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Assessment of heavy metal contamination in Gulf of Gabès coastland (southeastern Tunisia): impact of chemical industries and drift currents

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Abstract

The present work investigates the aspects of anthropogenic contamination in the littoral zone of Gabès city (Tunisia). Special interest was addressed to the effects of chemical industries and coastal dynamics on the pollutant input and distribution along the coast. As a first step, 16 superficial sediment samples were collected including 8 items on the beach and 8 in the intertidal zone. Subsequently, geochemical and granulometric analyses were carried out. Heavy metals (Zn, Cu, Pb, and Cd) as well as sulfates, phosphorus, chlorine, sodium, calcium, bromine, and the percentage of the fine fraction were quantified in all samples. Two approaches were adopted for the interpretation of results. The first descriptive approach revealed that the coastline is subjected to fairly significant anthropogenic pressure. Results showed that the littoral zone is highly contaminated by various toxic elements, notably heavy metals. It seems that the coastal dynamics have a major contribution in the transport and deposition of several contaminants. The second approach allowed identifying the potential origins of pollutants based on a principal component analysis. Results proved that the impact of releases from chemical industries is the most significant. More efforts are required to investigate the mechanisms of ion transfer and exchange between pollutants and the various media such as sediments, water, and air.

Keywords Contamination · Littoral · Anthropogenic activities · Heavy metals · Gabès · Tunisia

Introduction

The littoral is not only highly valuable but also a coveted area where transport infrastructures, tourist complexes, and industrial installations are agglomerated. The vulnerability of the natural littoral to an input of contaminants is mainly related to its own properties and its capacity to reduce the anthropogenic stress. In industrial zones, littoral areas have continually been subjected to the influence of several wastewater discharges. The study of pollutants' geochemical behavior in the littoral sedimentary system permits the identification of their biogeochemical mechanisms.

Since the industrial revolution, the anthropogenic input into aquatic environments has increased steadily both in terms of variety and concentrations. Water sediments and biota are major components in the accumulation and transport of contaminants. Several research studies dealing with coastal contamination have been issued in recent years (Balassone et al. 2016, Tranchida et al. 2011; Pérez-Lopez et al. 2011; El-Sorogy and Youssef 2015; Tang et al. 2013). Research issues concerned types of pollutants, origins, modes of transport, receiving environments, accumulation processes, dispersal mechanisms, mitigation processes, and methods for assessing contamination levels. Particular interest has been given to the contamination of marine sediments due to heavy metals coming, especially from phosphogypsum (El-Amier et al. 2017; Sainz and Ruiz 2006; Pérez-Lopez et al. 2011; Ikem and

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Adisa 2011; Pérez-Lopez et al. 2016). The list of pollutants identified in the water environments is fairly consistent. Heavy metals such as Cu, Zn, Mn, Ni, Pb, Cd, Cr, and Hg were mentioned by several authors (Gorinstein et al. 2006; Kaimoussi et al. 2004; El-Sorogy and Youssef 2015; Yaylali-Abanuz 2011). Marine sediments are not only a reservoir for these pollutants but also a natural indicator of their exchange and transport between the atmosphere, hydrosphere, and biomass (Yaylali-Abanuz 2011). Heavy metals accumulated in superficial sediments can be transferred to the water environment through a number of processes such as pH and redox potential (Pejman et al. 2015). Industrial waste rich in heavy metals, such as phosphogypsum, can be transported by the wind to the receiving environment and cause a more or less serious contamination (Pérez-Lopez et al. 2015). However, runoff is a major process in transporting heavy metals to the aquatic environment such as rivers, lakes, and lagoons (Song et al. 2010). Marine currents are very important vectors for the transport and accumulation of pollutants in the marine environment (Kim et al. 2013; Kharroubi et al. 2012). Rich in heavy metals, pollutants that accumulate in the aquatic environment are often ingested by the fauna and thus included in the food chain (El-Sorogy and Youssef 2015; Rodriguez-Ariza et al. 1993). A lot of hydrodynamic, biogeochemical, and physical processes determine the distribution and enrichment of various pollutants in the receiving environment. Some of these processes are well known while others remain to be identified. In this context, the spatio-temporal distribution of contaminants in the marine environment is often influenced by trapping processes (Tranchida et al. 2011), solubility, oxidation, and redox potential change (Pérez-Lopez et al. 2011), through acidification and pH variation processes (Wu et al. 2015; Pejman et al. 2015), adsorption mechanisms (Brennecke et al. 2016), and by reaction with other pollutants (Ma et al. 2016). Pollutants accumulated in superficial sediments can be transferred to the liquid phase by chemical processes such as pH change, sediment suspension, and contaminated marine species (Pejman et al. 2015). Polluted sediments can be moved far from origin by sea currents and the effect of tides and waves (Kharroubi et al. 2012).

Anthropogenic pressure along the Mediterranean coastline is one of the principal sources of contamination. It is considered a threat to human health and marine biodiversity (Rabaoui et al. 2013). The phosphate industry is one of the principal origins of marine pollution in Gabès due to the untreated phosphogypsum discharged into the sea. Areas near the chemical complex are widely affected by anthropogenic pollution coming from the phosphate transformation industry (El Kateb et al. 2018). In Gabès city, the spatial distribution of contaminants seems to be the effect of the harbor's position and the coastal currents (El Zrelli et al. 2015). The central part of the Gabès city was found to be the most polluted compared to northern and southern areas. High sediment enrichment

with heavy metals was observed along the coast of Gabès city (Rabaoui et al. 2014; El Zrelli et al. 2018a, b; Ayadi et al. 2015.)

Many coastal areas were affected due to anthropogenic activities in Tunisia. The littoral zone stretching from Sfax town to Boughrara lagoon is subject to a massive pollution coming from the phosphate processing industry (Kharroubi et al. 2011; Serbaji et al. 2012). It has been shown that coastal superficial sediments were widely contaminated due to many anthropogenic pollution sources. Numerical methods such as principal component analysis (PCA), hierarchical cluster, and geoaccumulation index can widely help to identify potential sources of contamination and determine contamination levels (Bahloul et al. 2018). Heavy metal contamination was observed along the coastline between Sfax and Gabès. The comparison of their concentration with values in natural marine sediment indicated a significant contribution of multiple anthropogenic sources (Ghannem et al. 2014; Guargouri et al. 2011). Pollution inputs in this area were mainly attributed to chemical industries. The phosphogypsum mud widely discharged in the sea is the principal source of coastal contamination. Phosphate transformation industries generate more than 10,000 tons/day of phosphogypsum wastes highly enriched with heavy metals (Kharroubi et al. 2012). However, the diversity of different approaches applied does not allow a comparison of the various results obtained. Considering the socio-economic sensitivity of the problem, it seems that some data provided by industrial laboratories are biased and take into account the sensitivity of the subject.

The present study reports the major results of interdisciplinary research focused on the impact of anthropogenic activities on the environmental quality of the Gabès city coast through the analysis of geochemical and physical aspects of superficial sediments collected from both intertidal and supratidal selected areas. Particular interest is attributed to the effect of industrial discharges on the degradation of the Gabès coastline. Various approaches like geochemical and statistical analyses are available for this study. The role of marine currents was taken into account to understand the spatial distribution of the various pollutants along the coastal line of Gabès city.

Materials and methods

Study area

The Gulf of Gabès is located in Southeastern Tunisia. It is a large platform limited to the north by the Kerkennah archipelago, to the south by the Tunisia-Libyan border and to the east by the isobath–200 m located more than 250 km from the coast (Bellaiche and Blanpied 1979). This platform is characterized by a low slope and low bathymetry (Bellaiche and Blanpied 1979). The field of study corresponds to the

coastline of the city of Gabès. It extends from Limawa in the south to Ghannouch to the north, along a distance of about 10 km of coastline (Fig.1). It has a privileged geographical position in southern Tunisia, constituting an important crossing point between the South and the other regions of the country. This location has allowed it to develop exchange flows on national and international scales. The natural resources of this region consist mainly of groundwater allowing the development of a major agricultural activity, an industrial area of 536 ha located at Ghannouch. The chemical industry accounts for most of the industrial activity. The production of phosphate by-products is in the order of 1340 million tons. This plant contributes irreproachably to the economic and social developments of the region but generates about 13,000 tons/day of phosphogypsum discharged without any treatment in the sea. Fishery resources are also a basic component of the region's economic activity, producing around 6500 tons per year (1980–2000).

Sampling and analyses

A total of sixteen samples were collected along the littoral of the study area. In each site, two samples were collected from the intertidal and supratidal zones (Fig. 1). Samples were collected in plastic bags and conserved in a fridge before analysis. In order to quantify the various elements in each sample (Cl, Na, Ca, Br, S, P, Zn, Cu, Pb, Cd), it was necessary to transform them into the ionic phase. The dissolution and digestion of the matrix of the various samples were provided by a microwave digester system (Milestone). Microwave mineralization is often adopted for solid elements such as superficial

sediments and rocks in order to dissolve the various elements contained in the solid matrix for subsequent analysis by liquid phase measurement systems. The microwave digestion system has made it possible to overcome the disadvantages of acid mineralization in terms of analytical precision, coast, and preparation speed. The procedure undertaken in the ISSTEG laboratory consists of mixing 2 g of sediment with 32 mL of nitric acid (65% concentration) and 20 mL of hydrochloric acid (37% concentration). Thereafter, the mixture was introduced in the microwave. The complete mineralization process was reached after 2 h of digestion. Finally, the obtained mud was diluted and filtered to obtain a clean solution ready to be analyzed. Polarography is a common technique to measure concentrations of heavy metals in the liquid phase. This method is based on a voltammeter device using electrodes and drops of mercury. The fundamental principle of this method was based on the analysis of oxidation and reduction in the liquid phase. It is an electrochemical process whose principle is the quantification of electron transfers during a chemical reaction. The detection limit of this method can reach the μg scale and depends on the calibration interval. In our case study, the zinc, lead, copper, and cadmium contents were quantified for the sixteen samples. The various major elements were measured for the solutions obtained after the digestion by microwaves using the technique of ion chromatography in the liquid phase (Metrohm 850 Professional IC). The chromatography method is based on the quantification of ion exchange between a solution and an ion exchange resin. Ion exchangers are insoluble macromolecules bearing ionizable groups which have the ability to reversibly exchange some of their ions when in contact with ions emanating from the

Fig. 1 Location map of study area and samples
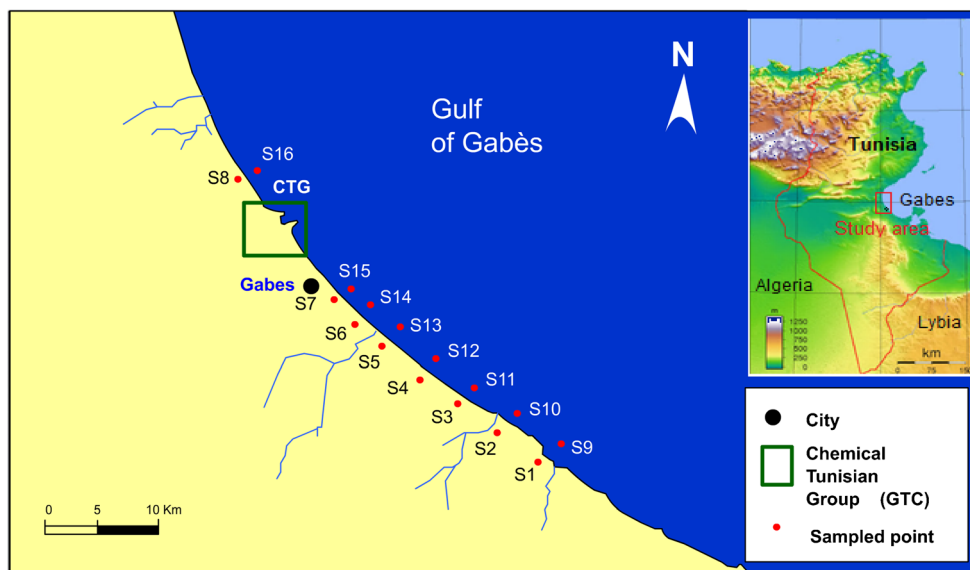
sample to be analyzed. The detection limit of this method can reach μg. The concentration of the following elements was measured for the sixteen samples concerned: Cl, Br, P, S, Na, and Ca. The fine fraction was quantified for the sixteen samples by wet sieving. A sample of 200 g is put in a sieve whose mesh is 63 μm. Subsequently, the fine fraction was recovered in a beaker and placed in an oven until total water evaporation. Subsequently, the fine fraction was weighed and its mass was determined. The percentage of the fine fraction was calculated by the ratio of the mass of the latter to the total mass of the sample (200 g).

Principal compound analysis

Principal component analysis (PCA) is a statistical method applied to study a large number of individuals and variables. It makes it possible to highlight the degree of correlations between the various individuals and variables. It is often used for complex data processing. The interpretation of the various projections makes it possible to understand the structure of the data and subsequently the affinities between the various variables and individuals. In our case, this method was used to possibly identify potential sources of contamination and affinities between various contaminants. The results obtained were represented in the form of a correlation and projection matrix on the factorial planes.

Contamination factor, index of geoaccumulation, and pollution load index

Contamination factor (C_f), index of geoaccumulation (I_{geo}), and pollution load index (PLI) were commonly computed to evaluate degrees of contamination in the study area. They were used to reveal a global contamination level of the whole area but not for each sample (Yaylali-Abanuz 2011). In our case, these indicators were calculated for heavy metals (Cu, Zn, Pb, and Cd) in all sampling sites which allowed characterizing the spatial distribution of contamination degree.

Contamination factor

The contamination factor (C_f) was calculated using the following relation:

$$C_f = C_i/C_c \tag{1}$$

where C_i is the metal content in the sample i and C_c is the concentration of the examined element in the earth's crust (Table 1). According to Hakanson (1980), the contamination vulnerability can be classified as a function of C_f below:

Table 1 Concentration of heavy metals in the crust and the sediment (Hakanson 1980)

Element	Concentration in the crust[1] (mg kg^{-1})	Concentration in the sediment[2] (mg kg^{-1})
Cu	50	41
Zn	77	39
Pb	14	18
Cd	0.11	5.5

$C_f < 1$, low contamination
$1 < C_f < 3$, moderate contamination
$3 < C_f < 6$, considerable contamination
$C_f > 6$, very high contamination

Index of geoaccumulation

The index of geoaccumulation permitted the pollution level estimation taking as reference the elements' content before contamination. It was computed using the following equation:

$$I_{geo} = log_2\left(C_i/(1,5C_b)\right) \tag{2}$$

where C_i is the metal content in the sample i and C_b is the geochemical background value before contamination (Table 1).

Pollution load index

The pollution load index (PLI) was calculated for each element using the following relation:

$$PLI = \left(C_f^1 x C_f^2 x.....x C_f^n\right)^{1/n} \tag{3}$$

where C_f^1 is the C_f of sample i.

PLI is a contamination indicator used to reveal a general contamination level of the whole studied area. PLI values over 1 indicate the existence of contamination and its absence otherwise (Pejman et al. 2015).

m-ERM quotient

According to (Long and MacDonald 1998; Long et al. 2006), it is possible to calculate a global indicator which makes it possible to establish a good evaluation of contamination level taking into account all heavy metal concentrations measured in the studied area. This method permits to quantify the impact of all metals, simultaneously, on the contamination of the studied area. The computed m-ERM value is given using the following relation:

$$m-ERM = \frac{\sum_{i=1}^{n} \left(\frac{C_i}{ERM_i} \right)}{n} \qquad (4)$$

where C_i is the metal (i) concentration, ERM_i is the ERM value of metal (i), and n is the number of metals.

Results and discussion

The main objective of this study was to discern the contamination processes of coastal environments in the city of Gabès subjected to significant anthropogenic pressures. Particular interest was attributed to the spatial distribution of pollutants and in the transport and accumulation of pollutants. Heavy metals from industrial sludge discharged into the marine environment are of paramount importance. The descriptive analysis was based on the spatial variability of the various pollutants. It was supported by a statistical study to link various elements and lead to the identification of potential sources of contamination.

Spatial variability of element concentrations (Cl, Na, Br, P, S, Ca)

Figure 2 shows an increase in the concentration of chlorine and sodium moving away from the phosphogypsum discharge zone (near site 7). This is explained by the mixing between liquid sludge and seawater at the point of discharge. The discharges, having a salinity of the order of 30 g L^{-1}, induced a dilution of the seawater (salinity = 38 g L^{-1}) and consequently a reduction of chlorine and sodium contents. Cl and Na concentrations are similar in the intertidal and supratidal. Na and Cl were found to have a dominant natural origin; their variability in superficial sediments is linked to fine fraction percentage. These elements pose no threat to the coastal environment and their presence is mainly related to seawater. The principal origin of bromides in coastal sediments is sea water. Their concentrations in the superficial sediment of the littoral were quite lower than their content in seawater (Fig. 2). The observation of P content along the coast (Fig. 2d) showed a significant geographic variability. Relatively low values were observed at the point of discharge. The highest values were

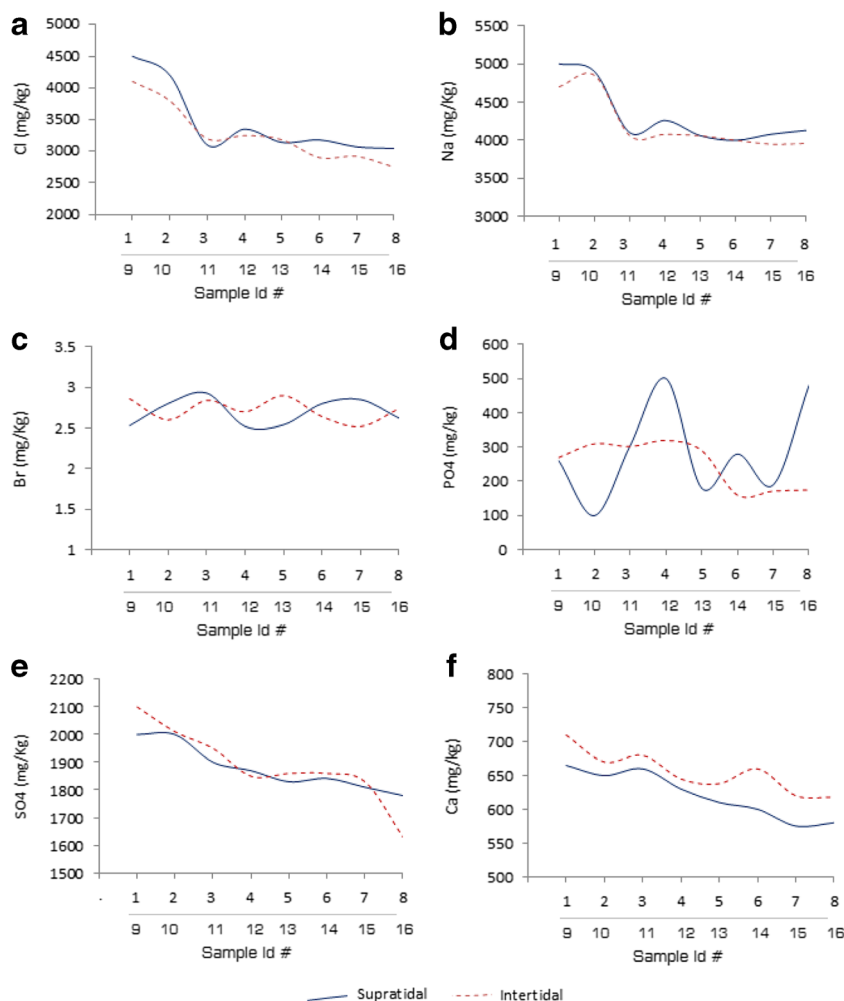**Fig. 2** **a**–**f** Major ions concentrations in superficial sediments

Table 2 Heavy metal content in the sands of the littoral and in discharged wastewaters

Element	Zn	Pb	Cu	Cd	pH
Mean concentration (mg kg^{-1})	7.15	133	97.5	3.8	–
Concentration in wastewaters (mg kg^{-1})	0.034	0.43	0.46	0.012	3.2

located towards the south and at the level of wadi Gabès. It seems that the ocean currents are responsible for the transport, south of this pollutant. Drainage contributes to P enrichment of intertidal superficial sediments. The presentation of the spatial variation of the sulfate content (Fig. 2e) showed a net increase by moving away from phosphogypsum. The highest concentrations were observed at the intertidal level of Limaoua. Coastal and marine currents, oriented North-South, should be responsible for the transport and deposit of this pollutant. Moreover, due to the pH of the mud rejected in the studied area, reducing sulfate phenomena take place in superficial sediments and contribute to their decrease. Figure 2f shows a large decrease in the calcium content approaching the point of discharge. The highest values were recorded towards the south of the city (Limaoua).

The superficial sediments of the beach consist essentially of grains whose composition is exclusively siliceous. The presence of calcium is related to the shell debris of marine species. Figure 2f shows higher calcium concentrations when moving away from the point of discharge. This variability can be explained by two processes:

- The phosphogypsum released from the chemical complex is acidic sludge. It helps dissolve the calcium shells, which decreases the calcium concentration around the discharge area.

- Sludge causes the pollution of the receiving environment near the point of discharge and prevents the appearance of any form of development of fauna and flora.

Heavy metals

The heavy metals quantified at the superficial sediments of the beach are as follows: zinc, lead, copper, and cadmium. Mean values (mg kg^{-1} dry weight) of these elements were respectively 6.5 mg kg^{-1}, 137 mg kg^{-1}, 98.7 mg kg^{-1}, and 3.95 mg kg^{-1}. Ranges of heavy metal concentrations widely exceeded the natural concentrations. Median metal concentrations were recorded according to the following order: Pb > Cu > Zn > Cd. The coastline seems to be extensively contaminated. High values of heavy metal concentrations give evidence of the serious contribution of the chemical industries to the contamination of the coast.

The observation of the spatial repair of heavy metals along the beach (Fig. 3) revealed abnormally high concentrations of these elements. This indicates a contamination of beach sediments by the various heavy metals diagnosed. The

Fig. 3 Heavy metals Concentration in superficial sediments along the coast
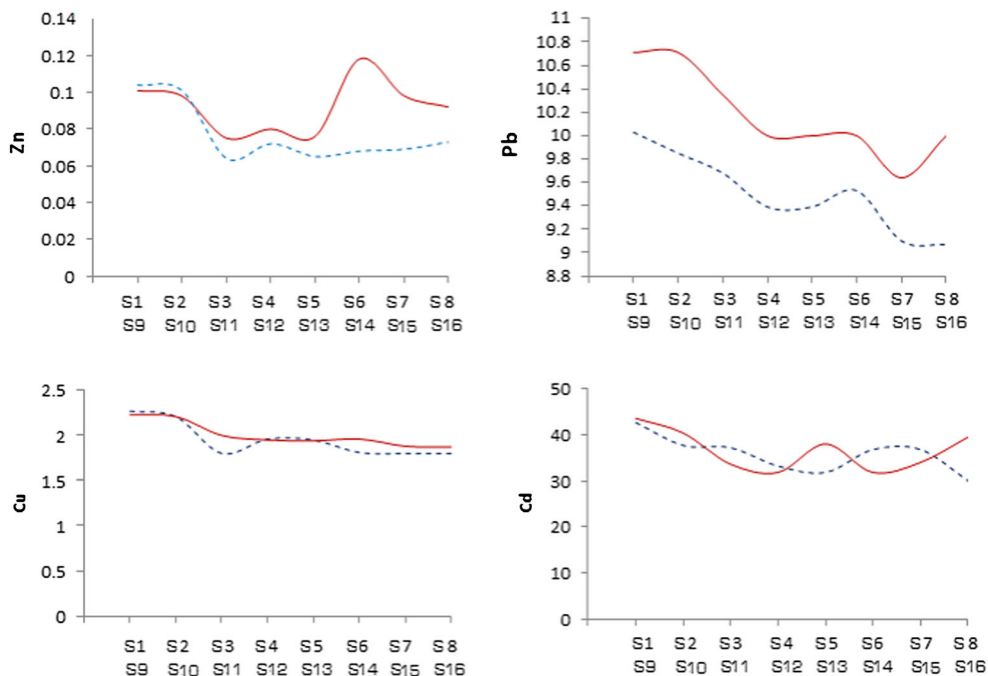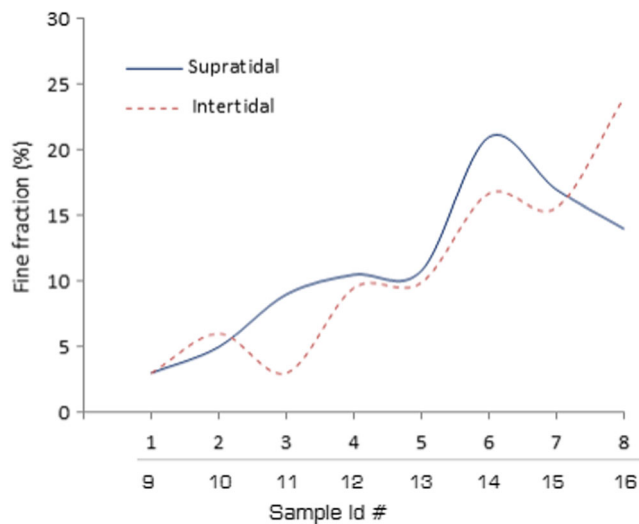
Fig. 4 Fine fraction distribution in superficial sediments along the coast

comparison of the average concentrations of heavy metals in the superficial sediments of the beach compared to those measured at the discharges (Table 2) shows that the superficial sediments are highly loaded heavy metals than the discharges. This finding demonstrates that a process of accumulation of heavy metals has taken place. It is responsible for enriching beach sediments with various contaminants. The heavy metal contents (Zn, Pb, Cd, and Cu) remain quite high in the intertidal superficial sediments. As in the case of the superficial sediments of the beach, accumulation processes take place and are responsible for an alarming enrichment of heavy metals, toxic for fauna, flora, and human health.

Fine fraction

Figure 4 clearly shows a significant change of the fine fraction. The latter increases significantly when approaching the rejection bridge. Phosphogypsum, having a rather fine granulometry, is at the origin of this anomaly. The fine

fraction decreases towards the south. Coastal dynamics through the waves plays an important role in the process of transport and deposit of the fine fraction. It seems that a large proportion is transported offshore by sea currents.

Numerical analysis

PCA is a statistical technique to study a large number of individuals and variables. It makes it possible to highlight the levels of correlations between the various individuals and variables. It is often used for complex data processing. The interpretation of the various projections makes it possible to understand the structure of the data and subsequently the affinities between the various variables and individuals. This method is used to identify potential sources of contamination and affinities between various contaminants. The results obtained are represented in the form of a correlation and projection matrix on the factorial plane. PCA applied to different element concentrations revealed three principal components. The threshold of significance taken was equal to 0.61. Moreover, 1×3 factorial plane reached a maximum inertia of 67%. Contributions of the first and second PCs of the total variance were 47% and 17% respectively.

The correlation matrix (Table 3) led to the following conclusions:

- The correlation factor between Br and other elements is very low and sometimes negative. This can be explained by the fact that bromine is not stable in sediments and has the ability to migrate to seawater quite rapidly.
- The correlation factor between phosphorus (P) is very low. The diversity of the origins of this contaminant may explain the lack of correlation with other pollutants (phosphorus comes from several sources).
- The levels of correlation between the various heavy metals remain quite modest. It seems that the physicochemical processes are responsible for this observation. Ion

Table 3 Correlation matrix of major elements

	Cl^-	Br^-	PO_4^{+3}	SO_4^{-2}	Na^+	Ca^{2+}	Zn^{2+}	Pb^{2+}	Cu^{2+}	Cd^{2+}
Cl^-	1									
Br^-	−0.02	1								
PO_4^{+3}	0.01	0.06	1							
SO_4^{-2}	0.75	0.19	0.08	1						
Na^+	0.92	−0.07	0.05	0.64	1					
Ca^{2+}	0.67	0.22	0.12	0.82	0.63	1				
Zn^{2+}	0.61	−0.31	0.12	0.23	0.52	0.13	1			
Pb^{2+}	0.34	0.14	−0.17	0.56	0.32	0.85	−0.05	1		
Cu^{2+}	0.83	0.07	−0.13	0.72	0.86	0.83	0.33	0.67	1	
Cd^{2+}	−0.27	0.26	−0.22	−0.10	−0.28	−0.08	−0.24	0.08	−0.11	1

Fig. 5 Variables projection on F1xF3 components
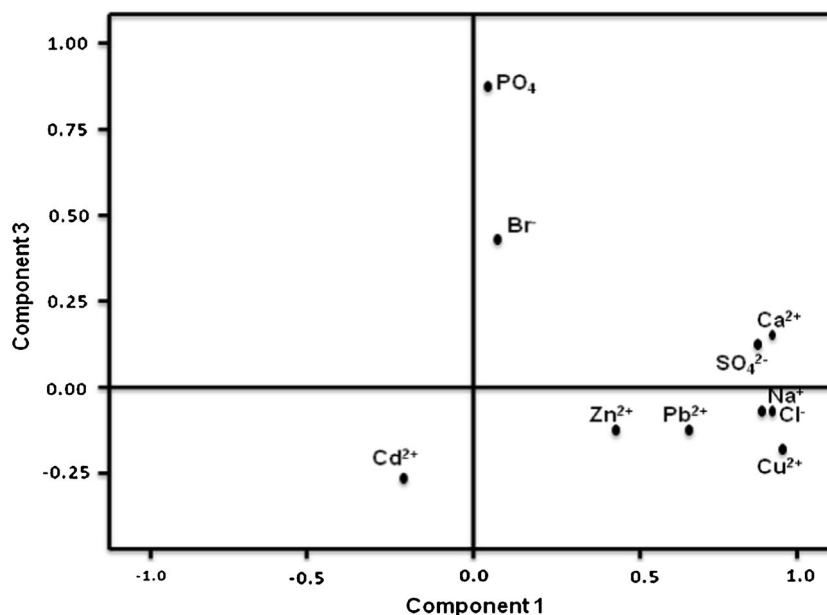
exchange mechanisms between the various receptor media seem to play a major role in heavy metal contents in sediments.

Figure 5 shows the projection of the variables on the factorial plane (F1, F3). It confirms the conclusions obtained from the correlation matrix and identifies several groups. A first group is formed by Zn, Pb, Cu, and Cd. The elements of this group seem to come from several sources but with a dominance of the phosphogypsum component. A second group consists of sodium and chlorine and emanates mainly from seawater. A third group is composed of calcium and sulfate. The elements of this group seem to come mainly from

phosphogypsum. A fourth group is formed by phosphorus (P). This element appears to come from a number of sources, the main source of which is discharge and drainage from agricultural activities.

The various statistical approaches show the complexity to identify various sources of contamination and their affinities on the coast of the city of Gabès. Anthropogenic activities leave an obvious mark on the abnormally high levels of pollutants. The various inter-elemental correlations and the analysis and main component allowed highlighting some origins of the contaminants. Other potential sources remain to be identified. The enormous quantities of phosphogypsum discharged into the sea during several decades have created a layer of surface sediments whose properties are different compared to sediments of natural origin. This is why the groups of elements projected using the PCA method seem to overlap, which makes the interpretation quite complex.

Contamination factor and pollution load index

Cf and PLI were calculated for each heavy element sample taking in account relations (1) and (2). Results obtained are given in Tables 4 and 5. Based on the C_f values, it appears clearly, when the classification of Hakanson is applied, that:

- Because C_f of Zn is under 1, it can be considered that the study area is little contaminated by zinc,

Table 4 Contamination factor values of heavy metals

Heavy metal	Heavy metal concentration (mg.kg^{-1})							
	Intertidal area							
	S1	S2	S3	S4	S5	S6	S7	S8
Zn	0.101	0.098	0.075	0.08	0.076	0.118	0.098	0.092
Pb	10.03	9.85	9.68	9.39	9.39	9.53	9.1	9.07
Cu	2.27	2.21	1.8	1.96	1.95	1.81	1.8	1.8
Cd	42.7	37.7	37.2	33.2	31.8	36.8	36.8	30
Supratidal area								
	S9	S10	S11	S12	S13	S14	S15	S16
Zn	0.104	0.101	0.064	0.072	0.065	0.068	0.069	0.073
Pb	10.71	10.71	10.35	10	10	10	9.64	10
Cu	2.23	2.21	2	1.95	1.94	1.96	1.88	1.87
Cd	43.6	40.4	33.6	31.8	38	31.8	34	39.5

Table 5 Pollution load index values

Element	Zn	Cu	Pb	Cd
LPI	0.08	1.97	9.8	35.7

Table 6   Sediment quality guidelines

Element	Concentration according to SQG (mg kg^{-1})
Cu	270
Zn	410
Pb	218
Cd	10

Table 8   m-ERM quotient

Element	m-ERM Quotient values	Probability of toxicity (%)
Cu	0.37	9
Zn	0.016	21
Pb	0.63	49
Cd	0.39	21

- C_f values of Cu varied from 1.8 to 2.27. It can be deduced that Gabès littoral is moderately polluted with copper,
- Cf of Pb and Cd are largely above 6. They show very high contamination of the area by lead and cadmium. Accumulation of these pollutants in littoral sediments certainly comes from phosphogypsum waste rejected in the area without any treatment.

Pollution load index values confirm a high contamination of the studied area. Notably, lead and cadmium PLI values were extremely high and proved a very negative impact of anthropogenic activities in Gabès littoral.

m-ERM quotient

The m-ERM-Q indicator was calculated for each heavy element sample taking into account relations (4) and sediment quality guidelines (Table 6). Based on the m-ERM values, four classes (Table 7) corresponding to the probabilities of toxicity were defined according to Long and MacDonald (1998). Results obtained (Table 8) showed that, except for Cu (9%), all elements had a non-negligible probability of toxicity, which clearly shows that the studied area is widely affected by heavy metal pollution. High ecotoxicological potential indicates that the coastline is significantly polluted by chemical industry sewages.

This study shows, according to the parameters investigated, that Gabès coastline is widely affected by important varieties of pollutants. Ion exchange phenomena as well as the marine current direction and the littoral drift have a major role in the spatial distribution of the various pollutants. Several studies undertaken have shown high levels of contamination in the

Table 7   Probability of toxicity as a function of m-ERM-Q

m-ERM-Q	Probability of toxicity (%)
m-ERM-Q < 0.1	Low probability of toxicity 9%
0.1 < m-ERM-Q < 0.5	Probability is about 21%
0.51 < m-ERM-Q < 1.5	Probability reaches 49%
m-ERM-Q > 1.5	Probability of toxicity is 76%

Gulf of Gabès (Kharroubi et al. 2012; El Zrelli et al. 2018a, b; Rabaoui et al. 2014). Heavy metal pollution levels were both high and variable in time and space.

Conclusion

This study on the distribution and origin of pollutants at the coast of the city of Gabès showed the complexity of the issue. However, the various analyses carried out show a fairly significant contamination of the coast from Limaoua to northern Gabès. This work clearly shows that the region is largely affected by several pollutants, notably heavy metals. The identification of the spatial distribution of contaminants highlights the major role of phosphorus discharges in pollutant inputs. The study area seems to be affected by anthropogenic activities through abnormally high levels of Cu, Zn, Pb, and Cd. Concentration of the various elements analyzed shows largely positive anomalies.

Superficial sediment contamination seems to be amplified by accumulation processes whose footprints are well marked on the coast of the city of Gabès. Geochemical and physical processes are responsible for the transport and deposition of various pollutants from phosphogypsum releases related to the industrial activities of the city of Gabès. Some of these mechanisms were depicted; others remain to be identified. Ion exchange phenomena as well as the orientation of the marine currents and the littoral drift have a major role in the spatial distribution of the various pollutants at the level of the coast of the city. The various statistical and numerical approaches showed a high level of contamination, as well as the complexity of the identification of the various sources of contamination and their affinities on the coast of the city of Gabès. Anthropogenic activities leave an obvious mark on the excessively high levels of pollutants. PLI and m-ERM-quotient values and the principal component analysis and main component allowed highlighting different sources of contaminants. Other potential sources remain to be identified. Even if several studies have been undertaken, it seems that the studied problem is distinguished by rather imposing spatio-temporal variability which needs new large-scale approaches.

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