J. Ocean Univ. China (Oceanic and Coastal Sea Research)
https://doi.org/10.1007/s11802-019-3608-0
ISSN 1672-5182, 2019 18 (4): 834-848
http://www.ouc.edu.cn/xbywb/
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Impact of Drain Effluent on Surficial Sediments in the Mediterranean Coastal Wetland: Sedimentological Characteristics and Metal Pollution Status at Lake Manzala, Egypt

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(Received July 29, 2017; revised January 16, 2018; accepted April 27, 2018)

Abstract Surface sediments were collected from Lake Manzala, the Mediterranean coastal wetland located to the east of the Nile Delta, Egypt, to assess the effect of drain effluent on the spatial variations of sedimentary characteristics and heavy metal pollution. Grain-size compositions, textures, and heavy metal distribution patterns in sediments are presented using GIS technique. Results of the analysis of the sediment showed a clear effect of drain effluent, with an increase in fine fractions and homogeneous suspensions in transportation mode. Lake sediments were dominated by sandy mud textures, and mode of transportation was homogeneous suspension and rolling. Spatial distribution of heavy metals (Fe, Mn, Zn, Cu, Ni, Cr, and Pb) was studied in the lake's surficial sediments, along with their relationship to drain effluent and their contamination status in the ecological system. Heavy metal pollution status was assessed by means of accepted sediment quality guidelines and contamination assessment methods (contamination factor, contamination degree, modified contamination degree, geo-accumulation, and enrichment factor). Among the determined heavy metals, Pb had the most ecological risk. Generally, the heavy metals in the surface sediments indicated pollution risk ranging from moderate to considerable, particularly, in those sites facing drains and inlets that had the highest toxic effluent. The results were interpreted by statistical means. A cluster analysis defined areas facing drain discharge and inlets as separated groups. ANOVA indicated that most of the sedimentation and studied metals directed this clustering.

Key words Lake Manzala; Mediterranean wetland; metal pollution; sedimentological characteristics

1 Introduction

Coastal lagoons, lakes, wetlands, and estuaries, as transitional environments, are among the world's most important aquatic ecosystems. Such ecosystems usually show strong environmental gradients produced by the interactions of land and marine processes. They are commonly located at the termini of land drainage systems. They are mostly dynamic environments that suffer from long and short-term environmental changes. In such environments, sedimentation processes are affected by many variables such as eco-hydrological functioning parameters and hydro-morphological indexes (Flower *et al*., 2009; El-Said *et al*., 2014). At the coastal provinces with large populations, high water usages has led to a significant reduction in the available water in the natural system, in addition to a reduction in the water quality due to eutrophication and pollution (Flower *et al*., 2009). Furthermore, decades of erosion, improved siltation, together with land reclamation of coastal wetlands has led to the diminution of many coastal lagoons and wetlands located in Southern Mediterranean Province (Ahmed *et al*., 2009; Flower *et al*., 2009).

Grain-size compositions are the important descriptive property of clastic sediments, and they have a key role in classifying sedimentary facies, modes of transportation, and deposition environments. Determination of sedimentary fractions such as gravel, sand, silt, and clays, are used as a basis for studying all textural features of deposits (Friedman and Sanders, 1978; Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011). Sediment textures reflect the weathering, erosion processes, and nature of transport, in addition to forming the basis of many schemes for classifying sedimentary environments (Folk, 1954; Passega, 1957, 1964; Passega and Byramjee, 1969; Román-Sierra *et al*., 2011; Marcinkowski and Mycielska-Dowgiałło, 2013).

Heavy metals pollution in the coastal wetland depositional basin has drawn specific attention due to its toxicity. The accumulation of heavy metals on lake sediments make them highly sensitive indicators for monitoring pollutants as they act as carrier and store for contaminants

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in the aquatic environment. The greatest anthropogenic sources of the metals are industrial and sewage disposal (Pereira *et al*., 2015).

Generally, heavy metals are natural components of aquatic environments, and their normal concentration in the ecosystem is an indicator of healthy ecosystem activities (Ntakirutimana *et al*., 2013). However, when distributed in high concentrations in the aquatic ecosystem, such as in sediment and water, metals might become a danger to the ecosystem due to its integral ecotoxic features, storage, and tendency to biomagnify. As a result, the high concentration of such metals in the ecosystem may cause human poisoning through the food chain (Jin *et al*., 2015; Wang *et al*., 2015). Sediments are used as an important indicator of the health of the aquatic ecosystem due to their natural actions as a metal reservoir: they contain more than 90% of the metals in the aquatic environment (Camargo *et al*., 2015). Also, sediments are considered a secondary source of metals that might return into the water column as a result of environmental changes such as pH, salinity, redox potential, mineral and organic content, and resident biota (Souza *et al*., 2015; Wang *et al*., 2015).

To analyze the organic enrichments caused by anthropogenic or natural sources of heavy metals, simple and integrated indices such as the enrichment factor (*EF*) and index of geo-accumulation (I_{geo}) are extensively used in environmental studies (Armid *et al*., 2014; Goher *et al*., 2014; Bastami *et al*., 2015; Lario *et al*., 2016).

The aim of the present study is to assess the effect of drainage effluent on both the spatial distribution and variations in sedimentological characteristics and the heavy metal pollution of Lake Manzala as an example of a coastal wetland connected to Mediterranean Sea.

2 Materials and Methods

2.1 Area of Study

Lake Manzala (Fig.1) is the largest of Egypt's Mediterranean wetlands. It is bordered by the Mediterranean Sea to the north, the Suez Canal to the east and the Damietta-Nile branch to the west. Generally, it is a shallow lagoon. It is a perfect coastal wetland depositional basin, receiving both marine and freshwater. The lake receives Mediterranean Sea water *via* three inlets, New El-Gamil (which has been recently established), El-Boughdady, and El-Gamil, from east to west, respectively, and freshwater from several drains and pumping stations (Abd El-Karim, 2008). Inlets are the zones of interaction between wetland and the coastal marine ecosystem due to the exchange of water masses having different physical and chemical properties (Zahran *et al*., 2015).

Lake Manzala was the most productive for fisheries. Nowadays, it suffers from land reclamation and overgrowth by water hyacinth. Over the last 60 years, Lake Manzala has been affected by various threats: agriculture drainage, municipal sewage, and industrial wastewater, which led finally to an unhealthy ecosystem and produced a polluted lake. As a perfect coastal wetland, fresh water (mostly from agricultural drainage) flows into Lake Manzala from many pumping stations and four major drains.

Drains receive wastewater from the very densely-populated area of the Eastern Delta (Cairo, Qalubyia, Sharkia, Ismailia, and Port Said Governorates) and contribute much to the deteriorating water quality of the lake, *i.e.*, from east to west: Bahr El-Baqar, Hadous, El-Serw and Faraskour (25%, 49%, 13%, and 4% of total inflow, respectively in addition to El-Qaboty canal links the lake with the Suez Canal.

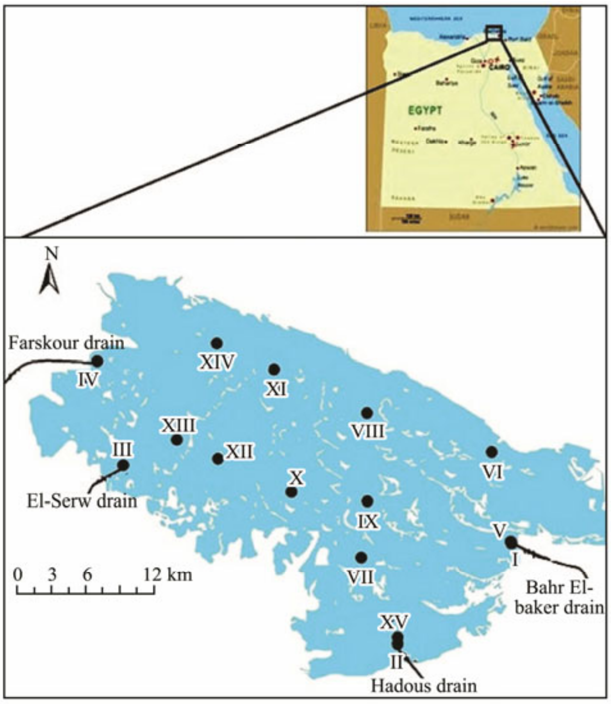

Fig.1 Sampling locations of sediment samples from Lake Manzala. I, Discharge point (DP) of Bahr El-Bakar drain; II, DP of Hadous drain; III, DP of El Serw; IV, DP of Farskour drain; V, Area facing Bahr El-Bakar drain; VI, Boughaz El- Gamil; VII, West of Bashteer; VIII, Temsah; IX, Lagan; X, Deshdy; XI, Hamrah; XII, Abwat; XIII, Degwy; XIV, Baragheta; XV, Genka.

2.2 Sampling

During February, 2016, a total of fifteen sediment samples from different sites were collected from investigated wetland (Fig.1); 11 samples covered the entire lake area, and four represented discharge points (DP) of the four main drains. Samples were collected using an Ekman dredge sampler. Sediment samples were quickly packed in airtight polyethylene bags. Then, subsamples of the sediments were oven dried at 105℃ to constant weight for analysis.

2.3 Analysis

2.3.1 Grain-size analysis, textural parameters, and mode of transportation

Sediment samples were prepared and grain-size analysis was performed by dry sieving technique (Folk, 2014). Each sediment sample contained mud fractions (less than 64 μm). More than 5% were analyzed using the pipette method described by Carver (1971). Cumulative curves were plotted on a log probability scale. Mean grain-size (Mz), median (Md) standard deviation (sorting σ_I), skewness (Sk_I), kurtosis (K_G), and textural parameters were calculated according to Folk and Ward (1957) and Folk (2014). To illustrate sedimentary mode of transportation, grain-size analyses are presented in a C-M diagram (Passega, 1957, 1964; Passega and Byramjee, 1969; Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011).

2.3.2 Heavy metals and total organic carbon (TOC%)

Complete digestion of sediment (ground and sieved to 120 µm) according to Kouadio and Trefry (1987) was done. A mixture of 15 mL of concentrated nitric acid, hydrofluoric acid, and perchloric acid were added to 0.5 g of prepared sediment into a Teflon beaker. Teflon beakers were covered and set aside for an appropriate time, then heated and evaporated to few drops. Then, 5 mL of perchloric acid was added again and evaporated just to near dryness. 10 mL of concentrated hydrochloric acid was added and samples were placed back on a hot plate until the solution became clear. By using deionized distilled water and a volumetric flask, the final material was filtered and completed to 100 mL. An atomic absorption model GBC Savanta AA901 with GF5000 Graphite Furnace was used to analyze Fe, Mn, Zn, Cu, Cr, Ni, and Pb. For quality assurance, sediment reference material (IAEA-433, International Atomic Energy Agency, Vienna, Austria) was examined with the sediment samples during the analysis for monitoring of the quality of analysis and to examine the accuracy of the data. The results of present work-selected metals showed good agreement with the reference materials (recovery rates for the studied metals from the standard reference material were 95.9%–101.1%). Sediment Quality Guidelines (SQGs) were used to estimate metal pollution status. (SQGs) were developed for the assessment of sediment quality from the concentrations of contaminants using a chemical and biological effects database (USA DOE (Jones *et al*., 1997); US EPA, 1999; Environment Canada, 2002). Total organic carbon (TOC%) was determined using an acid/dichromate titration method according to Gaudette *et al*. (1974). 10 mL of 1 mol L^{-1} $K_2Cr_2O_7$ solution was added to 0.2 g of ground sediment, sieved to 120 µm. 20 mL of concentrated H_2SO_4 was added and mixed for about a minute. The mixture was allowed to stand for 30 min. Then, the solution was diluted to a 200 mL volume with distilled water, and 10 mL (85% H_3PO_4), 0.2 g NaF, and 15 drops of diphenylamine indicator were added. The solution was back-titrated with 0.5 mol L^{-1} ferrous ammonium sulfate solution.

2.3.3 Statistical analysis of results

Cluster analysis is a comprehensive technique used to find groups of similar characters within a data set. Hierarchical cluster methods produce different groups; *i.e.*, from small clusters of very similar items to large clusters that include more dissimilar items (Kaufmann and Rousseeuw, 2009). In the present study, cluster analysis was applied to obtained data to test the relationship among sites and how these sites are related according to their sedimentological characteristics and their heavy metal contents. To verify the integrity of the cluster results, an ANOVA was run using the results as categorical values. A Kolmogorov-Smirnov (K-S) test was used to test the normality of the variables (the data were not normally distributed and did not pass the test of homogeneity of variances). Spearman Correlation Coefficient tests were used for measured parameters. The levels of significance were set at $P>0.05$. XLSTAT-Base software was used for all calculations.

2.4 Sediment Contamination Assessment

2.4.1 Contamination factor (*CF*)

According to Hakanson (1980), *CF* (single element index) is applied to assess sediment contamination. Calculations were simplified as:

$$CF = C_{\text{Smp}} / C_{\text{Ref}} ,$$

where C_{Smp} is the mean content of measured metal in the sample and C_{Ref} is the reference concentration of an individual metal (background concentration). This identifies a relationship between the concentration of a measured metal and its reference level. Four categories of *CF* were established according to Hakanson (1980) and Gong *et al.* (2008) in Table 1.

In the present study, the upper continental crust of studied metals was used as pre-industrial concentration according to Turekian and Wedepohl (1961).

Table 1 Terminologies for pollution classes of *CF*, *CD* and *EF*

CF^a		CD^b		EF^c	
Value	Pollution	Value	Pollution	Value	Pollution
$CF<1$	Low contamination factor	$CD<8$	Low degree of contamination	$EF<2$	Deficiency to mineral enrichment
$1<CF<3$	Moderate contamination factor	$8<CD<16$	Moderate degree of contamination	$2<EF<5$	Moderate enrichment
$3<CF<6$	Considerable contamination factor	$16<CD<32$	Considerable degree of contamination	$5<EF<20$	Significant enrichment
$CF>6$	Very high contamination factor	$CD>32$	Very high degree of contamination	$20<EF<40$	Very high enrichment
				$EF<40$	Extremely high enrichment

Notes: [a] According to Gong *et al*. (2008); [b] according to Hakanson (1980); [c] according to Sutherland (2000).

2.4.2 The contamination degree (*CD*)

The sum of *CFs* for all elements examined represented the contamination degree (*CD*; Hakanson, 1980) of the environment and four classes were recognized:

$$(CD) = (Cfi1 + Cfi2 + Cfi3 + \cdots\cdots + Cfin),$$

where n = the number of analyzed elements and $i1$, $i2$, $i3$,⋯ith element (or pollutant) and CF = Contamination factor. The *CD* of the environment has four classes (Hakanson, 1980) in Table 1.

2.4.3 Modified degree of contamination (*mCD*)

According to Abrahim and Parker (2007), modified degree of contamination (*mCD*) is calculated as the sum of all the *CFs* for a given pollutants divided by the number of analyzed pollutants:

$$(mCD) = (Cfi1 + Cfi2 + Cfi3 + \cdots\cdots + Cfin) / n,$$

where n = the number of analyzed elements and $i1$, $i2$, $i3$,⋯ith element (or pollutant) and CF = Contamination factor. The modified degree of contamination (*mCD*) in sediments has seven classes in Table 2.

2.4.4 Geo-accumulation index (I_{geo})

According to Müller (1969), I_{geo} was calculated using:

$$I_{geo} = \log_2(C_{\text{Smp}} / 1.5C_{\text{Ref}}),$$

where C_{Smp} is the measured concentration of the element in the sediment and C_{Ref} is the reference value. The constant 1.5 is used to analyze natural fluctuations in the content of a given substance in the environment and to detect very small anthropogenic influences. I_{geo} has seven classes in Table 2.

Table 2 Terminologies for pollution classes of *mCD* and I_{geo}

mCD[a]		I_{geo}[b]		
Value	Pollution	Value	Class	Pollution
$mCD<1.5$	Nil to very low degree of contamination	$I_{geo}<0$	I_{geo} class = 0	Practically uncontaminated
$1.5\leq mCD<2$	Low degree of contamination	$0<I_{geo}<1$	I_{geo} class = 1	Uncontaminated to moderate contaminated
$2\leq mCD<4$	Moderate degree of contamination	$1<I_{geo}<2$	I_{geo} class = 2	Moderate contaminated
$4\leq mCD<8$	High degree of contamination	$2<I_{geo}<3$	I_{geo} class = 3	Moderate to strong contaminated
$8\leq mCD<16$	Very high degree of contamination	$3<I_{geo}<4$	I_{geo} class = 4	Strong contaminated
$16\leq mCD<32$	Extremely high degree of contamination	$4<I_{geo}<5$	I_{geo} class = 5	Strong to very strong contaminated
$mCD\geq 32$	Ultra high degree of contamination	$I_{geo}>5$	I_{geo} class = 6	Very strong contaminated

Notes: [a] According to Abrahim and Parker (2007); [b] according to Buccolieri *et al.* (2006).

2.4.5 Enrichment factor (*EF*)

EF was calculated using the formula according to the equation suggested by Buat-Menard and Chesselet (1979):

$$EF = [(C_{\text{Smp}} / C_{\text{Ref}}) / (C_{\text{mb}} / C_{\text{rb}})],$$

where C_{Smp} is the content of the metal in the sample, C_{Ref} is the content of the reference element in the sample, C_{mb} is the content of the metal in the background sample, and C_{rb} is the content of the reference element in the background sample. Feng *et al.* (2011) indicated that either Al or Fe can be used for metal normalization due to the significant correlation between them.

In the present study $EF_{\text{Fe}} = [(C_{\text{Smp}} / C_{\text{Fe}}) / (C_{\text{mb}} / C_{\text{Feb}})]$, five contamination categories were recognized on the basis of the enrichment factor (Sutherland, 2000) in Table 2.

3 Results

3.1 Grain-Size Analysis, Textural Parameters and Mode of Transportation

Results indicated that the sediments of the lake are a mixture of sand and mud (generally, muddy sand), while coarse material and gravel fractions appear in rare locations, represented as shells and shell fragments reaching to 67.11% southeast of the lake (site XV).

The sand fractions were the dominant fraction, ranging from 30.34%–73.47%; at site (XV) and near the Bahr El-Bakar drain mouth (site V), respectively. Fine sand (reaching 51.43% at site XV) and very fine sand (reaching 41.53% at site III) were the dominant sand fractions, with lesser amounts of other sand fractions (Table 3).

The mud fraction (silt and clay) of the surficial sediments of the lake is dominated by silt fraction (6.61%–45.14%; 4–63 µm) northward at (V) and (XIV), respectively, with various amounts of clay fraction (1.45%–8.27%; < 4 µm) at site (I); southward, and at site (VII), respectively.

Silt fractions were dominated by coarse and medium silt (reaching 20.91% and 13.39%, respectively, northward; site VIII) with lesser amounts of both of fine and very fine silt fractions (Fig.2; Tables 3 and 4).

The main size fluctuated between very fine sand (−0.13 Ø) southeastward at Genka area (site XV) and very fine sand (4.2 Ø) at both DP of Bahr El-Baker drain (site I) and northward at Temsah area (VIII). Sorting varied between poorly sorted (1.22 Ø) DP of Bahr El-Baker drain (site I) and very poorly sorted (2.7 Ø) southwestward at Degwy (site XIII). The skewness was coarse-skewed to strongly fine-skewed (−0.25–0.85) southward, at West Bashteer (site VII) area and DP of Bahr El-Baker drain V, respectively. Kurtosis varied from platy-kurtic to very leptokurtic (0.70–2.14) southeastward at Genka area (site XV) and south of the mid-lake area at Deshdy area (site X), respectively (Table 5).

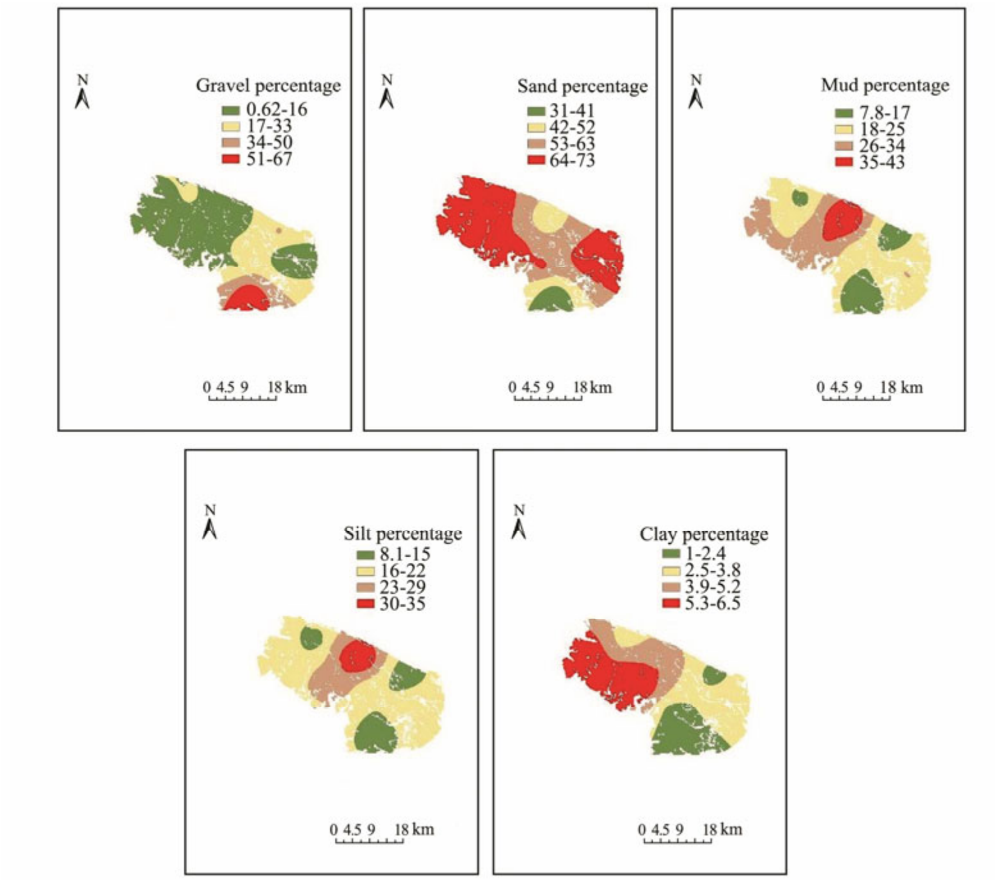

Fig.2 The spatial distribution of grain sizes in Lake Manzala using GIS technique.

Table 3 Site number, site name, sediments fractions percent and sediment type of Lake Manzala sediments

Site no.	Site name	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mud (%)	Sediment texture
I	DP of Bahr El-Bakar drain	0.00	65.88	25.85	8.27	34.12	Muddy sand
II	DP of Hados drain	0.00	66.99	28.19	4.82	33.01	Muddy sand
III	DP of El Serw	0.00	69.87	23.61	6.52	30.13	Muddy sand
IV	DP of Farskour drain	0.00	70.46	22.73	6.81	29.54	Muddy sand
V	Area facing Bahr El-Bakar drain	0.00	73.47	22.58	3.95	26.53	Muddy sand
VI	Boughaz El-Gamil	34.91	60.53	****	****	4.56	Muddy gravelly sand
VII	West of Bashteer	15.12	64.25	19.19	1.45	20.63	Gravely Muddy sand
VIII	Temsah	5.54	44.28	45.14	5.03	50.18	Gravely Muddy sand
IX	Lagan	26.39	58.57	11.45	3.59	15.04	Muddy gravelly sand
X	Deshdy	0.00	65.31	28.31	6.38	34.69	Gravely Muddy sand
XI	Hamrah	5.34	62.55	28.01	4.10	32.11	Gravely Muddy sand
XII	Abwat	0.00	64.08	29.04	6.88	35.92	Muddy sand
XIII	Degwy	11.80	69.87	13.00	5.33	18.33	Gravely Muddy sand
XIV	Baragheta	20.44	70.20	6.61	2.75	9.36	Muddy gravelly sand
XV	Genka	67.13	30.43	****	****	2.45	Muddy sandy gravel

Note: ****, Samples with mud fraction less than 5%.

Results indicated that there are high positive correlations between mean grain size and both silt and clay (R=0.87 and R=0.84; P<0.01, respectively, Table 4); this may be due to the occurrence of coarse silt fractions along most of the studied regions. Furthermore, there are moderately significant correlations between sand and skewness (R=0.54; P<0.05; Table 5) and kurtosis and clay (R=0.56; P< 0.05; Table 6).

3.2 Application of the C-M Diagram to Palaeoenvironmental Interpretation

The C-M diagram (Passega, 1957, 1964) is an important method for clarifying the mode of transportation of sediments by presenting the results of grain-size analyses as plotting values (in microns) of the first percentile (C) against the median (M) on the probability scale. The C-M diagram is used to study both fluvial and coastal deposits, as both contain different lithofacies, which may be divided into depositional sub-environments using the diagram (Ludwikowska-Kędzia, 2000; Szmańda, 2007).

Table 4 Sand and silt fractions percent of Lake Manzala sediments

Site no.	V.C. sand	C. sand	M. sand	F. sand	V.F. sand	C. silt	M. silt	F. silt	V.F. silt
I	0.00	0.00	0.00	40.14	25.74	10.23	6.78	3.77	5.07
II	0.00	0.00	0.00	32.68	34.31	17.34	6.31	1.66	2.88
III	0.00	0.00	0.00	28.34	41.53	11.65	7.22	2.82	1.92
IV	0.00	0.00	0.00	33.75	36.71	10.22	7.34	3.10	2.07
V	0.00	0.00	0.00	51.43	22.04	12.69	6.91	1.63	1.36
VI	21.45	9.17	7.80	12.79	9.32	****	****	****	****
VII	0.00	0.00	8.82	26.18	29.25	14.26	2.97	1.40	0.56
VIII	0.00	0.00	0.00	22.89	21.39	20.91	13.39	6.02	4.82
IX	10.18	6.96	10.26	18.79	12.38	6.65	1.50	1.78	1.53
X	0.00	0.00	7.77	25.89	31.65	13.92	8.52	2.98	2.89
XI	4.90	4.09	5.60	22.59	25.37	19.75	4.97	2.49	0.79
XII	0.00	0.00	0.00	43.00	21.08	11.88	11.37	4.70	1.09
XIII	9.58	11.10	13.17	23.39	12.62	8.73	2.48	0.15	1.65
XIV	12.33	13.62	12.62	18.00	13.63	4.63	1.10	0.35	0.53
XV	10.40	0.06	7.27	8.93	3.76	****	****	****	****

Notes: ****, Samples with mud fraction less than 5%. V.C., very coarse; C., coarse; M., medium; F., fine; V.F., very fine.

Table 5 Mean size, sorting, skeweness, kurtosis and organic matter percent of Lake Manzala sediments

Site no.	Mean size (Mz)	Sorting (σ_I)	Skewness (SK_I)	Kurtosis (K_G)	Organic matter (%)
I	Coarse silt	Poorly sorted	Strongly fine-skewed	Lepto-kurtic	6.88
II	Very fine sand	Poorly sorted	Strongly fine-skewed	Lepto-kurtic	4.50
III	Very fine sand	Poorly sorted	Strongly fine-skewed	Very lepto-kurtic	3.64
IV	Very fine sand	Poorly sorted	Strongly fine-skewed	Lepto-kurtic	4.17
V	Very fine sand	Poorly sorted	Strongly fine-skewed	Lepto-kurtic	5.18
VI	Coarse sand	Very poorly sorted	Strongly fine-skewed	Platy-kurtic	4.44
VII	Fine sand	Poorly sorted	Coarse-skewed	Very lepto-kurtic	3.90
VIII	Coarse silt	Very poorly sorted	Near symmetrical	Very lepto-kurtic	4.57
IX	Medium sand	Very poorly sorted	Near symmetrical	Platy-kurtic	5.65
X	Very fine sand	Poorly sorted	Strongly fine-skewed	Lepto-kurtic	6.32
XI	Very fine sand	Very poorly sorted	Near symmetrical	Very lepto-kurtic	5.98
XII	Very fine sand	Poorly sorted	Strongly fine-skewed	Meso-kurtic	6.39
XIII	Medium sand	Very poorly sorted	Fine-skewed	Lepto-kurtic	6.45
XIV	Medium sand	Very poorly sorted	Near symmetrical	Platy-kurtic	2.82
XV	Very coarse sand	Poorly sorted	Strongly fine-skewed	Very lepto-kurtic	3.09

Grain-size distributions of sediments have been studied in order to clarify the mechanics of transportation and deposition of lake sediments. Thus, a C-M patterns application is used to indicate and interpret the mechanics of transportation of lake sediments. Values of 'C' first percentile, are plotted against the 'M' median grain diameter.

Results indicated that mode of transportation of sediments in areas facing the drains were homogeneous suspension which was full in (S-R) segments. Also, mode of transportation of sediments of the lake's middle area and southward were homogeneous suspension (S-R) Abwat (site XII) and Dishdy (site XIII). Whereas Lagan area (site IX) was suspension with some rolling, mode of transportation of sediments at sites VI, VII, VIII, XI, XIII, and XV were by rolling (Passega, 1957, 1964; Passega and Byramjee, 1969; Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011; Fig.3).

3.3 Total Organic Matter (TOM%)

Organic matter content of investigated coastal wetlands fluctuated between 2.882% westward at Baraghita area (site XIV) and 6.88% at DP of Bahr El-Baker drain (site I), as seen in Table 5.

TOM% shows positively moderate correlations with silt, clay, and also mud (R=0.53, R=0.58 and R=0.52; $P<0.05$, respectively; Table 6). This may be due to the fermentation process, which may occur through sinking of dead microorganisms yielding organic matter (Dinakaran and Krishnayya, 2011).

3.4 Distribution of Heavy Metals

Fig.4 shows the distribution of heavy metals in the studied wetland. As expected, iron (Fe) was the most abundant heavy metal in Lake Manzala sediments. Mean concentrations of measured metals in the investigated wetland were found to be in the following order; Fe>Mn>Zn>Pb>Cu>Cr>Ni. Fe concentration ranged from 5.93 to 28.66 mg g^{-1} from the west at Degwy area (site XII) to El-Gamil new inlet (site VI), respectively. In agreement with Beltagy (1974), who stated that iron and manganese

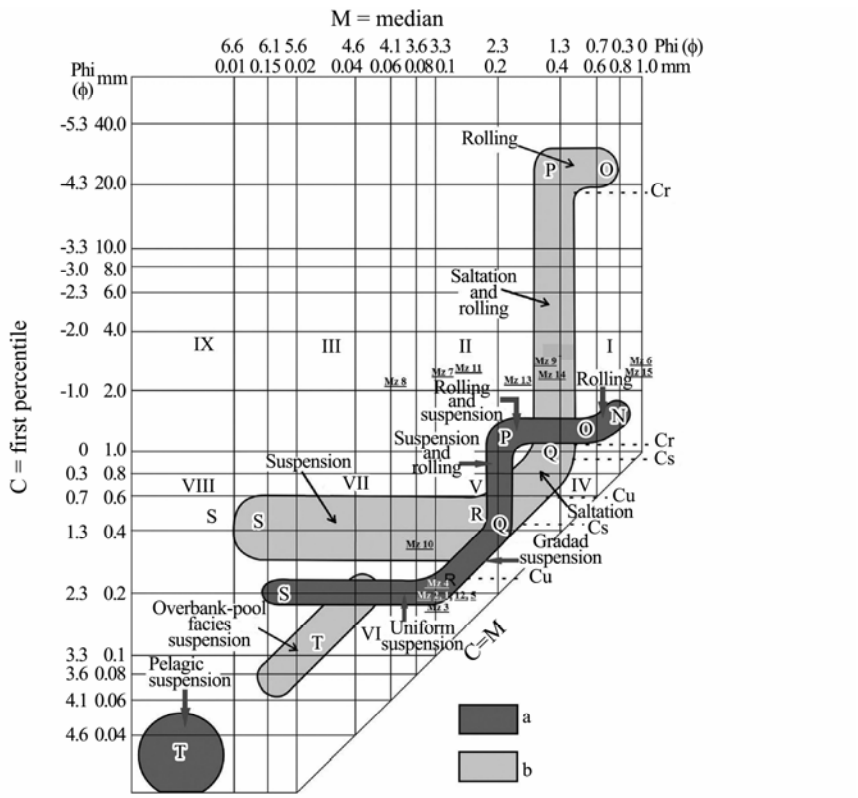

Fig.3 C-M diagram for Lake Manzala sediment. a, according to Passega (1964) and Passega and Byramjee (1969); b, according to Ludwikowska-Kędzia (2000).

Table 6 Spearman correlation matrix showing the coefficients of correlation among studied variables

Variables	Sand%	Silt%	Clay%	Mud%	Mz	Sorting	Sk_I	K_G	OM%	Fe	Mn	Zn	Cu	Ni	Cr	Pb
Sand%	**1**															
Silt%	**−0.88****	**1**														
Clay%	0.36	**0.69****	**1**													
Mud%	0.03	**0.99****	**0.74****	**1**												
MZ	**−0.72****	**0.87****	**0.84****	**0.91****	**1**											
Sorting	0.50	−0.21	-0.23	−0.20	−0.33	**1**										
Sk_I	**0.54***	−0.04	0.32	0.02	0.18	**−0.67****	**1**									
K_G	−0.08	0.17	**0.56***	0.14	0.18	−0.33	0.06	**1**								
OM%	−0.06	**0.53***	**0.58***	**0.52***	0.41	0.25	0.08	−0.30	**1**							
Fe	−0.10	−0.26	−0.32	−0.23	−0.26	0.03	−0.08	−0.07	−0.03	**1**						
Mn	**−0.69****	0.11	−0.25	0.10	−0.04	0.48	−0.46	0.31	0.10	0.27	**1**					
Zn	0.30	−0.06	0.08	−0.02	0.19	**−0.59***	0.44	0.09	−0.10	0.34	−0.26	**1**				
Cu	0.18	−0.26	−0.06	−0.21	−0.02	−0.48	**0.54***	−0.04	−0.12	0.48	−0.21	**0.93****	**1**			
Ni	−0.13	−0.14	−0.30	−0.10	−0.13	−0.26	0.31	−0.13	0.06	**0.61****	−0.06	**0.63****	**0.73****	**1**		
Cr	0.06	0.01	−0.13	0.05	0.12	−0.39	0.20	0.08	0.04	**0.64****	0.01	**0.78****	**0.74****	**0.80****	**1**	
Pb	0.28	−0.16	0.00	−0.13	0.06	**−0.54***	0.43	0.05	0.00	0.31	−0.30	**0.91****	**0.84****	**0.60****	**0.81****	**1**

Notes: Values in bold are at significance, where * at $P < 0.05$ and ** at $P < 0.01$. OM, organic matter; Mz, Mean size; Sk_I, Skewness; K_G, Kurtosis.

are closely associated in a geo-chemical cycle, manganese distributions came after those of iron. Mn varied from 288 to 764 $\mu g\,g^{-1}$ at DP of Hados drain and West Bashteer, regions II and VII, respectively. The distribution of zinc (Zn), copper (Cu) and nickel (Ni) indicated harmonic trends along all the studied areas with ranges of 187–17.56, 91.77–17.54, and 62.74–13.01 $\mu g\,g^{-1}$, respectively. Thus, the highest concentrations were at DP of Baher El-Bakar drain (site I), while the lowest levels were westward at Degwy area (site XIII).

High levels of heavy metals in sites facing drains indicate the effect of drains and discharge containing industrial, agricultural, and sewage wastes. High concentrations of heavy metals at the site facing New El-Gamil inlet may reflect the entrance of Mediterranean Sea water through New El-Gamil inlet, which is contaminated with industrial, agricultural, and sewage, as well as domestic effluent coming from the neighboring coastal governorate.

The results of the correlation analysis between studied heavy metals and other parameters are presented in Table

6. Results indicated that there were high positive correlations between copper and Zn, Ni, Cr, and Pb (R=0.93, R = 0.73, R = 0.74 and R = 0.84, respectively; P < 0.01), while it moderately correlated with skewness (R=0.54; P < 0.05). Iron moderately positively correlated with both Ni and Cr (R=0.61, and R=0.64, respectively; P<0.01). There was also a positive correlation between Zn and Ni, Cr, and Pb (R=0.63, R=0.78 and R=0.91, respectively; P < 0.01), while Zn and Pb were negatively moderately correlated with sorting (R=−0.59 and R=−0.54, respectively; P<0.05). There was a high positive correlation between Cr-Ni and Cr-Pb (R = 0.80 and 0.81, respectively; P < 0.01), while there was moderate positive correlation between Pb and Ni (R=0.60; P<0.01; Table 6).

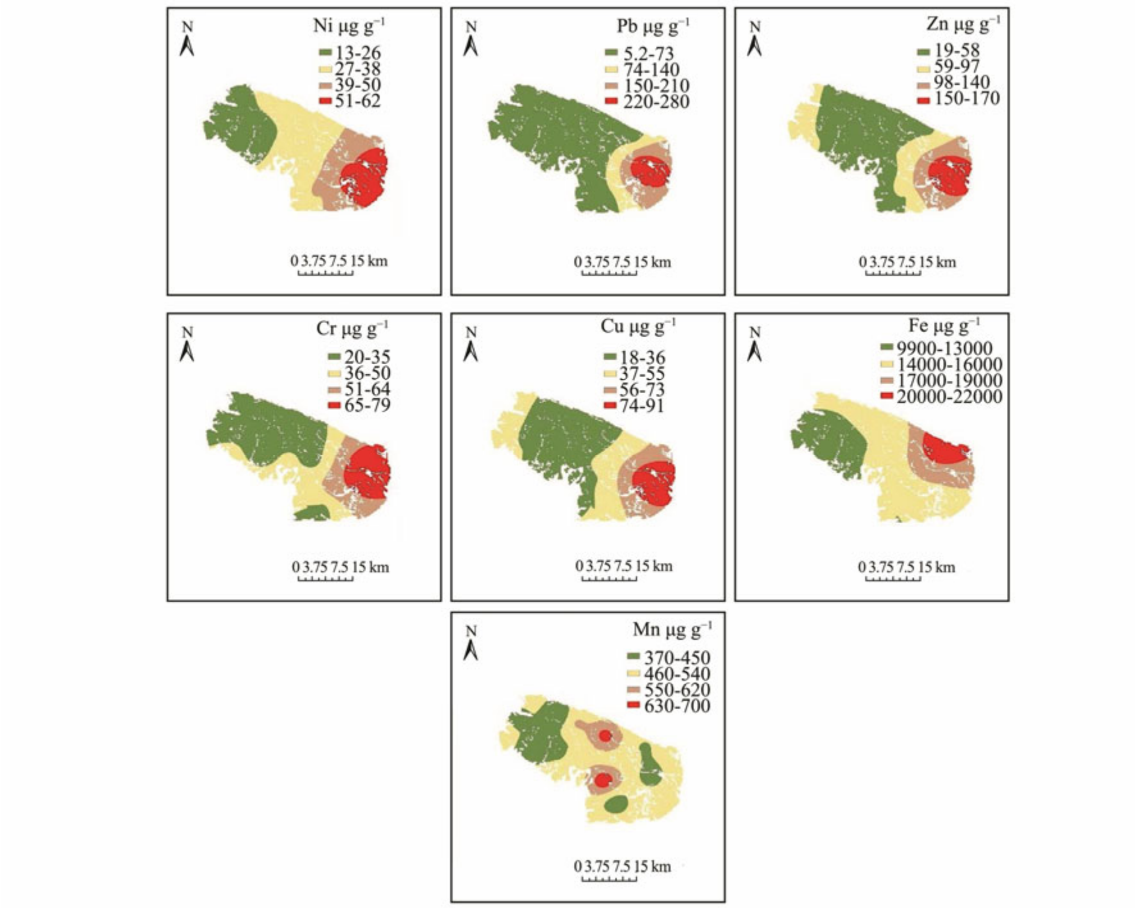

Fig.4 Spatial distribution of studied heavy metal in Lake Manzala sediments using GIS technique.

To assess the adverse biological effects and sediment toxicity of lake sediments, comparison of SQGs (USA DOE (Jones *et al*., 1997); US EPA, 1999; C-EQG, 2002) with results was done. According to USA DOE (Jones *et al*., 1997), only average values of Zn and Cr were in the range of TEC, while average values of Cu, Ni, and Pb were in the range of HNEC. By comparing average values of investigated metals with US EPA (1999), it was clear that only Zn was within range. According to C-EQG, only Cr and Pb were within PEL range, while Cu and Zn were within ISQG range, as seen in Table 7.

Table 7 Concentration of studied metals in Lake Manzala sediment, geochemical background and the toxicological reference for sediments ($\mu g\, g^{-1}$)

Metal	Present study average	Earth crust[a]	USA DOE[b]			US EPA[c]	C-EQG[d]	
			TEC	PEC	HNEC		ISQG	PEL
Fe	14007	56300						
Mn	461.20	850						
Zn	62.64	70	159	1532	541	110	123	315
Cu	41.64	55	28	77.7	54.8	16	357	197
Cr	39.44	100	56	159	312	26	37.3	90
Ni	32.18	75	39.6	38.5	37.9	16	−	−
Pb	55.42	12.5	54.2	396	68.7	31	35	91.3

Notes: TEC, Threshold effect concentration; PEC, Probable effect concentration; HNEC, High no effect concentration; ISQG: Interim sediment quality guideline; PEL, Probable effect level; US DOE, U.S. Department of Energy's; US EPA, U.S. Environmental Protection Agency; C-EQG, Canadian Environmental Quality Guidelines. [a], Taylor (1964); [b], Jones *et al.* (1997); [c], US EPA (1999); [d], Environment Canada (2002).

3.5 Sediment Contamination Assessment

3.5.1 Contamination factor (*CF*), contamination degree (*CD*) and modified contamination degree (*mCD*)

Results indicated that the values of *CF* for Fe, Mn, Ni, and Cr fell within <1 (low contamination). On the other hand, Zn showed low contamination (<1) at all sites, except at areas facing Bahr El-Baker drain, New El-Gamil

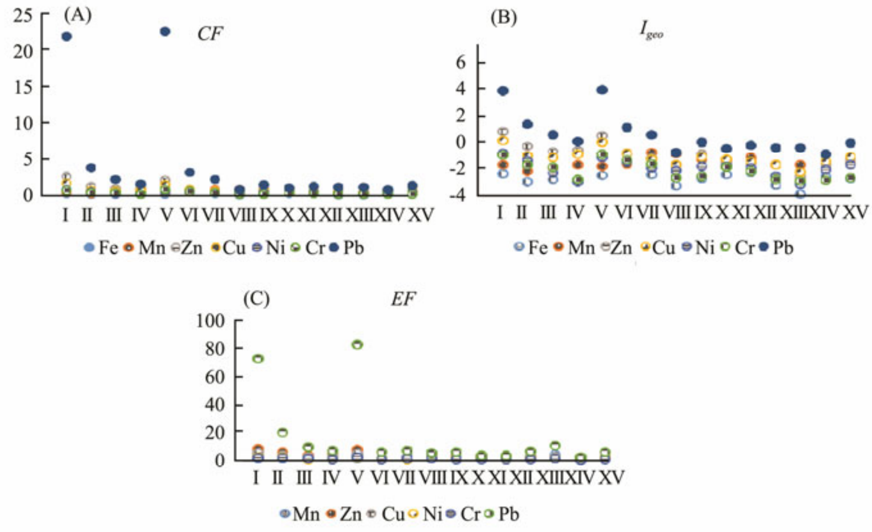

Fig.5 (A) Contamination factor (*CF*), (B) Geo-accumulation index (I_{geo}) and (C) Enrichment factor (*EF*) for studied metals in Lake Manzala sediment.

inlet, and DP of Faraskour drain (*CF*), which showed relatively moderate contamination status with values of 2.6, 2.17, 1.24, and 1.01, respectively. Meanwhile, the contamination by Cu along all studied areas was low (< 1), except at regions facing Bahr El-Baker drain , where it showed relatively moderate contamination status with values of 1.67 and 1.51 at sites I and V (areas facing Bahr El-Baker drain), respectively. Pb showed a distribution profile of contamination ranging between low contamination ($CF<1$) at Abwat and Baraghita regions, considerable

contamination northward at New El-Gamil inlet, and DP of Hadous drain with *CF* values of 3.83 and 3.22, respectively. Pb showed very high contamination at areas coping with Bahr El-Baker drain (sites I and V) with *CF* values of 22.58 and 22.54, respectively, while sites III, IV, VII, IX, X, XI, XII, XIII, and XIV showed relatively moderate contamination status with values of 2.25, 1.56, 2.21, 1.52, 1.10, 1.27, 1.14, 1.15, and 1.43, respectively, as seen in Fig.5A.

Furthermore, the average degree of contamination (*CD*) indicated that most of the sites had $CD<1.5$ (*i.e.*, low degree of contamination), except at areas facing Bahr El-Baker drain (sites I and V), which was very highly contaminated with $CD<28$, and at both New El-Gamil inlet and DP of Hadous drain, which were moderately contaminated. Generally, according to the average modified degree of contamination value for the studied heavy metals that exceed $mCD<1.5$, Lake Manzala can be classified as a low-contaminated area except near areas coping with Bahr El-Baker drain (sites I and V, where *mCD* were 4.04 and 4.06, respectively), which can be classified as a high contaminated area, per Fig.6.

3.5.2 Geo-accumulation index (I_{geo})

Results of I_{geo} for the studied heavy metals indicated that Lake Manzala sediments can be classified as Class 0 ($I_{geo}<1$; *i.e.*, practically uncontaminated; Fe, Mn, Ni, and Cr). Meanwhile, Cu and Zn are classified as Class 0 ($I_{geo}<1$, *i.e.*, practically uncontaminated at most lake areas). However, at regions facing Bahr El-Baker drain, lake sediments are classified as Class 1 ($0<I_{geo}<1$, *i.e.*, uncontaminated to moderately contaminated). Generally, Pb may classified as Class 0 to Class 1 for most of the lake regions, while DP of Hadous drain and at New El-Gamil inlet are recorded as Class 2 ($1<I_{geo}<2$, *i.e.*, moderately contaminated), and regions facing Bahr El-Baker drain (sites I and V) can be classified as Class 4 ($3<I_{geo}<4$, *i.e.*, heavily contaminated). Therefore, according to Müller (1981), Lake Manzala is uncontaminated with Fe, Mn, Cr and Ni, Cu, and Zn, while it is heavily contaminated with Pb, with an order of Pb > Zn > Cu > Fe > Mn > Ni > Cr (Fig.5B).

3.5.3 Enrichment factor (*EF*)

According to Sakan *et al*. (2009), the measured ranges of *EF* for Ni and Cr were 0.98–3.09 and 0.83–2.95, respectively (*i.e.*, ranged from depletion to mineral to moderate enrichment), whereas, Mn, Zn, and Cu ranged from 0.97–5.51, 1.60–8.94, and 1.69–5.58, respectively (*i.e.*, ranged from depletion to mineral to significant enrichment). Pb over all lake sediments ranged between 3.2 and 10.03 (*i.e.*, moderate to significant enrichment), not including regions facing Bahr El-Baker drain (sites 1 and 5), which were 72.12 and 82.02 (*i.e.*, extremely high enrichment), respectively, and DP of Hadous drain, which was 20.12 (*i.e.*, very high enrichment). According to Zhang and Liu (2002), *EF* within the range of 0.05 and 1.5 indicate metal, which is only from crustal materials and natural processes, while an $EF>1.5$ point to anthropogenic sources. With an order of Pb>Zn>Cu>Mn>Ni>Cr, all found heavy metals can be introduced to the Lake Manzala from anthropogenic origins, especially Pb, since *EF* values in the sediments generally exceed 1.5, as seen in Fig.5C.

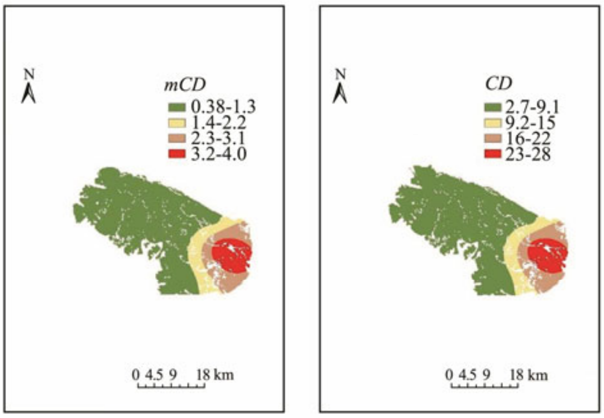

Fig.6 Contamination degree (*CD*) and modified contamination degree (*mCD*) for studied metals in Lake Manzala sediment using GIS technique.

3.6 Statistical Analysis of Results

The cluster analysis results showed that there were three groups, depending on studied parameters. The first group, which represents areas facing drain discharge (sites I, II, III, IV, and V), site VI, which represents the region facing New El-Gamil inlet, and sites X and XII, which represent the regions that are close to drain DP. The second group represents northern regions (site VIII), away from drain inflow, plus west-southward areas (site 13). The last group represents the remaining studied areas (Fig.7). ANOVA results showed that most sedimentological characteristics ($P<0.05$) and most of the studied metals directed this clustering.

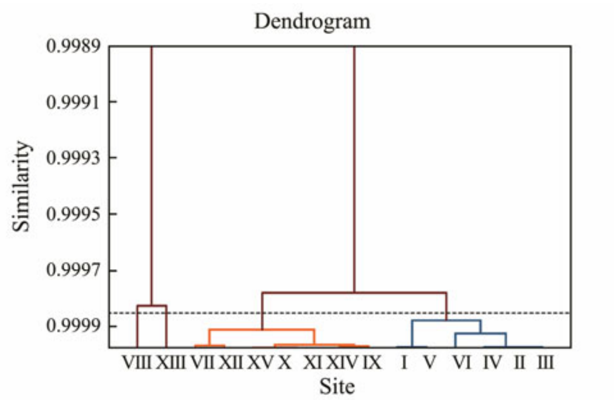

Fig.7 Dendrogram comparing the similarity of the sediment samples sites according to measured parameters.

4 Discussion

Coastal wetlands are foci for people through ecosystem services (*e.g.*, fisheries and tourism), as well as for biodiversity, *e.g.*, birds, fish, and vegetation. Sediment characteristics, such as sediment type and distribution, are major factors controlling, regulating, and characterizing wetland systems. They are also essential to the system's structure, and effective in management and conservation. Changes in sediment distributions and compositions indicate an array of environmental processes that operate during timescales. Minerogenic sediments are derived mainly from terrestrial erosion and are commonly characterized by textural analysis (Flower *et al*., 2009), while particle size distributions are primary indicators of transportation energy (Hakanson and Jansson, 1983; Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011). In Lake Manzala, as elsewhere, coarse sands in and near sea connections represent high-energy transporting environments, while fine sediments characterize more quiet depositional environments within the lake (El Wakeel and Wahby, 1970; Flower *et al.*, 2009; El-Said *et al*., 2014).

Lake Manzala varies from other Southern Mediterranean lagoons in many important characteristics. It is located at a shallow depression within the main Nile River Delta (Stanley and Warne, 1993), and riverine deposition is now stopped as a result of Aswan High dam building. Diminished sediment supply to the delta has inter alia caused erosion problems on the seaward margin of the lake (Shahin, 1985) with migration of redeposited bars (Ahmed *et al*., 2009). Furthermore, the fresh, but often contaminated Nile water inflow into Lake Manzala is now completely regulated (Thompson *et al*., 2009).

Grain-size analysis is one of the most important tools used for classifying environments of deposition, paleoenvironmental conditions, and subsurface depositional processes (Blott and Pye, 2001; El-Said *et al*., 2014; Farhat and Salem, 2015). In agreement with Flower *et al*. (2009), aquatic vegetation within the lake controls transportation and deposition of minerogenic sediment, and, together with high productivity, partly explains the high accumulation of carbonate shells (*i.e*., areas with high gravel fraction) and organic matter values in surface sediments from the western and central parts of the lake.

Areas facing drain effluent, where mud fractions are trapped and deposited immediately after entrance to the lake, hydraulic sorting controls relative abundance of mud fractions (silt and clay); coarse particles (silt) tend to accumulate in relatively shallow regions compared to finer clay particles, which redeposit in relatively deeper areas at the center of the lake. Distribution of mean grain size is mostly controlled by sediment sources. Studied areas received sediments from biogenic (alloctnous) and terrigenous (autoctonous) sources via different transportation agents. The change in mean grain size (very coarse sand to coarse silt) may prove different erosion and accretion regions, as well as the impact of shell fragments. Sediment sorting clarifies the changes in degree of kinetic energy and the effect of depositional regime on grain-size characteristics (Pettijohn, 1975; Blott and Pye, 2001). Sorting ranges (poorly to very poorly sorted) indicate turbulent conditions. Duane (1964) reported that negative skewness illustrates environments undergoing erosion, while positive skewness signals depositional trends, and, thus, the positive skewness of Lake Manzala indicates that it is classified as an environment undergoing depositional trends, and thus, in agreement with Flower *et al*. (2009) and El-Said *et al*. (2014).

Grain-size distribution in sediments has been studied in order to clarify the mechanics of transportation and deposition of lake sediments. The C-M patterns of sediments (Passega, 1957, 1964; Passega and Byramjee, 1969; Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011) make clear the mechanics of sediment transport including traction (rolling), saltation (homogenous suspension), and suspension with rolling. As deposits of various environments give characteristic patterns, C-M patterns of the studied sites mostly indicate homogenous suspension, especially at regions facing drain inflow, where suspended matter comes with drain water to deposit immediately upon entrance to the lake (possibly due to a sudden decrease in water velocity). In addition, elsewhere, redeposition of fine fractions in relatively deeper areas of homogenous suspension occurred. These agree with Passega (1964), Passega and Byramjee (1969), and Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011), who stated that homogenous suspension suggests higher turbulence, which proposes defining characteristics of grain-size distribution in sediments transported by running water and turbidity currents. Other sites indicated rolling patterns, where values of mean size increased (coarse fraction increase), indicating the impact of shell and shell fragments. C-M application is widely used by many authors to interpret different depositional environments (Srivastava *et al*., 2012; Pisarska-Jamroży, 2013; Farhat and Salem, 2015).

Organic matter is accumulated in the sediment because of the influence of terrigenous materials and the decay of living material by the action of microorganisms (Draz, 1983). Generally, lightweight materials characterize the composition of organic matter. In addition, composition and structure of organic matter in the sediment vary owing to its origin and geological history in aquatic environments (Grathwohl, 1990). A major anthropogenic source of organic matter in the lake was water entering the lake through drain effluent (southward), in addition to lake-sea connections through inlets (west-north region). Furthermore, organic matter, which adsorbed on the surfaces of clay minerals and oxide, was preserved in surface sediments (Dinakaran and Krishnayya, 2011). Decreasing organic matter may have occurred due to decomposition and transformation after sedimentation. The fine-grained nature of sediments, along with high productivity in the water column, explain the high content of organic matter in sediments in some sites of the lake. In agreement with Huang and Lin (2003), El-Said *et al*. (2014) and Goher *et al*. (2014), there was a positive correlation between mud fraction and organic matter, and both act as regulators of each other in the sediments.

Sediment is typically considered a major catchment for pollutants in the aquatic environment, where suspended sediment particles are deposited and the adsorbed contaminants are removed from the water column (Aston and Chester, 1973). Heavy metals bind to aquatic sediment, and only a small percentage becomes dissolved in the water column. They can extent widely into the food chain through aquatic organisms. Studies of heavy metal abundance in aquatic sediments must consider the sedimentary structure and possible allochthonous sources (Aston and Chester, 1973). Regions facing drain effluent record high concentrations of most studied heavy metals; these drains carry agricultural drainage, and industrial and domestic wastes, which indicate allochthonous sources; these results are in agreement with Zahran *et al*. (2015), but in the present study, values of studied heavy metals were higher than those recorded by Zahran *et al*. (2015). This may be due to differences in sampling sites (in the present work, samples were collected from sediment traps in areas as near as possible to drain DP). Many significant problems in metal studies, including uncertainty, originate from sampling, sample preservation, and sample analyses, and they require the use of difficult analytical procedures and certified reference materials (El-Said *et al*., 2014). There were variations in manganese concentrations in the lake sediment, possibly due to the variations in grain size, where the clay-rich sediments are enriched with manganese (Draz, 1983).

On the other hand, high Fe contents in regions facing inlets (at the entrance of the lake) may indicate the entrance of seawater through inlets from the Mediterranean Sea, which is contaminated by industrial, agricultural, and sewage waste, as well as domestic effluent coming from neighboring governorates.

Correlation analysis provides little information about the sources of metals; relations between Fe and Mn elements showed low or no significant correlations. It is obvious that the heavy metals with positive correlations were considered to have similar sources as estimated by Dan *et al*. (2014) (*e.g*., Zn, Cu, Ni, Cr, and Pb). Also, the positive correlations between studied metals indicated either similar origin or a common sink in the lake sediments, as well as the association of these metals with iron and manganese oxides as reported by Hassouna (1996). Results agreed with Dossis and Warren (1980); Gohar *et al*. (2014), who stated that the deposition of copper and zinc were enhanced by the adsorption of both copper and zinc on hydrated iron and manganese oxides.

Several guidelines of sediment quality have been proposed to assess adverse biological effects and sediment toxicity (Jones *et al*., 1997; US EPA, 1999; C-EQG, 2002). Areas facing drain effluent, such as Bahr El-Baker drain and inlet region, show sediment quality above the guideline limits. This supports the idea stating that drain effluent and inlets are the most effective sources of metals in Lake Manzala.

CF of all studied heavy metals were low ($CF<1$), not including regions facing drains, especially Bahr El-Baker; the inlet showed relatively moderate contamination. Noticeably, most *CF* values for Pb indicated moderate to very high contamination. These results agreed with Zahran *et al*. (2015), except for Pb, which may have been due to differences in sampling sites. *CD* is the sum of the *CF* for measured pollutant metals. It is designed to provide a measure of the grade of total contamination in the sampling site (Hakanson, 1980). As expected, drain effluent at Bahr El-Baker drain was the most productive source of metals in Lake Manzala, hence the region facing it recorded a considerable degree of contamination. The *mCD* is based on integrating and averaging all measured metals data for sediment samples. This modified equation can provide an integrated assessment of enrichment and contamination impacts of assemblages of pollutants in sediments (Abrahim and Parker, 2007). Also, *mCD* indicated Bahr El-Baker drain is the basic anthropogenic source of metals in Lake Manzala, as only areas facing Bahr El-Baker drain recorded $mCD>4$. This is due to the drain, which receives wastewater (agricultural drainage, industrial and domestic wastes) from a very densely-populated area of the Eastern Delta.

One of the most widely used approaches to characterizing the degree of anthropogenic pollution and establishing enrichment ratios is the *EF* (Zakir *et al*., 2008). *EF* was developed to illustrate the origin of metals in the atmosphere, rainfall, and seawater (Duce *et al*., 1975). It was formerly used for soils, lake sediments, and other environmental materials (Gong *et al*., 2008).

EF is an appropriate yardstick both for measuring metal distribution trends and comparisons between areas (Sinex and Helz, 1981). *EF* has been widely used to identify and quantify the anthropogenic origin of heavy metals since the 1970s (Goher *et al*., 2014; Lario *et al*., 2016; Saher and Siddiqui, 2016). It is supposed that high *EF* values illustrate an anthropogenic source of trace metals. Bioavailability and toxicity of trace metals in sediment depend not only on the metals' concentration, but also their chemical form (Kwon *et al*., 2001). It can be indirectly concluded that sediment samples contain heavy metals with the highest *EF* values; they may act as potential sources of mobility and bioavailability in the aquatic environment (Mohiuddin *et al*., 2010). Zhang and Liu (2002) stated that an *EF* between 0.05 and 1.5 indicate metal that is only from crustal materials and natural processes, while, an $EF>1.5$ points to anthropogenic sources, particularly regions facing drain inflow, with an order of Pb > Zn > Cu > Mn > Ni > Cr. All identified heavy metals can be introduced to Lake Manzala from anthropogenic origins, especially Pb, since *EF* values in the sediment generally exceed 1.5. The Igeo enables the assessment of contamination by measuring the difference between current and reference concentrations (Ji *et al*., 2008). I_{geo} was widely used after the 1950s, mainly in metal pollution studies. Müller (1969) was the first user of this index in sediments. It has also been used largely to assess contamination in harbors (Chen *et al*., 2007), lakes (El-Said *et al*., 2014; El-kady *et al*., 2015), soils (Rivera *et al*., 2015), and even rivers (Lario *et al*., 2016; Ma *et al*., 2016) and reservoirs (Goher *et al*., 2014; Palma *et al*., 2015). I_{geo} showed the same tendency as *EF*, indicating that Lake Manzala is mostly uncontaminated, except in zones facing drains; inlet Lake was heavily contaminated, especially with Pb.

5 Conclusions

Lake Manzala receives huge amounts of drainage water containing several types of waste, including domestic, industrial, and agricultural, from four main drains and several pumping stations. Drainage waters enter the lake mainly from the southern and eastern sides as well as from the northern inlet connecting to the Mediterranean Sea. Clay fractions in Lake Manzala tend to accumulate in relatively deep waters (redeposited in deeper waters at the center of the lake) compared to the coarse silt that accumulated in relatively shallow water. Fine fractions are trapped at and near regions occupied by drain inflow. Areas facing drain effluent were characterized by homogenous suspension as mode of transportation, whereas other regions were mostly characterized by rolling. Fine fractions were rich with organic materials and acted as storage for trace metals, particularly at drain DP, whereas coarser fractions resulted from accumulation of carbonate shells and their fragments.

The present work indicates that lake sediments adsorbed high levels of heavy metals at areas facing drains that were under the influence of discharged water, and near the inlet. This was reflected in the contamination being from industrial, agricultural, sewage, and domestic waste sources.

Results indicated that Lake Manzala was extremely contaminated with Pb (particularly in zones influenced by drain discharge). Obtained data revealed that heavy metals in the lake basin are mainly from anthropogenic sources and indicate that areas facing the drain DP and inlet regions are significantly different from other lake areas. These results could be helpful in the integrated management of wetlands similar to Lake Manzala.

Acknowledgement

The authors wish to thank Dr. Walid Ali for his helpful comments at various stages in the work.

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(Edited by Chen Wenwen)