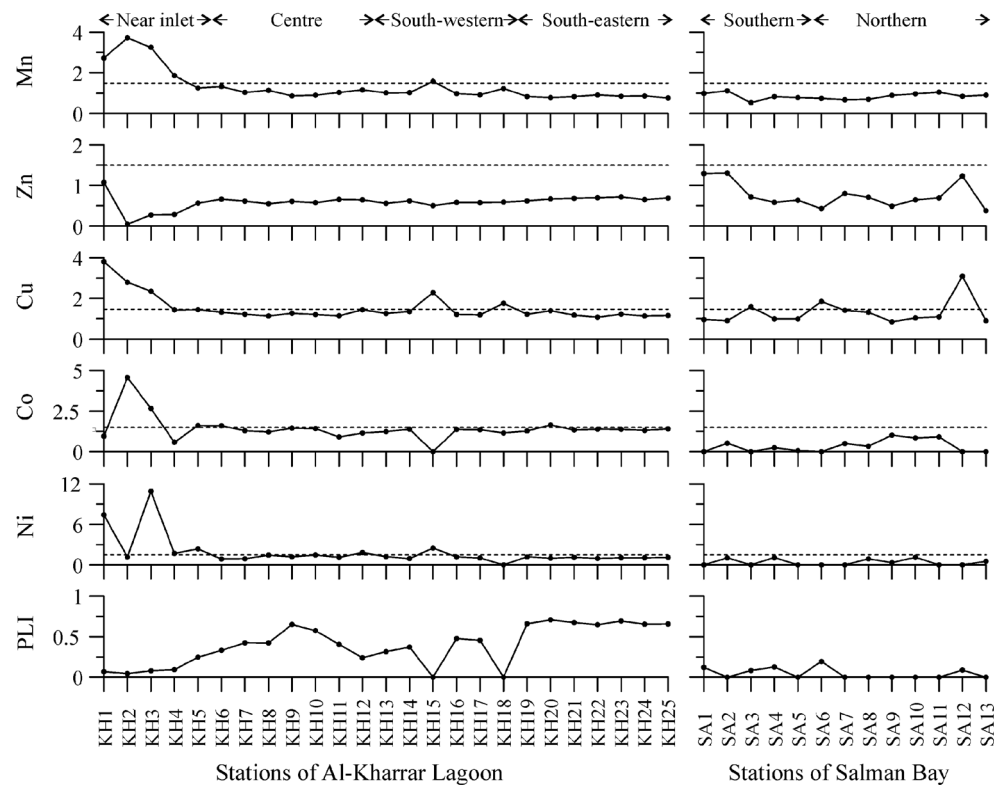
In the Salman Bay (SB), the EFs of the heavy metals (Mn, Cu, and Ni) were also slightly below 1.5, whereas those of the Zn and Co were around 0.5 (Fig. 7). The PLI of the studied sediment samples of the SB was around 0.0 (Table 5). The average EF of heavy metals in the SB follows this order: Cu > Mn > Zn > Co > Ni.

In both of the KL and SB, the average CF was < 1 and average Igeo was lower than 0.0 indicating uncontaminated sediment samples (Table 5).

Table 4 Comparison of average concentrations (mg/kg) of heavy metals Fe, Mn, Zn, Cu, Ni, Co, Cd, and Pb in this study (Al-Kharrar Lagoon and Salman bay) with others in the Red Sea and the world average shale values

Location	Fe	Mn	Zn	Cu	Ni	Pb	Co	Cd	Reference
Al-Kharrar Lagoon	18,734 ± 11,202	328.94 ± 143	23.61 ± 16	22.42 ± 12	26.85 ± 17	0.05 ± 0.25	9.18 ± 4.5	0.31 ± 1.6	This study
Salman Bay	6149 ± 2407	94 ± 40	8.90 ± 3.4	7.45 ± 4.1	2.72 ± 3.5	0.14 ± 0.5	0.94 ± 1.3	0.26 ± 0.82	This study
Jeddah Coast (Al-Arbaceen and Al-Shabab, <i>n</i> = 44)	14,138 (2500–46,900)	151 (20–674)	132 (18–639)	60 (4–323)	53 (27–195)	56 (24–278)		0.7 (0.1–3.5)	Abu-Zied et al. (2013)
Red Sea Coast Hariri (<i>n</i> = 27)	6866 (0–20,000)	162 (3–448)	51 (0–134)	11 (1.8–49)	5 (0–27)	4 (0–65)		0.05 (0–1.1)	Abu-Zied and Hariri (2016)
Jeddah (southern Corniche, <i>n</i> = 58)	1081 (73–6706)	24 (6–129)	23 (3.9–121)	6 (0.5–55)	21 (17–29)	4 (0–21)	18 (10–26)	0.1 (0–0.7)	Abu-Zied et al. (2016)
Shuaiba Lagoon (<i>n</i> = 48)	8921 (34–28,051)	106 (54–203)	11 (0–51)	6 (1–18)	20 (15–29)		29 (15–37)	2	Abu-Zied and Bantan (2015)
Shuaiba Lagoon (<i>n</i> = 22)	16,800 (12500–23,400)	297 (210–500)	31 (21–38)	32 (24–38)	15 (7–37)				Basaham et al. (2015)
Al-Kharrar Lagoon (<i>n</i> = 45)	2249 (1708–3686)	103 (53–225)	40 (30–51)	16 (11–28)	9 (8–10)	51 (40–63)	5 (2–8)	0.26 (0.188–0.33)	Youssef and El-Sorogy (2016)
Al-Kharrar Lagoon (<i>n</i> = 47)	38,000 (14400–63,800)	735 (298–1131)	61 (20–99)	47 (13–64)	50.6 (14–93)				Basaham et al. (2015)
Al-Mejarma Lagoon (<i>n</i> = 20)	20,800 (10900–42,500)	400 (215–771)	44 (20–101)	35 (30–48)	16 (2–40)				Basaham et al. (2015)
Farasan Islands (<i>n</i> = 20)	720 (398–996)	26 (19–31)	6.4 (5–9)	3.6 (3–4)					Bantan and Abu-Zied (2015)
Jeddah Coast (Sediment cores, <i>n</i> = 75)	8506.13	478.45	623.09	251.82		362.75			Al-Mtur et al. (2017)
Red Sea Coast (Jeddah)	2032–2671	34–205	52–76	17–24	68–86	80–99		3.1–3.5	Badr et al. (2009)
Red Sea Coast (Rabigh)	1366–2689	56–251	41–63	17–25	80	82–93		3.1–4	Badr et al. (2009)
Red Sea Coast (Yanbu)	1926–3912	181–413	55–94	18–26	79–91	75–84		2.3–3.6	Badr et al. (2009)
Sharm Obhur (Zone A, <i>n</i> = 14)	44,000 (28000–56,000)	674 (542–929)	82 (54–100)	47 (26–57)	57 (34–73)	5 (0.5–8.5)	16 (9.9–20.4)		Ghandour et al. (2014)
Sharm Obhur (Zone B, <i>n</i> = 27)	23,000(9000–41,000)	359 (155–542)	51 (22–81)	32 (14–49)	23 (4–38)	3 (0.08–8.38)	8 (1.4–13.7)		Ghandour et al. (2014)
Gulf of Aden	2140–2769	138–659	21.9–263	8.1–111	16–48	15–138			Saleh (2006)
Red Sea, Yemen	3078–4236	21–65	89–138	25–39	9.3–15	5.1–8.7			Hassan and Nadia (2000)
Gulf of Aqaba	15,350	246.375	83	16	52	158	39	8	Abu-Hilal et al. (1988)
Jizan Shelf (Sand + Mud)	13,800	311.5	38.5	13	93.5		9		Basaham (2009)
World average shale	47,200	850	95	45	50	20	19	0.3	Turekian and Wedepohl (1961)

Fig. 7 Enrichment factors (EF) of the heavy metals (Fe, Mn, Zn, Ni, Cu, Co, Cd, and Pb) and pollution load index (PLI) in the Al-Kharrar Lagoon and Salman Bay



Discussion

Heavy metals of the Al-Kharrar Lagoon

The Al-Kharrar Lagoon (KL) is very virgin and natural, and it is, up to date, not connected to any source of anthropogenic pollution. Thus, its heavy metal inventory could be originated from the siliciclastic influx through several wadies originated from the upland Al-Hejaz catchments such as: Rabigh (south), Rahab and Murayyikh (east), and Al-Khariq (North) and probably from in situ conditions such as separation from seawaters, authigenic or diagenetic processes. The siliciclastic materials of Wadi Rabigh are no longer reaching the KL since 2009 due to the construction of Rabigh Dam about 35 km east of Rabigh City. This conclusion is testified by comparing the recorded concentrations of heavy metals with the world average shale

background. The enrichment/pollution factors (EF, CF, PLI, and Igeo) applied for the concentrations of heavy metals were lower than the threshold values of these factors, indicating unpolluted, natural conditions for the KL. The average EFs indicated that the concentration behavior (relative to the world average shale) of heavy metals in the surficial bottom sediments of KL follows this order: Co > Cu > Ni > Mn > Zn.

The heavy metals of the surficial bottom sediments of KL could be also influenced by the eolian deposition in the catchment area and by the ability of sediments to bind and release metals that mainly controlled by salinity, pH, cation exchange capacity and organic matter content, redox conditions (Du Laing et al. 2008). Moreover, bacteria and algae play rule in the accumulation of heavy metals into the sediments (Da Costa et al. 2001; Bina et al. 2006; Jackson 2008; Jackson et al. 2011). Some sea-weeds are very efficient in scavenging

Table 5 Average values of the enrichment factor (EF), contamination factor (CF), and index of geoaccumulation (Igeo) of heavy metals in the Al-Kharrar Lagoon and Salman Bay

Location	Fe	Mn	Zn	Cu	Ni	Pb	Co	Cd
Al Kharrar Lagoon								
EF	1	1.32	0.59	1.52	1.42	0.03	1.87	12.01
CF	0.40	0.39	0.25	0.50	0.54	0.00	0.48	1.04
Igeo	-0.72	-0.64	-0.99	-0.56	-0.53	-0.05	-0.52	0.05
Salman Bay								
EF	1	0.85	0.76	1.30	0.34	0.08	0.38	8.97
CF	0.13	0.11	0.09	0.17	0.05	0.01	0.05	0.88
Igeo	-1.09	-1.17	-1.24	-1.01	-0.88	-0.09	-0.55	0.06

the heavy metals, and after death, they decompose contributing to the sediment budget of heavy metals; this is because they are mainly constituted of polysaccharide alginate, usually calcium and sodium alginates which are very efficient in scavenging the heavy metals (Da Costa et al. 2001).

The concentration distribution of the heavy metals Fe, Mn, Zn, Ni, Cu, and Co in the KL showed the same pattern. These metals were the lowest in the sediments of the near-inlet stations and at the south-western stations. On the other hand, they were the highest in the sediments of the lagoon's center and at the southeastern stations, testifying the effect of wadies on the geochemical inventory of the KL. At the near-inlet stations, the concentration of metals was the lowest, indicating that the siliciclastic influx from the surrounding wadies, at the present, was not strong enough to pass through the lagoon's inlet to the open waters of the Red Sea. Another explanation for the low concentration of heavy metals at the near-inlet station sediments could be attributed to the winnowing of bottom sediments which are mainly of coral debris (95% carbonates) by currents so that one important scavenger for heavy metals such as organic matters was the lowest in this channel (the inlet passage). However, the EF of the bottom sediments at the inlet stations showed a striking feature that is the EF values of the Mn, Zn, Cu, Co, and Ni, relative to the world average shale (Turekian and Wedepohl 1961) were the highest, but in the rest of samples, they were the lowest. These high EF values for metals at the inlet stations of the KL could not be anthropogenic but rather a natural biosorption by the polysaccharide alginates of the mucus algae that predominate, covering the coral debris and sand grains in this area. Xu et al. (2015) mentioned that EF value larger than 1.5 could indicate an important proportion of non-crustal materials delivered from either natural processes such as biota and/or anthropogenic influences. Also, a higher level of Zn in the deep-sea sediments of Gulf of Mexico was attributed to long residence time of organic matter in the water column (Armstrong-Altrin et al. 2015).

The statistical analysis (PCA, cluster analysis, and Pearson correlation coefficients) indicated that the metals of the KL sediments have no relationships with the organic carbon of the studied sediments. This may be related to the great influence of terrestrial influx on the concentrations of heavy metals in the lagoon, and most of organic carbon (OC) is short-lived in the lagoon's water column and freshly derived from marine sources such as the decay of algae and sea-grasses (Abu-Zied and Hariri 2016). Ramos-Vázquez et al. (2017) concluded that the river-influenced coastal areas are considered as active interfaces between the continental and oceanic environments, which have huge dispersal of detrital, fine-grained sediments enriched in heavy metals.

Also, these organic matters may not be partially oxidized to form complexes attractive to heavy metals due to occurrence of highly oxygenated water. Inside the Al-Arbaeen and Al-Shabab inlets (Jeddah's coast), the concentrations of Fe and Mn showed

an inverse relationship with the OC due to the occurrence of reducing conditions so the bottom sediments exporting Fe-Mn to the waters, whereas outside the inlets, the OC showed a direct relationship with Fe-Mn due to the occurrence of oxidizing conditions leading to fixation of Fe and Mn into the sediments (Abu-Zied et al. 2013). The OC was inversely correlated with gravel and sand sediments, but with a direct correlation with the mud fraction which showed positive relationships with heavy metals such as Fe, Mn, Zn, Cu, and Ni. However, with a plenty of dissolved oxygen in the KL, the organic matters are a favorable place for aerobic bacteria to play an important role in metal fixation. Jackson et al. (2011) discussed that most bacteria play a role in the variations of element distribution and relationships controlling diagenesis, precipitating oxides, degradation of adsorbed clay, and synthesis of intracellular and extracellular clay. They also reported that Fe oxides precipitated abiotically and indiscriminately on bacteria and minerals, but Mn oxides were purely biogenic, precipitating only on certain bacteria. Thus, it is possible that the occurrence of plenty of Fe-Mn oxides and high oxygenated waters in the KL may be deleterious on the role of organic matter for fixation or precipitation of heavy metals in the bottom sediments of the KL. On the other hand, the heavy metals showed an opposite relationships with the water temperature and CaCO_3 .

The heavy metals (Fe, Mn, Zn, Ni, Cu, and Co) and the hydrochemical parameters (salinity, dissolved oxygen, and pH) are positively correlated. Taking in our mind that the mean source of these metals is via wadies influx, this means that these metals come to the Al-Kharrar Lagoon (KL) as detrital, colloidal, or soluble substances (as reduced forms with lower oxidation state) in a freshwater medium. Once these substances, specially the soluble substances, reach high saline, alkaline waters of the lagoon, they get oxidized and precipitated immediately near the lagoon's shoreline or spread far away from it depending on the magnitude of flood events. Takáč et al. (2009) reported that the decreased availability of metals is affected by higher adsorption and precipitation in alkaline and neutral environments. Also, the dissolution of heavy metals in sediment pore-waters from minerals and their availability in a solution decreased with increasing pH (Buykx et al. 2002).

The direct relationship of DO with the heavy metals is apparent, giving information about the redox potential in the KL that may need a further study due to its control on the bio-availability of these metals in the lagoon's water. Violante et al. (2010) reported that redox reactions, both biotic and abiotic, are of great importance in controlling the oxidation state and thus, the mobility and the toxicity of many heavy elements depending on the particular metal species and microenvironments. During this study (winter), the bottom water of KL was well ventilated with DO not less than 5 mg/l; thus, any humic substances carrying heavy metals get readily oxidized and precipitated on the lagoon's bed. The surficial bottom sediments of the KL have high load of heavy metals, for example; the

concentrations of Fe, Mn, Ni, Zn, Cu, and Co were $18,734 \pm 11,202$, 328.94 ± 143 , 26.85 ± 17 , 23.61 ± 16 , 22.42 ± 12 , 9.18 ± 4.5 mg/kg, respectively. These concentrations are higher than those of the eastern Red Sea coast sediments (Badr et al. 2009; Abu-Zied and Hariri 2016; Abu-Zied et al. 2016; Al-Mur et al. 2017), so under reducing conditions, they may be more mobile, exporting bio-reactive metals into the lagoon's water. However, the highest concentrations of Fe and Mn may be advantageous for the fixation of extra heavy metals into the lagoon sediments, since they have very high adsorptive capacity (Violante et al. 2008; Marchand et al. 2011; Abu-Zied et al. 2013). But, if the precipitates formed during oxidative precipitation are nanoparticulate and colloidal, they may greatly enhance the mobility of associated trace metals in aquatic and subsurface environments (Violante et al. 2010). Therefore, the KL acts as a buffer zone, preventing heavy metals from dispersion into the Red Sea waters. Kuriata-Potasznik et al. (2016) mentioned that natural lakes, connected to rivers, can counteract stress by temporarily removing toxic metals from circulation and depositing them mostly around the delta, where heavy metals undergo an array of biogeochemical processes on natural reactive surfaces such as surfaces of clay minerals, metal oxides and oxyhydroxides, humic substances, plant roots, and microbes.

The mean concentration of heavy metals in the surficial bottom sediments of the KL is twofold lower than those recorded by Basaham et al. (2015) and higher than those recorded by Youssef and El-Sorogy (2016) in the same lagoon (Table 4). This is because authors did not use the surficial (upper 2 cm) bottom sediments as this study did or may be as a result of using different analytical techniques. They are, more or less, similar to those of the lagoonal systems such as Sharm Obhur (Ghandour et al. 2014), Al-Mejarma and Shuaiba (Basaham et al. 2015). On the other hand, the heavy metals of the KL (this study) are threefold higher (especially Fe and Mn) than those of the open shoreline sediments of the eastern Red Sea coast (Abu-Zied and Hariri 2016; Abu-Zied et al. 2016; Al-Mur et al. 2017) and those of the surficial sediments of the Salman Bay (this study). This testifies that the lagoons of the Red Sea act as a filter inhibiting the dispersion of a high quantity of heavy metals into the open waters of the Red Sea. Vodyanitskii (2010) concluded that iron compounds are used as ameliorating agents and geochemical barriers for fixing heavy elements. The concentrations of Ni and Co in the KL were 10 times higher than those of the Salman Bay, whereas the concentrations of Pb and Cd in the sediments of the both of SB and KL were very low or undetectable, indicating that no industrial effluents enter these water bodies and their pristine natural conditions are still unaffected.

Heavy metals of the Salman Bay

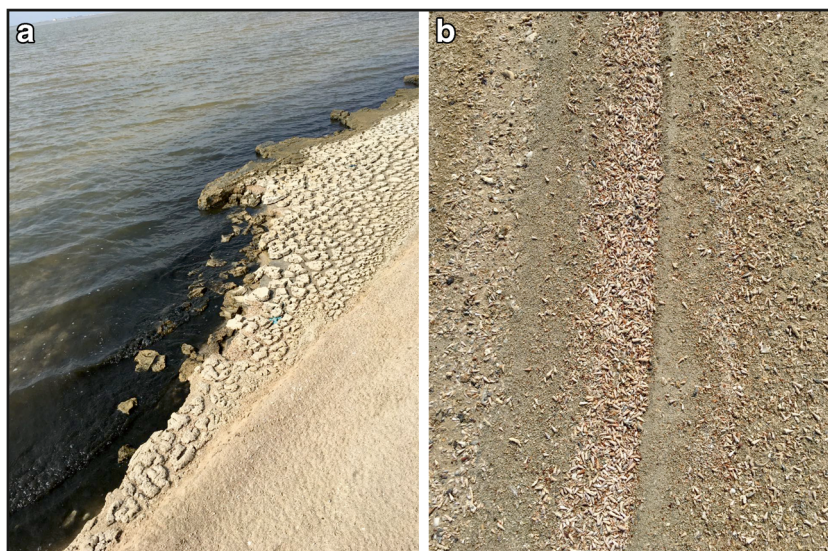
The Salman Bay (SB) is nearly closed, very shallow water body with very high salinity up to 76‰. It is not directly

connected to the siliciclastic materials of the catchment area. Therefore, its heavy metals may originate from marine, atmospheric sources and water runoff (winter rainfalls) from adjoining alluvium. The concentration of heavy metals in SB shoreline sediments is threefold lower than those of the Al-Kharrar Lagoon, but they are, more or less, similar to those of the open shoreline sediments of the eastern Red Sea coast (Abu-Zied and Hariri 2016; Abu-Zied et al. 2016; Al-Mur et al. 2017), in spite of the spread of thick layer of black sludge emitting bad odors at the studied sites (Fig. 8a). This means that this black layer of sludge could be mainly derived from the decay of algal mats that after death, they get drift by wind and current to accumulate on the eastern shoreline of the bay; they do not accumulate on the western side of the bay. In fact, there is one or couple houses at the western coast of the bay, but field observations could not attribute this black sludge to wastewaters of these houses. To confirm that this black sludge is attributed whether to natural or anthropogenic conditions, stable isotopes of nitrogen ($\delta^{15}\text{N}$) in the organic matters should be carried out in a further study. The EF, CF, PLI, and Igeo of the heavy metals in the shoreline sediments of SB showed also very low values, suggesting that these sediments may occur in uncontaminated conditions. The average EF indicated that the concentration behavior (relative to the world average shale) of heavy metals in the surficial bottom sediments of SB follows this order: $\text{Cu} > \text{Mn} > \text{Zn} > \text{Co} > \text{Ni}$. The heavy metal concentrations in the shoreline sediments of SB was much lower than those recorded by Youssef (2015) in the same area, due probably to his extraction of heavy metals only from the shells of calcareous benthic foraminifera.

The spatial distribution of hydrogeochemical parameters and heavy metals in the shoreline sediments of SB have divided the bay into southern and northern parts. This division is also indicated by the Q-mode hierarchical cluster (Fig. 9). The concentrations of Fe, Mn, Zn, Cu, and Ni were the highest in the sediments of the northern part of the bay and decreased to lower values in the southern part, following the trend of water temperature that increased towards the northern part. These distribution concentrations of heavy metals were in opposite correlations with water salinity and pH which were the highest in the southern part; also, the $\text{CaCO}_3\%$ showed an inverse relationship with the heavy metals. Moreover, the OC and DO showed no relationships with the heavy metals, except Zn and Cu showed a weak correlation with the OC.

First, the inverse correlation between heavy metals and the shoreline sediment carbonates (CaCO_3) of Salman Bay could be normal due to its dilutive effect where the carbonates in the bulk sediments were around 71% and contain a considerable amount of biogenic components such as small gastropods that tolerate the high salinity (76‰) of the bay (Fig. 8b). Second, the inverse correlation between heavy metals and water parameters of SB such as salinity and pH is elusive. It is possible that

Fig. 8 Field photos from the Salman Bay. Black sludge (a) and shingle of small gastropods (b) spread on the eastern beach



the high salinity (brine) of the SB leads to formation of many soluble salts preventing precipitation of heavy metals into the sediments, and hence, they get disposed into the sea via the inlet. Also, the precipitation of a high quantity of mineral salts may act a dilution factor as carbonates do. However, some results pointed out that the availability of reactive heavy metals increased in the pore water of the sediments with increasing salinity (McLaughlin et al. 1994; Kadkhodaie et al. 2012). Du Laing et al. (2008) mentioned that increasing organic matter and clay contents and sulfide contents were found to enhance metal accumulation in the intertidal sediments, whereas higher salinities resulted in reduced metal accumulation. Also,

increasing metal mobilization with increasing salinities was demonstrated by both of the laboratory (Paalman et al. 1994) and field experiments (Hatje et al. 2003). So, the SB brine ions could prevent heavy metals to precipitate into the sediments, leading to the occurrence of inverse relationships between metals in sediments and water salinity of the Salman Bay.

The water temperature in both of the Al-Kharrar Lagoon and Salman Bay behaved with the heavy metals in two opposite ways, showing an inverse correlation in the KL and direct correlation in the SB. This indicates that each environment has its own geological, physical, and biological characters interacting with the chemical species to give, at the ultimate, the geochemical inventory of the environment. For example, the accumulation of heavy metals in the sediments of each environment is determined by an input amount from rivers, atmosphere or industrial and domestic waste, and the ability of sediment to bind and release metals (Du Laing et al. 2008). All of these processes are governed by certain biogeochemical processes on natural reactive surfaces such as surfaces of clay minerals, metal oxides and oxyhydroxides, humic substances, plant roots, microbes (Jackson 2008; Kuriata-Potasznik et al. 2016), sediment characteristics such as pH, cation exchange capacity and organic matter content, redox conditions, and chloride content (Du Laing et al. 2008).

The southern part of Salman Bay of the highest salinity showed a lower temperature than that recorded in the northern part by about 3 °C. The explanation for this could be related to the effect of brine water (salinity > 50‰) on temperature which decreases when salinity of the brine increases.

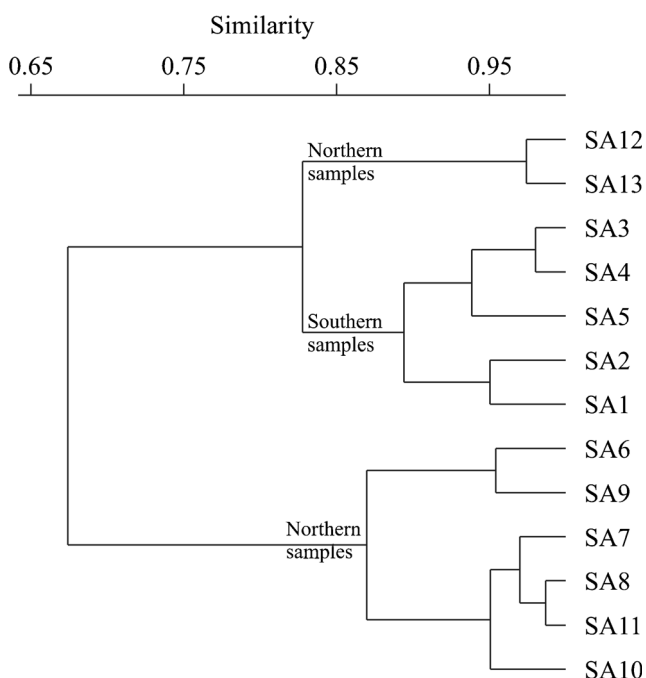


Fig. 9 Plot of Q-mode hierarchical cluster of Salman Bay data, using Bray-Curtis similarity and UPGMA algorithm

Conclusions

The concentrations of heavy metals Fe, Mn, Ni, Zn, Cu, Co, Cd, and Pb were studied in the bottom sediments of the Al-

Kharrar Lagoon (KL) and Salman Bay (SB) and correlated with the hydrogeochemical parameters and sediment grain sizes. In the KL, the concentrations of metals were the highest in the center and southeastern stations where the influx of heavy metal-rich siliciclastics from wadies dominated, but they were low in the sediments of the near-inlet stations.

Also, the occurrence of hypersaline, high pH, and dissolved oxygen conditions in the lagoon could favor the oxidation and precipitation of soluble heavy metals near the lagoon's shoreline or could spread far away depending on the magnitude of the flood events.

In the KL, the metals were also directly correlated with Fe and Mn, but with no relationships with the organic carbon due probably to the occurrence of a plenty of Fe-Mn oxides and highly oxygenated waters that could affect the role of organic matters to form complexes readily for fixation and precipitation of heavy metals into the lagoon's sediments. Where, all metals showed positive relationships with the dissolved oxygen and muddy sediments.

The EF of metals in the bottom sediments of the KL were the highest at the inlet sediments, due probably to a natural biosorption by the polysaccharide alginates of the mucus algae that cover the coral debris and sand grains in this area. In the rest of sediment samples, the EF were the lowest far below the threshold level, indicating that the KL was influenced mainly by natural processes. Also, the CF, PLI, and Igeo showed very low values, categorizing the KL under uncontaminated conditions.

The concentrations of Fe-Mn and Ni-Co in the sediments of KL were threefold and 10 times higher than those of the Salman Bay, respectively, whereas the concentrations of Pb and Cd in the sediments of the SB were undetectable, indicating that no industrial effluents enter this water body. The occurrence of black sludge on the eastern shoreline of SB may be related to the decay of algal mats, a natural process, since the concentrations of heavy metals in this sludge and their CF, PLI, and Igeo values were very low. The metals of the SB showed a positive relationship with temperature and no relationships with DO, OC, carbonate, and sediment grain size, but with an inverse relationship with salinity. The brine water of the SB showed an adverse effect on the concentrations of heavy metals in the sediments of the bay due to the occurrence of many soluble salts that could preclude precipitation of heavy metals into the sediments.

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