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Monitoring of Changes of Sediment Nature by Environmental Impacts of El-Zeit Bay Area, Gulf of Suez, Egypt

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ABSTRACT

The El-Zeit Bay area has been significantly affected by petroleum operations, including drilling and backfilling activities for pier construction, leading to changes in the coastline, especially on the eastern side, displacing coral reefs and rocky masses. This has negatively impacted marine sediments in the area. Mechanical and geochemical analyses were conducted on 11 surface marine sediment samples from El-Zeit Bay. The results revealed that sand was the dominant sediment type, accompanied by varying proportions of mud and gravel. In certain deeper samples, there was a noticeable increase in gravel content. The sediment particles exhibited a wide range of sizes, spanning from very coarse to fine grains. The carbonate content in the sediments varied from 13.1% to 68.8%, averaging 47.0%. Some samples had high organic material content, influenced by sediment nature. Heavy metal concentrations were measured in the samples: Fe (3155 – 20765 ppm, average 8377 ppm), Mn (79 – 305 ppm, average 143 ppm), Zn (18.6 – 56.8 ppm, average 37.2 ppm), Cu (4.9 – 23.6 ppm, average 11 ppm), Pb (13.6 – 28.9 ppm, average 22.4 ppm), Ni (9.4 – 21.7 ppm, average 15.2 ppm), Co (1.4 – 6.2 ppm, average 3 ppm), and Cd (0.6 – 2.9 ppm, average 2 ppm). The assessment of pollution levels in the sediment employed enrichment factors (EF), geoaccumulation indices (Igeo), and pollution load indices (PLI) to gauge the extent of metal contamination. This research offers strategic recommendations aimed at reducing environmental harm in El-Zeit Bay, while also informing future development initiatives to promote sustainability and prevent additional deterioration of the marine ecosystem.

INTRODUCTION

El-Zeit Bay, situated along the Gulf of Suez approximately 80 km north of Hurghada, hosts several oil companies on its eastern coast. One notable presence is Petrojet Company, which has established a sea dock (Yard) that serves as the focal point of the study under consideration. (Table 1; Fig.1). Petroleum activities have significantly affected the marine environment in El-Zeit Bay, as demonstrated by mechanical and geochemical studies carried out on 11 surface sediment samples collected from the eastern part of the bay, near the platform (Yard). Comparable studies have also been conducted along the Egyptian Red Sea coast to assess the influence of such activities on marine sediments in those areas. These analyses provide valuable insights into the extent of environmental impact caused by oil exploration and extraction operations (among them are: El- Askary *et al.,* (1988); Piller and Mansour (1990); Frihy *et al.,* (1996); Mansour *et al.,* (1997); Mansour (1999); Mansour *et al.,* (2000); Dar (2002), Madkour (2004); Madkour (2005); Mohammed *et al.* (2005); Madkour and Dar (2007); Ahmed and Madkour (2006); Madkour *et al.;* (2006); Mohamed *et al.,* (2011); Madkour (2011); Madkour *et al.*, (2012); El-Taher and Madkour (2013); Madkour *et al.,* (2013); Mansour *et al.,* (2013); Madkour *et al.,* (2014); El-Taher and Madkour (2014); Madkour *et al.,* (2015); Uosif *et al.,* (2016); Madkour *et al.,* (2016); El-Taher *et al.,* (2018); Badawy *et al.,* (2018); Madkour *et al.,* (2019a); Madkour *et al.,* (2019b); Zakaly *et al.,* (2019); Osman *et al.,* (2020); Youssef *et al.,* (2020); Madkour *et al.,* (2020); Badawi *et al.,* (2022) and Assran *et al.,* (2022). However, studies assessing the impact of development activities along the Egyptian Red Sea coast are infrequent.

The current task involves monitoring sediment changes in El-Zeit Bay due to environmental impacts and documenting recent development activities. The impact assessment of development in this area focuses on surveying and analyzing marine sediment surface conditions.

MATERIALS AND METHODS

Field works:

eleven sediment samples were meticulously gathered from various locations in the El-Zeit Bay area. Comprehensive details about the exact locations, depths, and seabed characteristics of these samples are meticulously documented in Table 1 and illustrated in Figures 1, 2, and 3. The collection techniques employed included both grab sampling and Scuba diving to ensure diverse and representative sample collection. For each sample, a grab sampler was deployed to the seabed, allowed to stabilize momentarily, and then retrieved. The sediments were then carefully placed in clearly marked plastic bags and transported to the laboratory for thorough analysis. Additionally, detailed measurements of the surface water's physical properties were conducted to enhance our understanding of the area's prevailing environmental conditions.

Laboratory Methods and Treatment of Data:

Sediment samples underwent grain size analysis through wet sieving, while carbonate content and organic matter were evaluated by the Red Sea Branch of the National Institute of Oceanography and Fisheries. Surface marine sediments were further analyzed for heavy metal concentrations. Duplication of analysis done to insure accuracy. To assess pollution levels in the region, statistical tools such as enrichment factors (EF), geoaccumulation indices (Igeo), and pollution load indices (PLI) were employed.

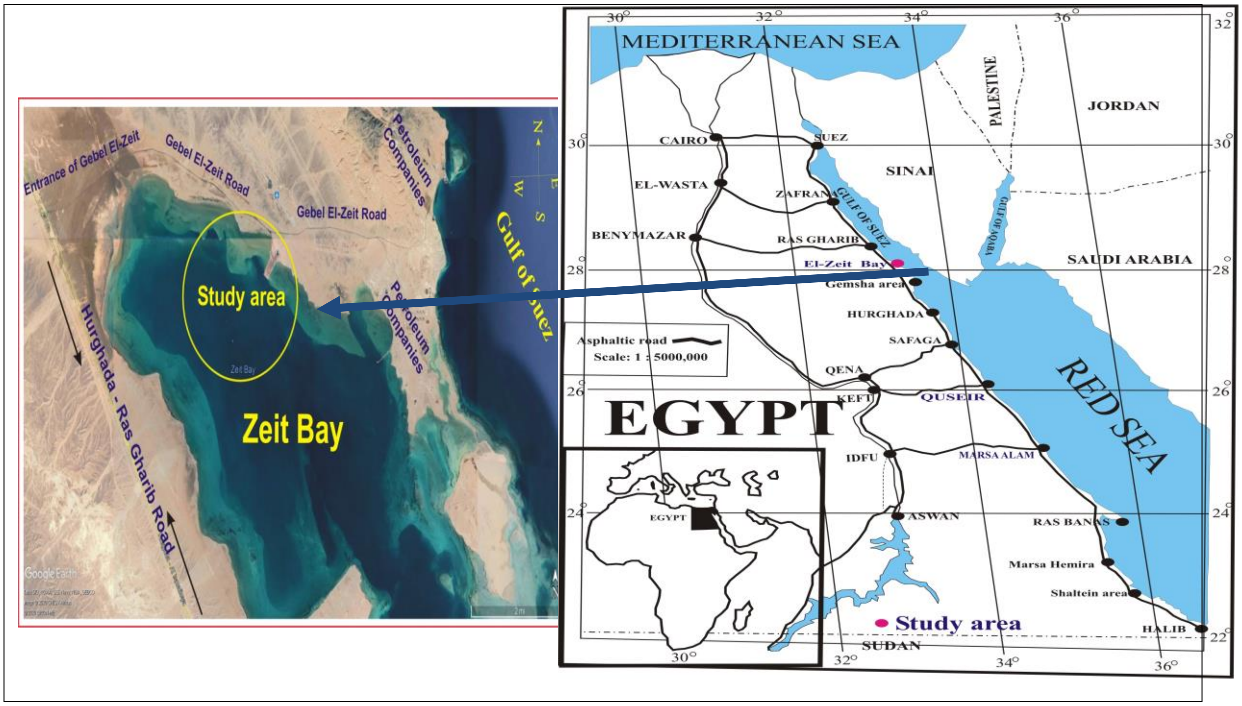

Fig. 1. Satellite image with location of study area

Table 1. Sample location, physical parameters of surface water, and depth and bottom facies

No.	Position		Physical parameters of sea water				Depth	Bottom facies
	Lat. o / // N	Long. o / // E	Temp. C^o	PH	Salinity %o	Do mg/L	(m)	
P1	27 49 13.8	33 31 31.1	18.93	8.03	39.02	6.55	0.5	sand
P2	27 49 11.7	33 31 29.4	19.44	8.02	39.21	6.35	1.2	sand
P3	27 49 06.7	33 31 26.1	19.5	8.01	39.3	6.2	1.5	sand
P4	27 49 05.4	33 31 25.1	19.16	8.1	39.38	6.6	1.2	coarse sand
P5	27 49 03.4	33 31 26.8	19.37	8	39.43	6.99	1.5	coarse sand
P6	27 49 01.7	33 31 29.7	19.57	7.99	39.4	6.31	2.0	silty sand
P7	27 49 2.8	33 31 31.6	19.97	7.98	39.48	6.52	2.5	sand
P8	27 49 06.1	33 31 34.0	19.86	7.99	39.44	7.5	6.5	sand
P9	27 49 09.1	33 31 36.2	19.7	7.98	39.2	6.98	8.5	coarse sand
P10	27 49 09.2	33 31 36.56	19.89	7.86	39.45	7.02	7.5	biogenic sand
P11	27 49 09.3	33 31 36.45	19.55	7.89	39.78	7.03	8.0	biogenic sands

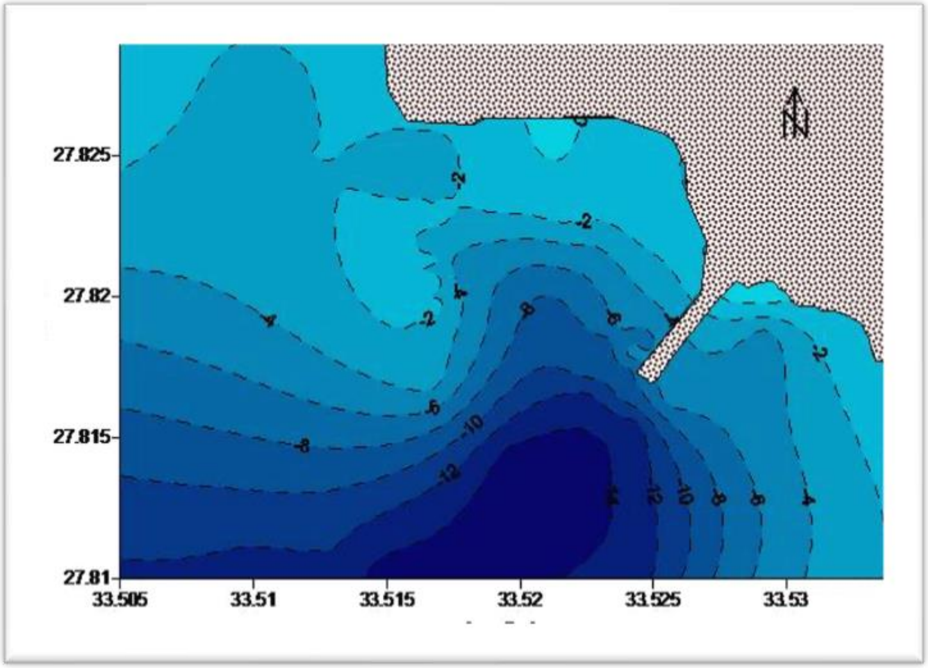

Fig. 2. Bathymetric map of the at El-Zeit Bay area

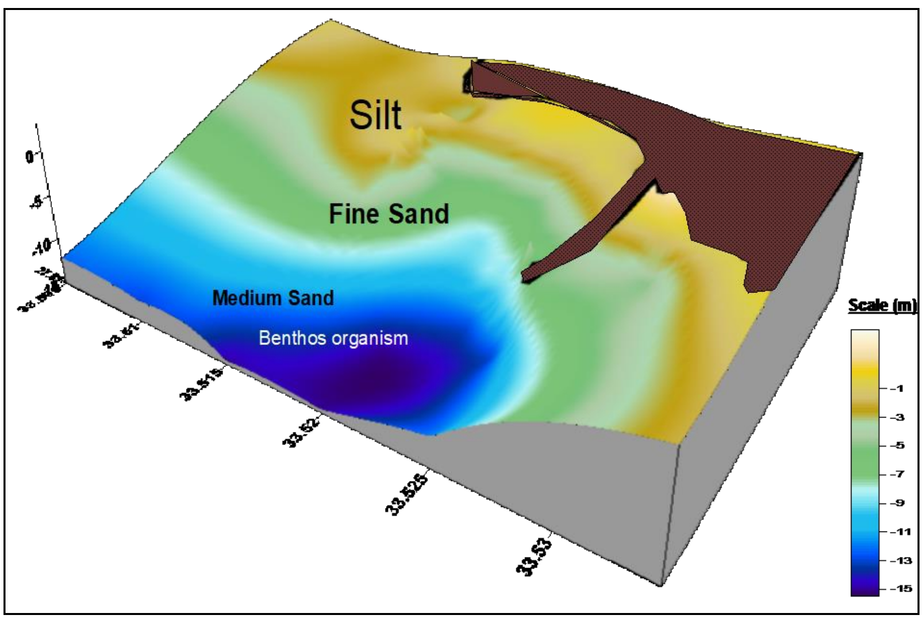

Fig. 3. A three-dimensional diagram showing the characteristics of the bottom sediments of the marine areas at El-Zeit Bay.

RESULTS AND DISCUSSION

Nature of sediments:

The sediments found in El-Zeit Bay encompass a blend of carbonates and siliciclastics, influenced significantly by petroleum activities such as landfilling and drilling. The predominant component is sand, ranging from 71% to 99%, with clay materials being scarce near the shoreline and increasing with depth. Mud content is generally minimal, averaging less than 5%. In comparison to the nearby beach and intertidal zones, the sediments in El-Zeit Bay are finer in texture. The marine sediments are predominantly made up of sand (with an average of 87.0%, ranging from 71.3% to 99.8%), gravel (averaging 9.4%, with a range of 0.1% to 28.2%), and minimal amounts of mud (averaging 3.6%, ranging from 0.000% to 12.5%) (refer to Table 2; Figs. 3 & 4). Generally, mud content increases with depth and distance from the shore, while the higher gravel content is largely a result of landfill and dredging activities. In El-Zeit Bay, grain size distribution is primarily influenced by water depth, sediment facies, and proximity to the shoreline.

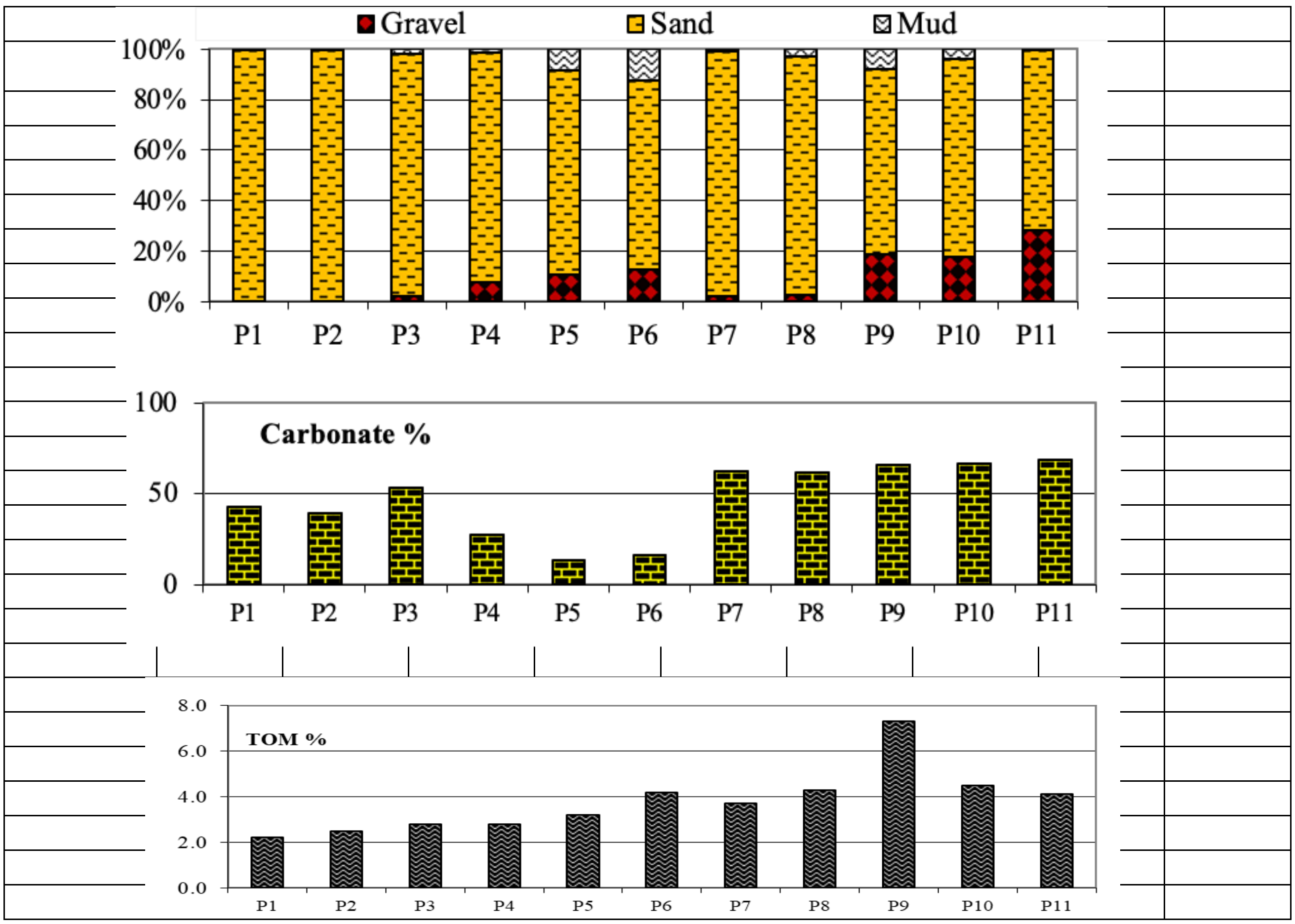

Fig. 4. illustrates the distribution of grain sizes, carbonate content, and total organic matter (TOM) present in marine sediments.

Table 2. presents the sediment types, grain size distributions, and results of the geochemical analysis of surface marine sediments.

	Sediment types					grain size parameters				Geochemical analysis	
No.	Gravel	Sand	Silt	Clay	Mud	*MZ*	6_I	SK_I	K_G	CaCo3 %	TOM %
P1	0.07	99.69	0.2	0.0	0.24	1.8	0.6	0.0	1.3	43	2.2
P2	0.15	99.81	0.0	0.0	0.04	1.3	0.6	0.1	1.3	39.2	2.5
P3	2.34	96.07	1.6	0.0	1.59	2.4	0.5	-0.1	1.5	53	2.8
P4	7.52	91.19	1.3	0.0	1.29	1.1	1.2	-0.2	1.2	27.5	2.8
P5	10.65	80.97	8.4	0.0	8.384	1.4	2.0	0.1	0.9	13.1	3.2
P6	12.58	74.93	12.5	0.0	12.49	1.8	2.2	-0.2	0.9	16.4	4.2
P7	2.12	97.03	0.8	0.0	0.85	1.3	1.0	0.0	1.2	62.7	3.7
P8	2.79	94.64	2.6	0.0	2.58	1.3	1.1	0.1	1.3	61.4	4.3
P9	18.7	73.29	8.0	0.0	8.01	1.0	2.0	0.2	1.0	66.1	7.3
P10	17.84	78.38	2.8	1.0	3.79	0.6	1.4	0.0	0.9	66.3	4.5
P11	28.21	71.31	0.5	0.0	0.49	-0.2	0.9	0.1	0.7	68.8	4.1
Min.	0.1	71.3	0.0	0.0	0.0	-0.2	0.5	-0.2	0.7	13.1	2.2
Max.	28.2	99.8	12.5	1.0	12.5	2.4	2.2	0.2	1.5	68.8	7.3
Avg.	9.4	87.0	3.5	0.1	3.6	1.2	1.2	0.0	1.1	47.0	3.8

Geochemistry:

Carbonate content:

The sediment samples from the area display low to moderate carbonate levels, reflecting the influence of past backfilling activities, which introduced land-derived sediments into the marine environment. Carbonate content varies from 13.10% to 68.8%, averaging 47.05% (Table 2; Fig. 5). According to Maxwell's (1968) classification, sediments are categorized by carbonate levels as high carbonate (>80%), impure carbonate (60-80%), transitional (40-60%), terrigenous (20-40%), and highly terrigenous (<20%). The marine sediments from El-Zeit Bay fit within the transitional range, with an average carbonate content of 47.05% (Table 2). The sediments primarily originate from terrestrial sources, with some marine sediment contribution due to earlier backfilling for platform construction. Carbonate levels exhibit weak positive correlations with specific sediment types, while showing negative correlations with metals such as Fe and Mn, and strong positive correlations with Pb and Cd (Table 4). The biogenic content is relatively low in the offshore sediments, which are less affected by terrigenous material.

Organic matter content:

The total organic matter (TOM) content in the marine sediment samples generally falls within acceptable limits, although some samples show higher levels, likely due to the area's petroleum activities. The TOM content in these sediments ranges from 2.2% to 7.3%, with an average value of 3.70% (Table 2; Fig. 5). This organic matter content often mirrors the carbonate content, as both can increase closer to the sea (Fig. 5). The sediments largely result from both terrestrial and marine origins. The region, which is known for petroleum operations, has been impacted by past backfilling activities during platform construction. Correlation coefficient analysis (Table 4) reveals a weak relationship between TOM and carbonate content, as well as heavy metal concentrations, except for Pb and Ni. This weak correlation is likely due to the TOM in surface sediments being mainly controlled by differences in lithogenic and biogenic sediment components.

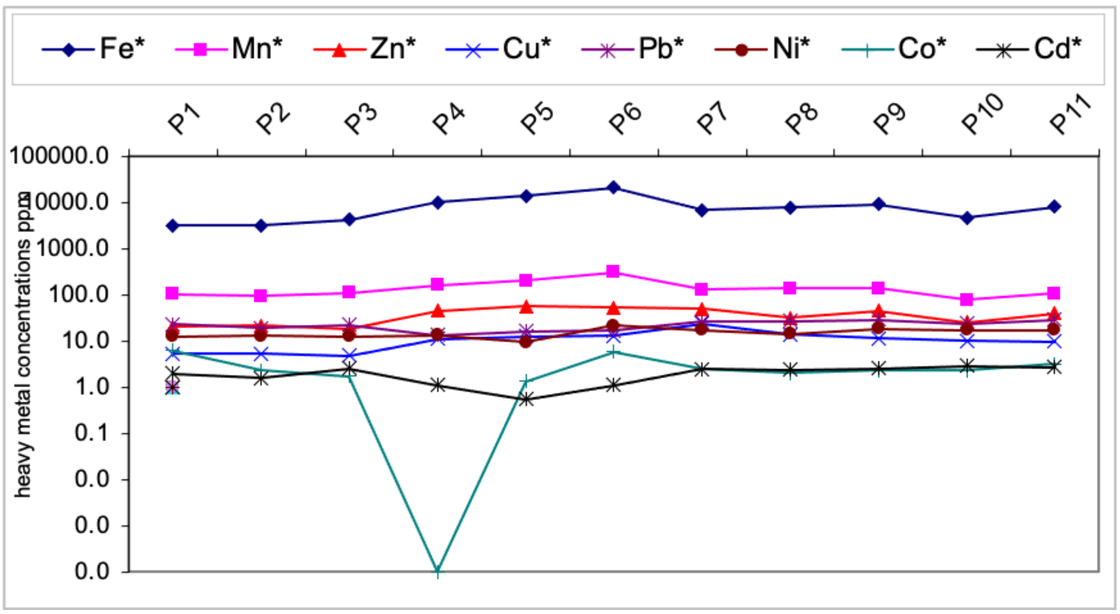

Fig. 4. Heavy metal concentrations of surface marine sediments

Distribution of heavy metals:

Marine sediments exhibit a complex and varied composition, heavily influenced by their source materials whether originating from marine organisms or terrestrial sources and the climate conditions they are exposed to (Chen *et al*., 2000). Behavior and distribution of trace metals within these environments are primarily dictated by their interactions with different geological phases found in the sediments described by (Förstner and Wittmann, 1981). Along the coast, trace metals are generally bound to sediment particles, with their distribution being strongly affected by coastal dynamics, including longshore drift and wave-driven movements. The movement of these metals is intrinsically tied to the density and size of the sediment particles. According to Gnandi and Tobschall (1999), where smaller grains tend to harbor higher levels of metals, facilitating their exchange with the surrounding water a concept first noted by Gibbs in 1977. Particularly, sediment types like mud, sandy mud, and sandy silt are noted for their higher concentrations of metals compared to coarser sandy types (Padmalal et al., 1997). For instance, silt and clay can show enrichment factors of seven to eight times for copper (Cu) and cadmium (Cd), and five to six times for zinc (Zn) and two to five times for nickel (Ni), relative to sand.

In El-Zeit Bay, an extensive analysis of eight trace metals iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), lead (Pb), nickel (Ni), cobalt (Co), and cadmium (Cd) has shown considerable variability in their concentrations and distribution patterns (Table 3; Figure 5). Factors such as the grain size and organic material, and proximity to pollution sources heavily influence these patterns, as outlined by Madkour et al. (2012). The concentration levels observed range widely, with Fe levels fluctuating between 3155 and 20765 ppm, and Mn, Zn, Cu, Pb, Ni, Co, and Cd also displaying significant variances.

Compared to other coastal areas such as Quseir, Safaga, and Hurghada Harbours, El-Zeit Bay exhibits higher average concentrations of metals like Cd, Zn, Cu, and Pb (Mansour et al., 2011). Nevertheless, studies by Madkour et al. (2013) indicate higher metal concentrations in El-Hamrawein Harbour than in El-Zeit Bay. The high metal concentrations in El-Zeit Bay are largely attributed to substantial terrestrial inputs, including those from landfill and dredging activities, which have led to an accumulation of fine sediments and, consequently, increased metal concentrations, posing risks to marine life and human health.

Furthermore, correlations among metals in the bay's sediments are significant, with a strong positive correlation observed between Cd and Pb ($r = 0.88$), and Cd and $CaCO3$ content ($r = 0.97$), while negative correlations exist between Cd and Fe ($r = -0.6$) and Mn ($r = -0.68$). These correlations underscore the influence of terrestrial contributions and historical dredging activities on the metal distribution within El-Zeit Bay, which have had substantial adverse effects on the marine ecosystem.

Assessment of metal concentration by using different indexes:

The assessment of surface marine sediment contamination in El-Zeit Bay can be conducted through various analytical approaches, including the Enrichment Factor (EF), the Geo-accumulation Index (Igeo), and the Pollution Load Index (PLI). These metrics offer a robust framework for quantifying pollution levels and determining the influence of anthropogenic activities on sediment quality within the bay (refer to Tables 5 and 6).

Table 3. The results of heavy metals concentrations in surface marine sediments at Zeit Bay of Gulf of Suez.

	heavy metals concentrations							
No.	Fe*	Mn*	Zn*	Cu*	Pb*	Ni*	Co*	Cd*
P1	3180.0	104.0	20.4	5.4	23.2	12.6	6.2	2.0
P2	3155.0	95.4	22.0	5.3	19.0	13.1	2.4	1.6
P3	4220.0	112.0	18.6	4.9	22.6	12.7	1.8	2.6
P4	10220.0	162.8	45.8	11.0	13.6	13.5	ND	1.1
P5	14080.0	205.0	56.8	12.8	16.1	9.4	1.4	0.6
P6	20765.0	305.0	52.9	13.2	17.1	21.7	5.8	1.1
P7	6805.0	129.0	49.2	23.6	26.1	17.1	2.5	2.5
P8	7835.0	137.1	32.3	14.1	27.1	14.5	2.1	2.4
P9	9155.0	139.1	45.9	11.3	28.9	18.5	2.3	2.6
P10	4650.0	79.0	25.6	10.2	24.0	17.1	2.3	2.9
P11	8085.0	107.4	39.8	9.7	28.8	17.3	3.2	2.8
Min.	3155.0	79.0	18.6	4.9	13.6	9.4	1.4	0.6
Max.	20765.0	305.0	56.8	23.6	28.9	21.7	6.2	2.9
Avg.	8377.3	143.2	37.2	11.0	22.4	15.2	3.0	2.0

Table 4. presents the correlation coefficients between different sediment types and the concentrations of heavy metals in surface marine sediments.

	Gravel	Sand	Mud	CaCO3 %	TOM %	Fe*	Mn*	Zn*	Cu*	Pb*	Ni*	Cd*
Gravel	1											
Sand	**-0.94**	1										
Mud	0.33	**-0.64**	1									
CaCO3 %	0.27	-0.05	-0.46	1								
TOM %	**0.60**	**-0.67**	**0.50**	0.45	1							
Fe*	0.32	**-0.57**	**0.85**	**-0.61**	0.25	1						
Mn*	0.08	-0.37	**0.82**	**-0.72**	0.10	**0.96**	1					
Zn*	0.36	**-0.52**	**0.62**	-0.39	0.36	**0.81**	**0.71**	1				
Cu*	0.04	-0.11	0.21	0.10	0.31	0.37	0.31	**0.69**	1			
Pb*	0.31	-0.16	-0.24	**0.91**	**0.55**	-0.42	**-0.51**	-0.23	0.16	1		

Ni*	0.48	**-0.54**	0.41	0.29	**0.62**	0.39	0.32	0.27	0.35	0.34	1	
Cd*	0.25	-0.05	-0.42	**0.97**	0.39	**-0.60**	**-0.68**	-0.49	0.00	**0.88**	0.34	1

Table 4. presents the values of the Metal Enrichment Factor (EF) and the Geochemical Index (Igeo) measured in surface marine sediments from El-Zeit Bay.

Sa.No.	Fe		Mn		Zn		Cu		Pb		Cd	
	EF	I_{geo}	EF	I_{geo}	EF	I_{geo}	EF	I_{geo}	EF	I_{geo}	EF	I_{geo}
P1	-	-1.15	0.18	-3.62	0.32	-2.80	0.18	-3.66	1.72	-0.37	9.65	2.12
P2	-	-1.17	0.17	-3.74	0.35	-2.70	0.17	-3.68	1.42	-0.66	7.98	1.83
P3	-	-0.75	0.15	-3.51	0.22	-2.94	0.12	-3.80	1.26	-0.41	9.51	2.50
P4	-	0.53	0.09	-2.97	0.22	-1.64	0.11	-2.62	0.31	-1.15	1.69	1.29
P5	-	0.99	0.08	-2.64	0.20	-1.33	0.09	-2.40	0.27	-0.90	0.61	0.29
P6	-	1.55	0.08	-2.06	0.13	-1.43	0.07	-2.35	0.19	-0.82	0.83	1.29
P7	-	-0.06	0.11	-3.31	0.36	-1.53	0.36	-1.52	0.91	-0.20	5.66	2.44
P8	-	0.15	0.10	-3.22	0.20	-2.14	0.19	-2.26	0.82	-0.15	4.82	2.42
P9	-	0.37	0.08	-3.20	0.25	-1.64	0.13	-2.58	0.74	-0.05	4.38	2.50
P10	-	-0.61	0.09	-4.01	0.27	-2.48	0.23	-2.73	1.22	-0.32	9.64	2.66
P11	-	0.19	0.07	-3.57	0.24	-1.84	0.13	-2.80	0.84	-0.06	5.35	2.61
Std.er	-	0.17	0.03	0.14	0.06	0.13	0.03	0.08	0.29	0.11	1.39	0.32
Min	-	-1.17	0.03	-4.01	0.06	-2.94	0.03	-3.80	0.19	-1.15	0.61	0.29
Max	-	1.55	0.18	0.14	0.36	0.13	0.36	0.08	1.72	0.11	9.65	2.66
Avg.	-	0.02	0.10	-2.97	0.24	-1.86	0.15	-2.53	0.83	-0.41	5.13	1.86

Std.er = standard error Min =minimum Max. =maximum Avg =average

Geo-accumulation Index (I_{geo}) = $Log_2(C_n/1.5B_n)$ (Muller, 1979), E

Enrichment Factor (EF_M) = (C_M/C_{Fe}) sample/(C_M/C_{Fe})shale

Table 5. Contamination factors (Cf) for heavy metals and pollution index of surface marine at El-Zeit Bay of Gulf of Suez.

Sa.No.	Cf for the heavy metals						PLI
	Fe	Mn	Zn	Cu	Pb	Cd	
P1	0.212	0.171	0.321	0.133	0.585	1.778	0.000
P2	0.210	0.157	0.346	0.131	0.479	2.833	0.000
P3	0.281	0.184	0.293	0.121	0.569	1.222	0.000
P4	0.681	0.267	0.720	0.273	0.342	0.611	0.001
P5	0.939	0.336	0.894	0.318	0.407	1.222	0.007
P6	1.384	0.500	0.833	0.329	0.431	2.722	0.037
P7	0.454	0.212	0.775	0.589	0.659	2.667	0.013
P8	0.522	0.225	0.509	0.350	0.684	2.833	0.007

P9	0.610	0.228	0.722	0.282	0.730	3.167	0.011
P10	0.310	0.130	0.402	0.254	0.606	3.056	0.001
P11	0.539	0.176	0.627	0.242	0.727	3.278	0.006
Min	0.210	0.130	0.293	0.121	0.342	0.611	0.000
Max	1.384	0.500	0.894	0.589	0.730	3.278	0.037
Average	0.558	0.235	0.586	0.275	0.565	2.308	0.008

Enrichment Factor (EF):

The Enrichment Factor (EF) technique is widely utilized to differentiate metals derived from natural geological sources from those introduced by natural or human activities (referenced in studies by Zhang et al., 2009; Chen et al., 2007; Amin et al., 2009). Typically, aluminum serves as the reference element in EF calculations due to its prevalent nature, resistance to anthropogenic alteration, and its integral role in the structure of clay minerals. This relationship helps maintain consistent ratios with other metals within the Earth's crust. However, for this particular study, iron (Fe) was chosen as the reference element. Iron is the fourth most common element in the crust and is less likely to be affected by contamination. The evaluation of EF values for heavy metals in the sediment samples of the study area involved comparing their concentrations to the global shale average a well-established standard (cited by Harikumar et al., 2009; Karageorgis and Hatzianestis, 2003; Ong and Kamaruzzaman, 2009; Shyamalendu et al., 2001). The EF calculation method adopted follows the protocol outlined by Atgin et al. (2000).

$$EF_{metal} = (Mx/Fex)_{sample}/(Mc/Fec)_{shale}$$

In this research, the term Mx indicates the concentration of a specific metal in the analyzed sample, while Fex refers to the corresponding concentration of iron (Fe) in that same sample. Mc represents the metal concentration in an average shale or sediment that has not been disturbed, and Fec stands for the concentration of iron (Fe) in this undisturbed sediment. When site-specific data is unavailable, the reference values provided by Turekian and Wedepohl (1961) are used as benchmarks for undisturbed conditions. These "world shale" values for Fe, Mn, Zn, Cu, and Pb are 4720, 850, 95, 45, and 20 ppm, respectively, and serve as background levels.

Table 5 outlines the enrichment factor (EF) values for four heavy metals in surface marine sediments from El-Zeit Bay, Gulf of Suez. The EF values were interpreted using a methodology similar to Chen et al. (2007), where EF<1 indicates no enrichment, EF<3 represents minor enrichment, EF values between 3 and 5 show moderate enrichment, EF=5-10 is categorized as moderately severe enrichment, EF=10-25 as severe enrichment, EF=25-50 as very severe enrichment, and EF>50 indicates extreme enrichment. The study results show that the EF for Mn ranges between 0.03 and 0.18, with an average of 0.1; for Zn, the EF ranges from 0.06 to 0.36, with an average of 0.24; for Cu, the EF ranges between 0.03 and 0.36, with an average of 0.15; and for Pb, the EF ranges from 0.19 to 1.73, averaging at 0.83. The EF for Cd was found to range between 0.61 and 9.65, with an average of 5.13 (see Table 5).

A general examination of the calculated EF data (Table 5) indicates that most sampling sites in the study area show EF values of less than 1 for most of the metals. However, the average EF for Pb (0.83±0.29) was greater than 1, suggesting that Pb contamination likely results from minor to significant enrichment. Similarly, the average EF for Cd (5.13±1.39) exceeded 5, indicating moderately severe enrichment. Among the metals analyzed, cadmium and lead exhibited the highest EF values, likely linked to localized point sources contributing to their elevated concentrations.

Geoaccumulation Index (I_{geo}):

The Geoaccumulation Index (I_{geo}) was utilized to evaluate metal contamination within the surface sediments of El-Zeit Bay, situated in the Gulf of Suez. Originally proposed by Muller in 1979, this index measures the extent of metal accumulation by comparing current sediment concentrations to those of pristine, undisturbed sediments, which act as a reference point. In 1981, Muller further developed his earlier classification system by introducing seven specific categories of pollution. These ranged from unpolluted conditions, labeled as Class 0 where the geoaccumulation index (Igeo) is less than 0, to very strongly polluted conditions, identified as Class 6 with an Igeo greater than 5. At the extreme end, Class 6 signifies metal concentrations that are more than 100 times the baseline values. The determination of the geoaccumulation index employs the following mathematical formula:

$$I_{geo} = \log_2 (C_n/1.5B_n)$$

In this context, C_n refers to the observed concentration of the metal *n* within the sediment, while B_n signifies the geochemical baseline concentration of the same metal. The factor 1.5 is introduced to account for possible fluctuations arising from natural lithogenic contributions. Notably, the background metal concentrations utilized in the calculation of the geo-accumulation index (I_{geo}) are aligned with those employed for determining the enrichment factor.

As indicated in Table 5, the Igeo values for Fe, Mn, Zn, Cu, and Pb are generally below zero across all sediment samples in the study area, signifying a lack of significant contamination. However, Fe and Cd levels exceed zero in most samples, and in many stations, the Igeo for these metals falls within Classes 1, 2, and 3 (Igeo > 0), implying that the region ranges from uncontaminated to moderately contaminated.

Pollution Load Index (PLI):

The Pollution Load Index (PLI) for each sampling site was calculated following the method developed by Tomilson et al. (1980). This method involves calculating the geometric mean of the contamination factors (CF) for each metal detected in the sediment, using the background concentrations as a reference point. The PLI values were then visually represented to demonstrate the pollution levels across different sample locations. Table 6 provides the PLI results for the 11 surface sediment stations analyzed in this study. According to the standards set by Chakravarty and Patgiri (2009) and Seshan et al. (2010), a PLI greater than 1 indicates the presence of pollution, while a value less than 1 suggests that the area is free from pollution.

As shown in Table 6, all the PLI values for heavy metals in the surface sediments of El-Zeit Bay are below 1, signifying no pollution across the 11 sampling sites. However, certain samples from El-Zeit Bay in the Gulf of Suez exhibited notably high Enrichment Factor (EF) values, especially for Pb and Cd. While the EF values generally indicate no significant enrichment in the surface sediments, there are exceptions, with specific samples showing substantial Pb and Cd enrichment at El-Zeit Bay.

CONCLUSION

The surface sediments of El-Zeit Bay exhibit a pronounced accumulation of heavy metals, predominantly covered by rocky limestone layers originating from tidal flats. Human activities such as land reclamation and dredging disrupt these rocky layers, exposing finer sediments and leading to the concentration of heavy metals in localized pools. This study evaluated the extent of metal pollution through the use of the enrichment factor (EF), geo-accumulation index (Igeo), and pollution index (PLI) for various metals, including Fe, Mn, Zn, Cu, Pb, and Cd. Results revealed that Pb and Cd exhibited the highest levels of enrichment, while Mn, Zn, and Cu were less concentrated. The Igeo values suggested that the sediments ranged from "uncontaminated" to "moderately contaminated" with respect to individual metals. Both natural processes and human activities were identified as contributors to Pb and Cd pollution in the area, with significant land-derived material inputs detected in the bottom sediments, primarily from hinterland basement rocks. While most heavy metal concentrations in the bay are not currently a cause for significant environmental concern, the levels of Pb and Cd necessitate continued monitoring. The metal concentration ranges identified in this study provide essential baseline data for evaluating future pollution and supporting the sustainable development and management of El-Zeit Bay.

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