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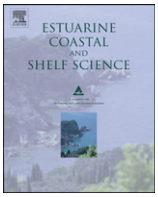

Lagoons of the Nile delta, Egypt, heavy metal sink: With a special reference to the Yangtze estuary of China

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ABSTRACT

Lagoons of the Nile delta are a vital aquacultural base for millions of people in Egypt. Since the 1960s, when the Aswan High Dam was completed, the estuary has changed from high to low turbidity and this has dramatically altered the eco-hydrological environment. In this study we attempt to explore the spatial and temporal distribution of heavy metals (Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) based on 6 short sediment cores recovered from Manzala, Burullus and Edku lagoons on the Nile delta. Radiometric dating indicates that the upper 10–15 cm of the core sediment is post-Aswan Dam. Manzala on the eastern delta coast is severely polluted by almost all metals analyzed in the present study, especially Mn, Pb, Zn and Cd, due to its connection to the city of Cairo, and the direct human input from neighboring megacities, where the petro-chemical industry is thought to be a major source. Although Burullus on the central delta coast has the lowest concentrations of Mn and Pb, there is an increasing trend, implying a linkage to local agricultural sources, and the recently expanding megacities in the central delta plain. Edku on western delta coast seems remote from any major pollution sources, but higher Mn, Pb, and Zn in the upper portion of the lake sediment suggest human influences from Alexandria to the west via the littoral current. The horse-saddle distribution pattern of polluted metals along the Nile coast, as evidenced by the Enrichment Factor (EF), is closely associated with the regulated runoff to the lower delta plain and coast, where extremely low precipitation occurs. This physical setting is certainly prone to concentrating anthropogenic heavy metals in the lagoons. The opposite example is the intensively-cultivated Yangtze estuary in China, where monsoonal precipitation flushes out a huge amount of metals as manifested by the lower EF than that of the Nile.

1. Introduction

River water discharges a large amount of sediment load into the seas, together with abundant organic and inorganic constituents. Fine-grained sediment that serves as an effective carrier of adsorbed heavy metals has been deposited selectively in the estuarine wetlands in association with littoral currents (Chen et al., 2004). Intensifying anthropogenic activities adds more heavy metals into the estuaries, which has caused an adverse impact on estuarine eco-health through food chain transformation (Siegel et al., 1994; Soliman et al., 2006).

The Nile River of Egypt is an unusual river system because of its arid climate setting and the impact of the Aswan Dam, completed in 1964. The river has built its huge delta on the southern Mediterranean coast and this supports >80 million people, whose livelihoods are mainly dependant on agriculture and aquaculture (Hamza, 2009). In recent decades, as a result of rapid economic development, increasing population in the delta region and associated industrialization exerts high environmental pressures. Industrial wastes and municipal effluents have been largely pumped into the delta coast lagoonal wetlands, causing eco-environmental degradation with significant public health concerns (Easa et al., 1995; Soliman et al., 2006).

Over the past decades, many studies on heavy metals have been documented in the four lagoons (Manzala, Burullus, Edku and Mariut) of the Nile delta, through studies on sediment (Siegel et al., 1994; Chen et al., 2010a,b), water (Abdel-Moati, 1990), fish (Adham

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et al., 1999; Rashed, 2001) and plants (Radwan and Salama, 2006; Abdel-Azeem et al., 2007). These helped reveal various distribution patterns of heavy metals on the delta coast. Especially, the Mariut lagoon sited close to the city of Alexandria has drawn much concern due to its notoriously high pollution levels (Abdel-Shafy and Aly, 2007). Less attention has been paid to the other three lagoons though a few papers record some attempts. For instance, Siegel et al. (1994) indicated that the southeastern Ginka subbasin of Manzala lagoon had a high metal loading and other areas of the lagoon didn't. Abdel-Moati and El-Sammak (1997) assessed the man-made impact on the environment in the surface sediment of the three delta lagoons during the last 20 years. Chen et al. (2010a, b) revealed an increasing trend of heavy metals in the upper 10-cm core sediments in Burullus lagoon with Mn, Pb and Cd as the diagnostic heavy metals. However, information on heavy metals in the other three coastal lagoon sediments is still quite limited, especially taking into consideration the spatial and temporal distribution of heavy metals from the perspective of the whole delta both pre- and post-Aswan Dam.

The Yangtze is a typical monsoon river supplying a huge amount of discharge and sediment to its estuary. Heavy metal-related issues have also risen due to the rapid economic growth in the recent decades (Chen et al., 2004). It is notable that both the Nile River and Yangtze River have been undergoing tremendous changes and the intense anthropogenic activities (e.g. reclamation and urbanization, upstream damming, etc.) under their specific physical settings must have played a crucial role in the formation of subsequent pollution patterns in their lower deltas. Moreover, previous studies on the two deltas have mainly focused on the distribution and contamination levels of heavy metals, but the process mechanisms controlled by both natural and anthropogenic forces are still unclear. We thus propose a comparison between the two deltas based on the information from sediment cores, to compare and contrast the distribution patterns of heavy metals linked to the regional physical settings and anthropogenic forcing. The objectives of the present study are not only to reveal heavy metal distribution, but also to address related issues raised by local coastal administration.

2. Background

2.1. The Nile River and Nile delta

The Nile traverses a variety of landscapes and a medley of cultures, flowing from its remotest highland regions (Equatorial lakes plateau and Ethiopia plateau) with abundant precipitation (1000–2000 mm a^{-1}), to the lowland coastal plain with semiarid to arid conditions. The river bifurcates into the Rosetta and Damietta branches enclosing the delta region between them (Dumont, 2009). Egypt is the most downstream country traversed by the Nile River, and is well known for its arid climate with the precipitation varying from ~50 to 100 mm a^{-1} along the Nile coast. The arid climatic conditions in Egypt inevitably lead to heavy reliance on the freshwater of the Nile River released annually from the Aswan High Dam (AHD), approximately 55.5 km^3 a^{-1} according to the agreement signed between Egypt and Sudan in 1959, which accounts for 95% of annual water requirements of Egypt. Though the total volume of water released annually from the AHD is similar to the original average annual discharge (~84 km^3, 1899–1959) (Hamza, 2006), only about half of it reaches the delta (~30 km^3) (Stanley, 1996). One-third of this amount is lost in the delta by evaporation and infiltration to groundwater aquifers (Sestini, 1992). On the delta plain, the Rosetta and Damietta branches are heavily extracted for Egyptian agricultural irrigation via thousands of canals extending to the coastal lagoons and wetlands. Consequently, much less of the Nile water than originally flows through the branches into the sea (Stanley, 1996).

The Nile delta is located on the Egyptian Mediterranean coast, covering an area of 22,000 km^2 with a mean tidal range of 0.3–0.4 m and a mean wave height of 0.4–0.7 m in the estuary (Frihy, 2003). The Nile River carried a sediment load of 1.60–1.78 $\times$ 10^8 t a^{-1} into the sea before the 1960s, which abruptly dropped to almost none presently due to impoundment of the AHD after 1964 (Sharaf El-Din, 1974). In addition, since the 1990s the large-scale construction of protective hydro-engineering structures along the coast has been implemented to combat against strong coastal erosion, largely due to weakening fluvial processes related to the AHD (Frihy et al., 2003).

Egypt is the only country in the Nile basin that has intensive industrialization. Egyptian industry has experienced a boom period fueled by low-cost hydroelectricity since the 1960s and most industrial activities focus on the Greater Cairo and Alexandria regions (Wahaab and Badawy, 2004). Egyptian industry uses 0.638 km^3 a^{-1} of water, of which 0.549 km^3 a^{-1} is discharged back into the drainage networks, mostly connected to the delta lagoons (Wahaab and Badawy, 2004).

The lagoons of Manzala, Burullus and Edku consist in large part of the Nile coast from east to west (Fig. 1). They are in common shallow (~1 m), wind mixed basins, with salinity varying from fresh to brackish, and are important wetland reserves for the maintenance of biodiversity in Egypt (Ramdani et al., 2001). The lagoons are also regarded as optimal fishery grounds, supplying to 50% of the annual Egyptian fish yield (Hamza, 2006). At the same time, the lagoons serve as collection basins for agricultural drainage, municipal sewage, and industrial wastewater (Fig. 1). Consequently, Egyptian lagoons are suffering severe ecological degradation in relation to societal development (Hamza, 2006).

2.2. The Yangtze River and Yangtze estuary

Before the impoundment of Three Gorges Dam (TGD) the Yangtze River had a mean annual discharge of 924 km^3 and carried 4.86 $\times$ 10^8 t a^{-1} of sediment to the coast, of which approximately half was deposited to produce an extensive intertidal zone in the estuary (Zhang et al., 2009). The sediment discharge has decreased to approximately 1.7 $\times$ 10^8 t a^{-1} since the closure of TGD in 2003 while the annual discharge has remained unchanged (Yang et al., 2006; Chen et al., 2010a,b). The Yangtze estuary is a mesotidal estuary with a mean tidal range of 2.6 m. The waves are mainly wind-driven, with a mean wave height of 0.9 m and maximum wave height of 6.2 m (GSCI, 1988; GSII, 1996).

Shanghai, located in the Yangtze estuary (~50,000 km^2) is one of the largest cities in China and has a significant level of industrial activity. It has a direct impact on the Yangtze delta. It was reported that ~1.8 km^3 a^{-1} of industrial waste and domestic sewage are discharged into the Yangtze estuary (Dai and Gu, 1990). In addition, Yangtze estuary received ~30 km^3 a^{-1} of sewage discharged from its drainage basin, among which domestic and industrial wastewater volume consist of 32% and 68%, respectively (CWRC, 2006).

3. Material and methods

In 2007–2008, six short sediment cores were recovered manually in the lagoons of Manzala (M-1, M-2, M-3), Burullus (B-4) and Edku (E-1, E-2) (Fig. 1). Sediment cores were 7 cm in diameter, and ranged from 25 to 50 cm in length. Sediment cores were split and logged for sediment texture and structure, color and biogenic occurrences, etc.

There were 68 samples taken for grain-size analysis at 3 cm intervals from 6 sediment cores. Grain-size distribution was carried

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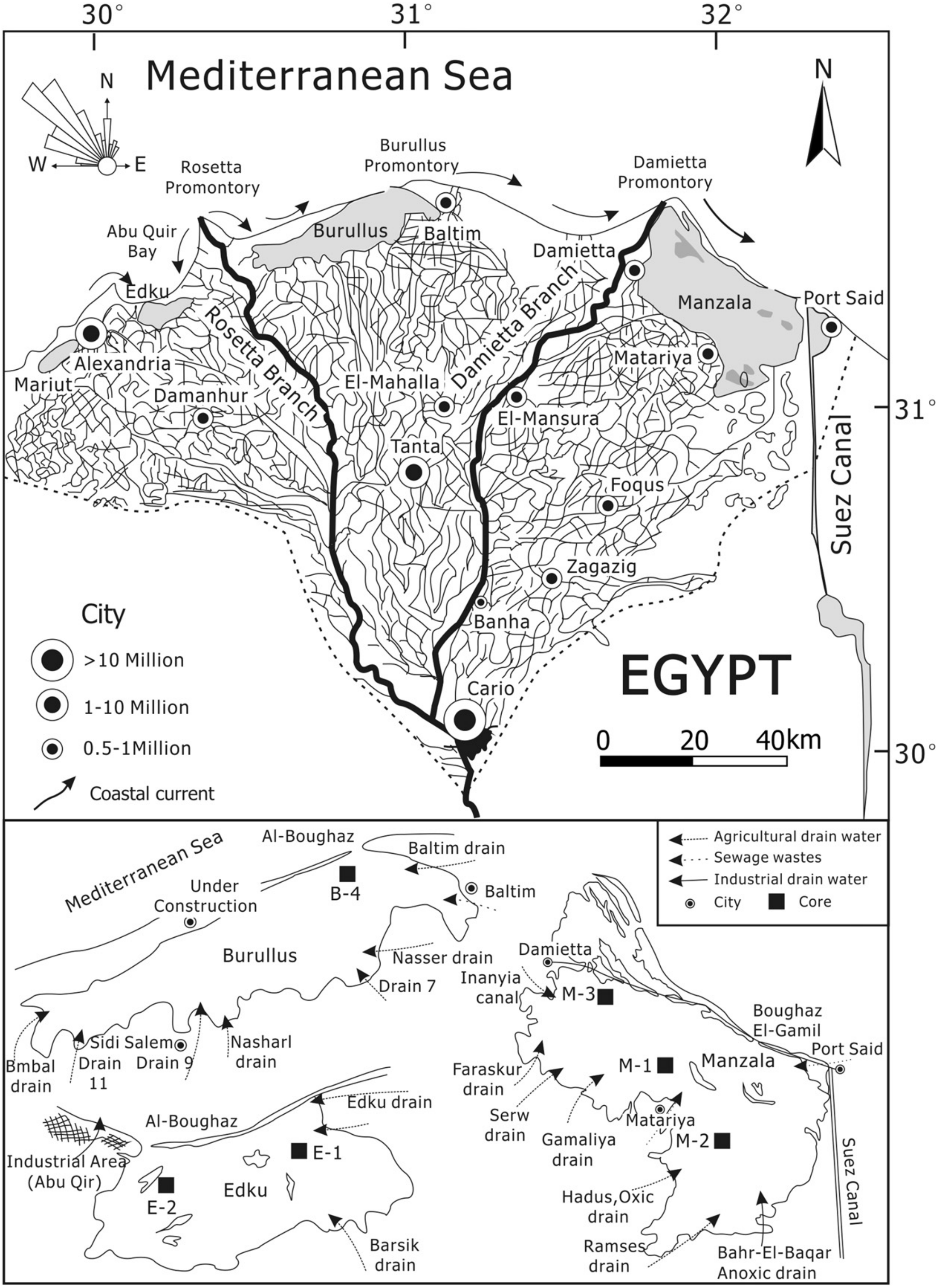

Fig. 1. Geographic location of the Nile delta coast, showing sampling sites in the lagoons. Major drains to the lagoons and megacities are also shown.

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out with a particle-size analyzer (LS13320). Sediment proportion, i.e. sand (63–2000 μm), silt (4–63 μm) and clay (<4 μm) was worked out for the present study. Forty-five (45) sediment samples were taken from M-1, B-4 and E-1 for radiometric (^{210}Pb and ^{137}Cs) analysis in Nanjing Institute of Geography and Limnology (NIGLAS), Chinese Academy of Sciences. For details of measurement procedures refer to Gu et al. (2011).

192 sediment samples were dried at 40 °C then ground and screened through an 88-μm sieve to obtain the fine-grained proportion. Dried samples (0.1 g) were dissolved by a three-step procedure (HNO_3 + HF + $HClO_4$) (Chen et al., 2001). Nine major and trace metal elements (Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) were measured by inductively coupled plasma-optical emission spectrometer ICP-OES (Varian 710-ES) in the laboratory of the East China Normal University (ECNU). Chinese National Reference Material (GSD-9), issued by the National Research Center for Geoanalysis, was analyzed along with the samples. The analytical values of the reference material were within the range of the certified values (~5–10%).

Aluminum is used for normalization in order to minimize grain-size effect while assessing metal distribution (Windom et al., 1983; Zhang et al., 1988). Well-identified radiometric records in our early report have revealed that ~10–15 cm of the lagoon sediments were deposited after completion of AHD in 1964 (for dating details refer to Gu et al., 2011). The Enrichment Factor (EF) was calculated by using the values of heavy metals of the surficial sediment (grouped from that of core sediment of 10–15 cm above) divided by the background (pre-Aswan dam) value of these metals. Heavy metals of the lower sediment section of B-4 was used as the reference background value of the pre-dam heavy metals, given the sedimentation rate of 0.22–0.27 cm a^{-1} as reported in our earlier study (Gu et al., 2011). The heavy metal data on the Nile coast (20) and that of Yangtze coast (14) were summarized from the published documents (Table 1). The EF values of the Nile and the Yangtze coast were also established for purposes of comparison. An EF of 1.5, as recommended by Zhang and Liu (2002) is used as an assessment criterion in the present study, i.e., when $0.5 < EF < 1.5$ this suggests that the trace metals may be entirely from crustal materials or natural weathering processes while $EF > 1.5$ suggests that a significant proportion of the trace metals are delivered from non-crustal materials. A cluster analysis between metals can differentiate sources and will help determine the diagnostic contaminated metals in the 6 sediment cores (Zhang et al., 2009). Cluster analysis (R-type cluster plot) was applied for all metals

Table 1
Heavy metal concentrations in the Nile and Yangtze estuaries grouped from the upper sediment section of <50 years and the background values, both defined primarily from B-4 of Burullus of the Nile delta, and Y7 off the Yangtze estuary (Chen et al., 2004).

	Cd	Cr	Cu	Fe (mg/g)	Mn	Ni	Pb	Zn	Reference
Nile									
Manzala	0.17		207	44.5	776		9.6	119	Saad et al. (1985)
Manzala	3.00		14	25.0				59	Saad et al. (1981a, b)
Manzala	7.50		42	36.5	716		51	67	Abdel-Moati and Dowidar (1988)
Manzala	0.50		128		933		42	245	Siegel et al. (1994)
Manzala	11.80		74	35.9	847		79	164	Abdel-Moati and El-Sammak (1997)
Manzala	15	221	105				99	188	Samir (2000)
Manzala	7	148	73				65	129	Samir (2000)
Manzala	1.61	69	9.3	23.2	995	31	16	101	This study
Manzala	1.91	127	55	29.7	1151	52	85	198	This study
Manzala	1.74	67	43	22.7	990	35	16	87	This study
Burullus	0.11		34	53.6	1009	72	11	78	Chen et al. (2010a, b)
Burullus	0.05		53	64.2	949	95	9	103	Chen et al. (2010a, b)
Burullus	0.09		68	77	918	115	6	80	Chen et al. (2010a, b)
Burullus	1.48	103	34	29.9	933	41	15	121	This study
Burullus			16	4.5	62				Darrag (1984)
Burullus	5.2		25	17.9	85		14	90	Abdel-Moati and El-Sammak (1997)
Rosetta prom.	0.88		61					122	Saad and Hassan (2002)
Rosetta prom.	0.77		43					135	Saad and Hassan (2002)
Rosetta prom.	0.84		16					81	Saad and Hassan (2002)
Edku	2.11	105	58	43.6	1125	54	18	276	This study
Edku	1.19	98	62	31.4	2373	51	15	146	This study
Edku	7.30		19	23.6	115		20	317	Abdel-Moati and El-Sammak (1997)
Mariut	10.00		106			242	69	232	El-Rayis (2005)
Mariut	10.80		574	31.9	598		114	229	Abdel-Moati and El-Sammak (1997)
Mariut	3.00		14	25				59	Saad et al. (1981a,b)
Mariut	0.20		38		958		7.3	94	Saad et al. (1985)
Background*	1.7	62	48	31.5	586	60	4.8	50	This study
Yangtze									
FQ		33	31				23	124	Chen et al. (2000)
SDK		39	50				28	162	Chen et al. (2000)
GL		36	34				25	118	Chen et al. (2000)
BLG	0.33	30	36	43.4	982		30	119	Chen et al. (2000)
PD	0.23	37	39				29	149	Chen et al. (2000)
DH	0.16	21	38	48.8	1167		31	104	Chen et al. (2000)
CM	0.21	41	27	34.9		29.5	17	80	Chen et al. (2001)
HS		39	29				21	99	Shen et al. (2006)
JDS		55	46				39	104	Chen et al. (2000)
Y4		16	33	25.5	511	28.6	17	66	Chen et al. (2004)
Y5		12	25	34.5	669	36.2	15	81	Chen et al. (2004)
Y6		12	43	33.9	582	36.9	21	80	Chen et al. (2004)
Y7		18	31	45.9	694	42.1	19	107	Chen et al. (2004)
Y9		10	22	26.9	575	38.2	18	77	Chen et al. (2004)
Background*	0.09	13	23	32.5	542	34.9	19	87	Chen et al. (2004); Xu et al. (1997)

* The background values of heavy metals of the Nile delta and the Yangtze estuary.

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derived from the upper core sediment sections (10–15 cm above). In addition, heavy metal data of surficial samples in the three sediment cores (B-1, B-2, B-3 from the Burullus lagoon) retrieved in our previous work are also employed to help reveal the spatial distribution of heavy metals on the Nile delta (Chen et al., 2010a,b).

4. Results

4.1. Core sediments

Cores M-1 and M-2 were both characterized by two marked sediment sections, i.e. the coarser sediment with some shell fragments in the upper core sediment section (0–10 cm in M-1; 0–24 cm in M-2) and the finer sediment with a few shell fragments in the lower core sediment section (10–25 cm in M-1; 24–30 cm in M-2) (Fig. 2). Core M-3 sediment was more homogeneous in nature with a few shell fragments (Fig. 2). Remarkable variations in sediment composition occurred in Core B-4. There were 4 sediment sections identified from the core top downward, i.e. darkish gray clayey silt (0–9 cm); darkish silty clay (9–20 cm); grayish sandy silt (20–30 cm) and grayish clayey silt (30–49 cm). Shell fragments appeared throughout the core, especially in the sandy sediments (Fig. 2). The sediment was more homogeneous in Core E-1, showing little shell debris in the core sediments (Fig. 2). Core E-2 was characterized by three sediment sections, i.e. darkish gray silty clay with a few shell fragments (0–5 cm), silty sand with abundant shell fragments (5–22 cm) and grayish silty clay with no occurrences of shell fragments (22–28 cm) (Fig. 2).

4.2. Heavy metals in the lagoons

4.2.1. Temporal distribution

The absolute and normalized heavy metal distributions in the 6 sediment cores are shown in Fig. 3. The results show that the absolute content of most heavy metals had a similar vertical trend to that after normalization (Fig. 3). But, there were still some metals whose contents showed a marked increase in the upper part (~10–15 cm) of the core sediment.

In Core M-1, some absolute heavy metal contents decreased gradually upward, for example, Al, Cd, Cr, Fe, Ni; others like Cu, Mn, Pb showed a decrease in their contents, but a quick increase above the core sediment of 10–15 cm. Zn showed a stable profile throughout, but with a noticeable peak at 10 cm core depth. However after normalization almost all metals demonstrated an increasing trend in the upper core section (<10 cm), with the exception of Zn that still kept the same distribution pattern as described above (Fig. 3).

In Core M-2, it seemed that all absolute heavy metal contents shared a similar temporal pattern where concentrations increased slightly from the bottom of the core upwards. This trend was much more obvious above the core depth of 10 cm. Of note, all normalized metals have kept the same trends as the absolute ones (Fig. 3).

In Core M-3, almost all heavy metals stayed within the stable distribution pattern in the core sediment, though their values fluctuated with time. Pb seemed the only one with a slight increase above the core depth of 10 cm. It was also of noted that all normalized metals have kept the same pattern as the absolute ones (Fig. 3).

In Core B-4, most absolute heavy metal concentrations fluctuated in the lower sediment section. Mn and Pb increased obviously above the core depth of 13 cm, while Al, Cd, Cr, Cu, Fe, Ni and Zn showed a sharp decrease above that sediment horizon. After normalization to Al, all metals displayed the highest values in the surface sediment (Fig. 3).

In Core E-1, most absolute heavy metal concentrations appeared fairly stable in the lower core sediment section, but there is an apparent increase in the upper core sediment section. Normalized metals remained the same pattern as that of the absolute ones (Fig. 3).

In Core E-2, absolute metals demonstrated great fluctuations throughout the core sediment, among which Mn, Pb and Zn reached their maximum values at the core top sediment. Al, Fe and

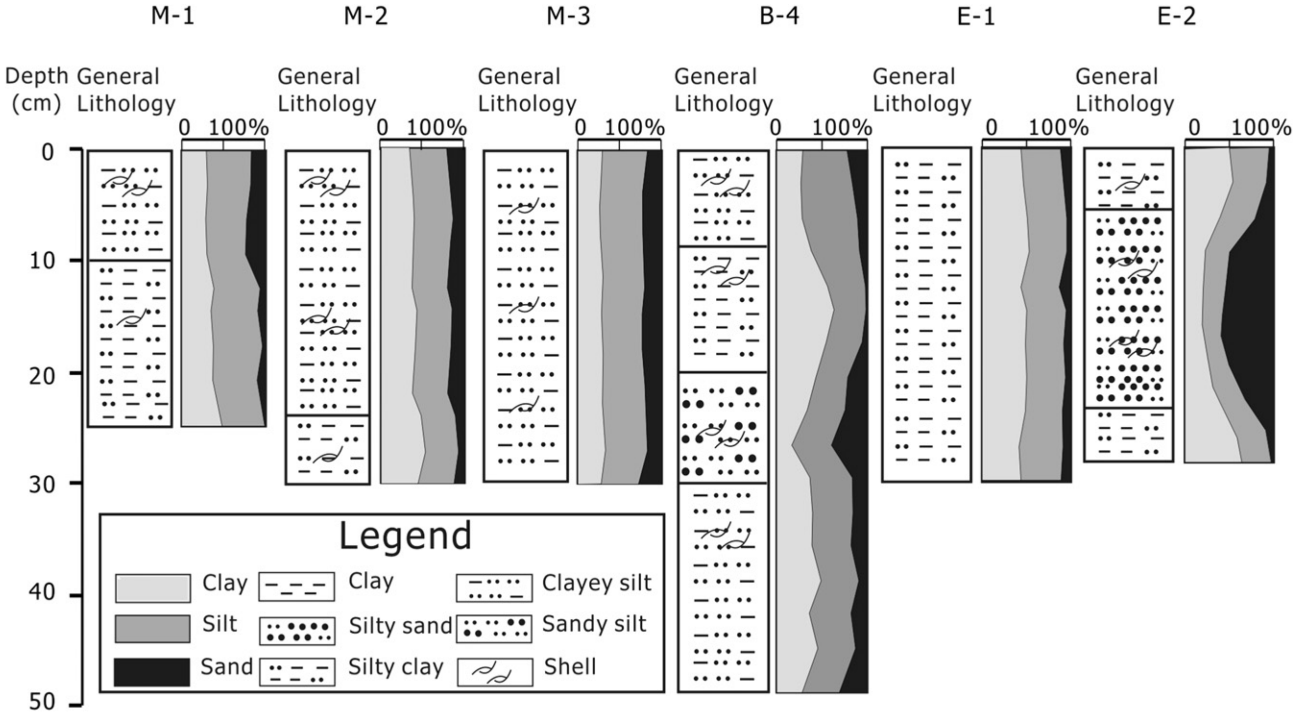

Fig. 2. Lithological characteristics of 6 sediment cores.

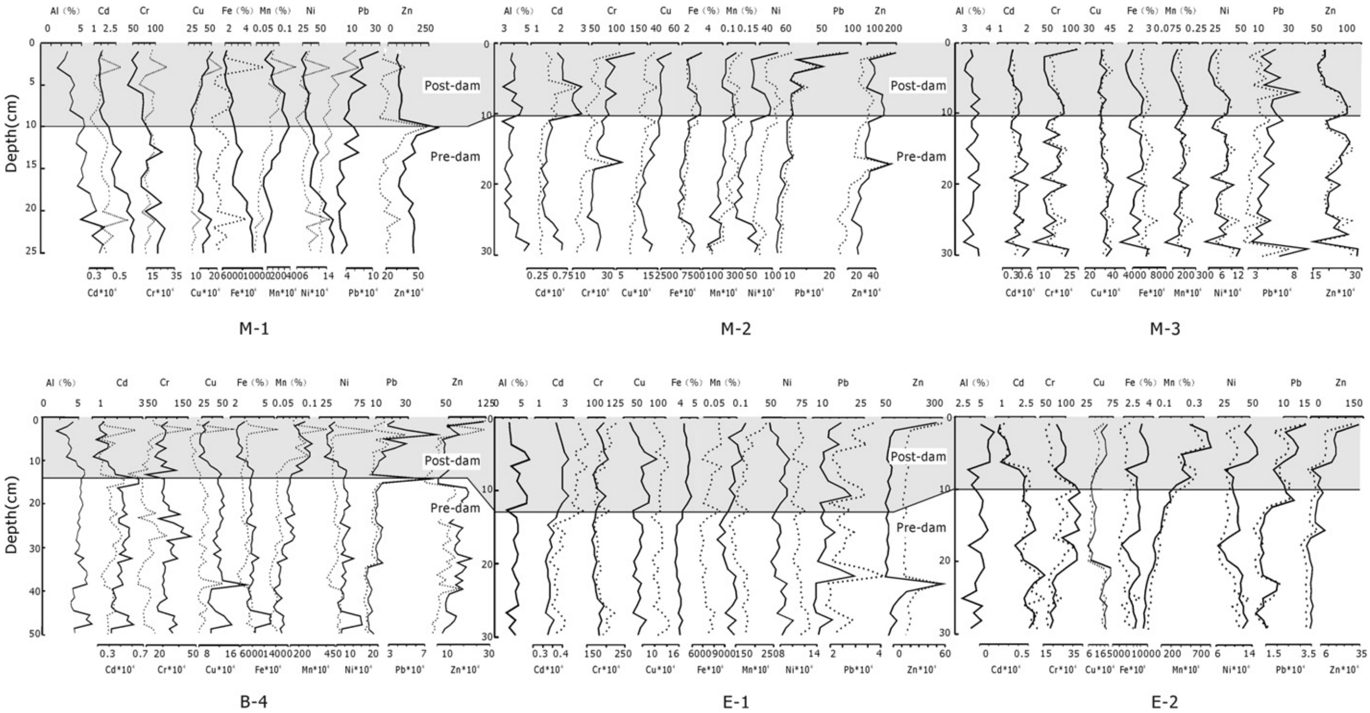

Fig. 3. Temporal distribution of heavy metals in 6 core sediments; solid line – absolute content (ppm), dashed line – normalized to Al (element × 10^4/Al). Also marked is the AHD timing for the upper core sediment sections of 10–15 cm (chronology reference is cited from Gu et al. (2011)).

Ni increased slightly upward while Cd and Cr decreased. Cu was highest in the upper and lower core sediments. Still, normalized metals have kept the same distribution trend as that of the absolute ones (Fig. 3).

4.2.2. Spatial distribution

Fig. 4 shows the spatial distribution of heavy metals along the Nile coast, i.e. from Manzala, Burullus and Edku. Using the heavy metals concentrated in the surficial sediment as an example, there occurred two clear distribution patterns for both the absolute and normalized values. Al, Fe, Ni of absolute value demonstrated highs in the central Burullus lagoon, but lows in the eastern Manzala and western Edku lagoons. It was however, that other metals, including Cd, Cr, Cu, Mn, Pb and Zn, exhibited lows in the central lagoon, but highs in the eastern and western lagoons. In addition, the normalized metals have seen the similar distribution pattern as absolute one.

4.2.3. Enrichment level

Fig. 5 shows the occurrence of EF for all heavy metals in the 6 sediment cores. The results showed that EF (Cd) ranged from 1.1 to 1.8, EF (Cr) from 1.3 to 1.9, EF (Cu) from 0.7 to 2.6, EF (Fe) from 0.6 to 1.6, EF (Mn) from 1.7 to 4.2, EF (Ni) from 0.8 to 1.3, EF (Pb) from 2.6 to 7.3, and EF (Zn) from 1.5 to 3.1. Overall, the average EF of Cd, Fe and Ni were found to be less than or close to 1.5 ($EF < 1.5$), while Cr, Cu, Mn, Pb and Zn were found to be more than 1.5.

4.2.4. Cluster analysis

Fig. 6 shows the results of a hierarchical cluster analysis for all heavy metals in the upper (10–15 cm) sediment sections of the 6 sediment cores. It demonstrated that M-1 and B-4 had a very similar cluster pattern, which was characterized by two main clusters, one including Fe, Ni, Cd, Cr, Al, Zn and Cu, and the other including Mn and Pb. M-2 showed a very distinctive cluster pattern, in which Al remained relatively independent from other metals of the present study. There were several sub-clusters, including Fe and Ni, Cu, Pb, Cr and Mn, and Cd and Zn. M-3 has demonstrated a stepwise pattern, in which Fe, Ni, Mn, Zn, Cd, Cr, and Al were closely associated, but Pb and Cu. E-1 and E-2 demonstrated the two patterns of heavy metal sub-clusters composed of different metals. Sub-clusters of E-1 included Fe, Cd, Cr, and Mn, and Cu, Ni, and Al, separate from the cluster of Pb and Zn. E-2 showed the affinity of Mn, Pb, Zn, Al, Fe, Ni, and Cu, but Cr and Cd (Fig. 6).

5. Discussion

Lagoons of the Nile delta formed since 7000 years BP (Fig. 1) served exclusively as an aquacultural and ecological base for the early Egyptian agricultural civilization (Stanley and Warne, 1993). However, recent human activities on the delta coast have altered the lagoon eco-hydrological setting, especially over the last half-century since the AHD was completed in 1964 (Hamza, 2006). Industrial and domestic wastewaters have been discharged directly into the seas exclusively through the drainage networks and associated lagoon wetlands in the delta plain. The present heavy metal study describes the physical processes, with an emphasis on a better integrated coastal management in future.

5.1. Post-Aswan Dam sedimentation rate

To understand the sedimentation rates of the Nile lagoons is vital for better understanding of the behavior of heavy metal transport and accumulation in the Nile coastal wetlands (Benninger et al., 1998; Appleby et al., 2001; Chen et al., 2010a,b). On the basis of radiometric analysis of ^{210}Pb and ^{137}Cs of the lagoonal sediment, we have reported in our earlier study that the post-Aswan Dam sedimentation rates in Manzala, Burullus and Edku range from 0.22 to 0.27 cm a^{-1} (for details see Gu et al., 2011). Our study has also revealed that the upper part of the lagoon sediments of 10–15 cm referred to the post-Aswan Dam sedimentation (Gu et al., 2011).

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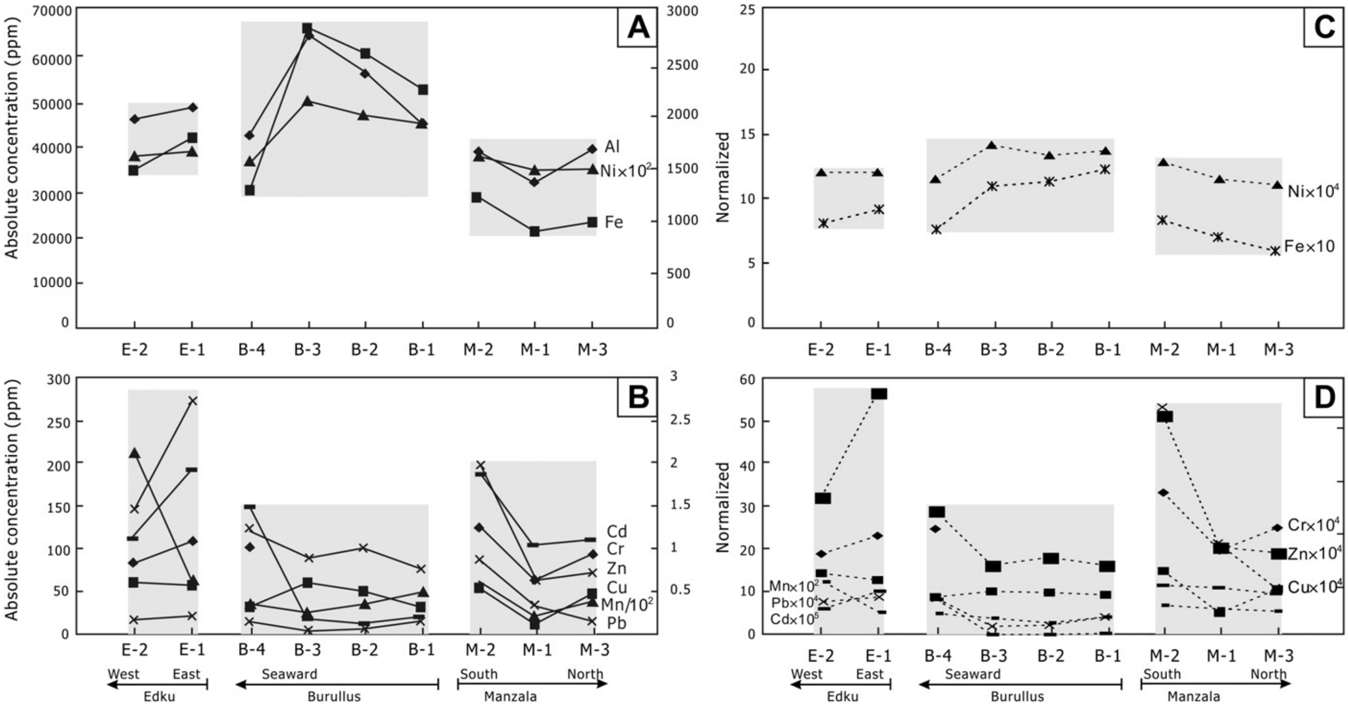

Fig. 4. Spatial distributions of heavy metals in the Nile delta lagoons (A and B – absolute content, C and D – normalized). Noted is the horse-saddle distribution of the normalized pattern, showing highs of metals in the eastern and western lagoons and low in the central lagoon.

Extremely low, but relatively uniform sedimentation rates that prevail in the lagoons reflect a lack of sediment sources upstream as a result of water impoundment (Appleby et al., 2001).

5.2. Contaminated heavy metals

In general, our results have revealed a tendency for increased heavy metal concentrations (both absolute and normalized) in our 6 sediment cores (Fig. 3). Heavy metals are particularly concentrated in the post-dam core sediments (above 10–15 cm), a close association with recent industrial and agricultural development after 1960s, when low-cost hydroelectricity supplied by the AHD became available (Siegel et al., 1994). By close examination of the temporal sequences of heavy metals in the 6 cores, we can certainly identify unique patterns in different lagoons, linked to sources of local metal contamination. The spatial distribution of heavy metals (absolute and normalized), with the high levels in Manzala and Edku confirms the enormous anthropogenic contribution to the coastal metal contamination given that the three lagoons of the Nile delta have long shared the same natural sediment provenance (Stanley, 1996; Hamza, 2006) (Fig. 4).

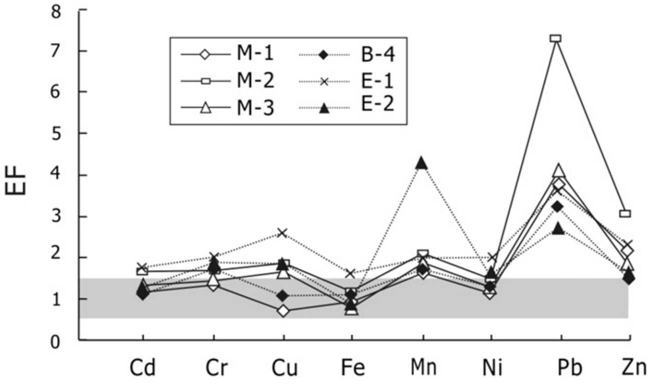

Fig. 5. Enrichment Factors (EF) of heavy metals derived from the upper (10–15 cm) sediment sections of the 6 cores from the Nile lagoons (the criteria of EF ($0.5 < EF < 1.5$) is denoted by the gray zone).

EF and cluster analysis can further detail diagnostic metals in each lagoon. M-1 and B-4 that have similar cluster patterns indicate Mn and Pb as the main contaminating metals in certain areas of Manzala and Burullus lagoons. This is also evidenced by EF, showing the high values (>1.5) in the surficial sediments (Fig. 5). The rest of the metals that are closely affiliated with Al, used as a clay content proxy, which indicates terrigenous sediment sources (Fig. 6) (Schropp et al., 1990). Our early metal study on B-1, B-2 and B-3 in Burullus also corroborated this observation, designating Mn and Pb as the contaminant metals (Chen et al., 2010a,b).

In M-2 that almost all metals in the present study do not have close affinity with Al (Fig. 6), suggesting heavier contamination, especially Cd, Pb and Zn, etc. from local pollution sources (Fig. 3). EF values of Cd, Pb and Zn also show the highest enrichment (>1.5) in the 6 cores (Fig. 5). Of note, M-2 is geographically sited on the southern (inland) lagoon coast (Fig. 1), where there occurs the notorious Bahr E1-Baqar drain that carries a huge amount of untreated sewage, and agricultural and industrial wastewater (3 km^3 a^{-1}) from eastern delta into Manzala lake (Siegel et al., 1994; Abdel-Moati and El-Sammak, 1997; Abdel-Azeem et al., 2007). EF and the increasing trend of most metals in M-2 record this observation (Figs. 3 and 5). On the contrary, M-3, with a stepwise pattern, has Cu and Pb as the contaminant metals, which is also supported by EF (>1.5) and the increasing trend of Pb, although Cu sees a slight increment in the upper core sediment section (Figs. 3, 5 and 6).

In Edku lagoon, E-1 has defined Pb and Zn as the most contaminated metals by its clustered metal pattern and EF values (Figs. 5 and 6), though other metals also showed a slightly increasing tendency (both absolute and normalized) (Fig. 3).

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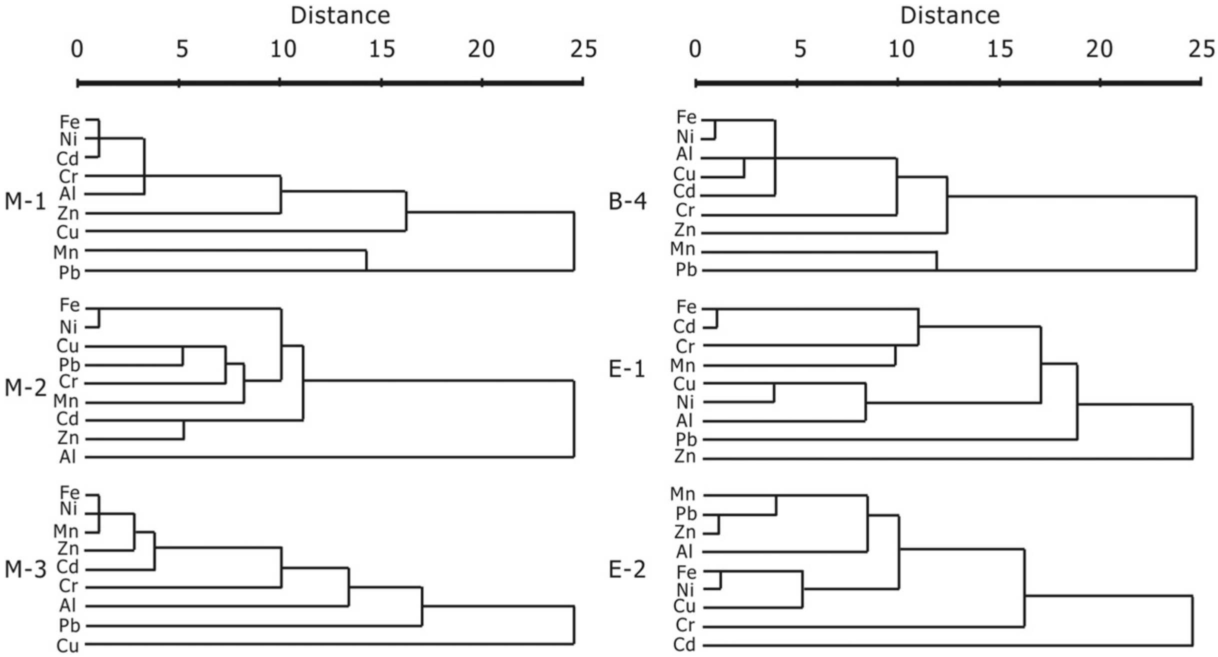

Fig. 6. R-type cluster plots of heavy metals derived from the upper (10–15 cm) sediment sections of the 6 cores in the Nile lagoons.

Similarly, E-2 has Mn, Pb and Zn as contaminant metals in spite of the different clustered metal pattern, which is also clearly evidenced by EF (>1.5) and the obvious increase in their values (both absolute and normalized) in the upper core sediment sections (Figs. 3, 5 and 6).

5.3. *Pollution sources*

Defined polluted heavy metals for the target lagoons can be used to trace possible pollution sources in the Nile delta, where the metropolitan cities like Cairo and Alexandria have become increased sources of wastewater due to the industrial growth in the past century (Siegel, 1995). Wastewater mainly drains into coastal lagoons through Damietta and Rosetta, and also through the extensive drainage networks in the delta plain (Fig. 1).

Manzala lagoon on the eastern delta coast is heavily affected by petroleum refining and associated chemical by-products, which is responsible for >60% of the heavy metal discharges into the region (Wahaab and Badawy, 2004; Barakat, 2004). The polluting metals of the present study, primarily diagnosed by Pb, Mn, Cu, Zn and Cd (Figs. 3 and 5), indicate the linkage to local industries, located at Matariya and Damietta City near the lake (Khalil, 1990; Rasmussen et al., 2009) (Fig. 1). In particular, Cd is a special metal related to local pollution and illnesses. High incidence of pancreatic cancer in the Manzala district probably results from Cd contamination (Soliman et al., 2006). High levels of Mn, Pb, Cu and Zn can inevitably cause severe health issues through food-web networks, leading to the degradation of societal development (Siegel, 1995; Rashed, 2001; El-Rayis, 2005).

In comparison, Burullus has a relatively low level of heavy metal pollution (Figs. 3 and 5). The metal loading into Burullus is chiefly derived from agricultural sources (6.7 $km^3\ a^{-1}$) (Abdel-Moati and El-Sammak, 1997). However, the recent change in land-use in the central delta plain where several megacities, like Tanta and El-Mahalla, concentrations of millions of people, have discharged enormous volumes of untreated wastewater into Burullus via drainage networks (Fig. 1) (Hamza, 2006). The increasing trend in Mn and Pb in the lagoonal sediment, although lower than that of Manzala, is a warning of eco-degradation in relation to the prevailing tourism industry centered at Baltim resort (Fig. 4).

Edku on the western delta coast is geographically isolated from any heavier industrial sources of the delta coast. However, the highly concentrated Mn, Pb, and Zn indicate pollution that has already occurred to some extent (Figs. 3–5). The previous study has revealed that the lake is presently affected by saline water from neighboring Abu-Qir Bay to the west, when the northwest wind circulation drives huge amounts of raw industrial wastes from the east basin of Alexandria city (Abdel-Moati, 1990) (Fig. 1).

5.4. *Distribution pattern of polluted heavy metals: a comparison to the Yangtze estuary*

On the basis of our observation, together with previous results (Table 1, Fig. 7) the heavy metal pollution on the Nile coast and in the estuary are highly concentrated at the two Nile promontory areas (including Manzala and Edku), and Mariut lake further west. EF of 26 sampled sites of the Nile coast clearly demonstrates this pattern (Fig. 7A and B). Of note is the lower EF at the sites of S8–S10 off the Rosetta River mouth, and S11–16 on the central delta coast where the more open coastal setting is affected by strong westerly littoral transport (Frihy et al., 2003). In contrast, the semi-enclosed Nile lagoons are becoming heavy metal sinks, largely due to the weakening fluvial discharge regulated by the AHD. Runoff flowing down to the delta (about half of water discharge released by the AHD Stanley (1996)) has been evenly diverted throughout the year, particularly under such an arid climate setting in the lower Nile, and could never flush the contaminants off the delta plain again. Limited and evenly distributed discharge with increasing heavy metals of anthropogenic origin has aggravated the eco-health in the Nile lagoons (Soliman et al., 2006).

It is of great interest to examine the pattern of heavy metals on the Yangtze coast and in the estuary (Table 1, Fig. 7C and D). This pattern shows a gradually lowering content of heavy metals from the coast seaward, and metals right off the river mouth are even lower in concentration. We understand that the total load of the Yangtze wastewater is 30 $km^3\ a^{-1}$, which is obviously much greater

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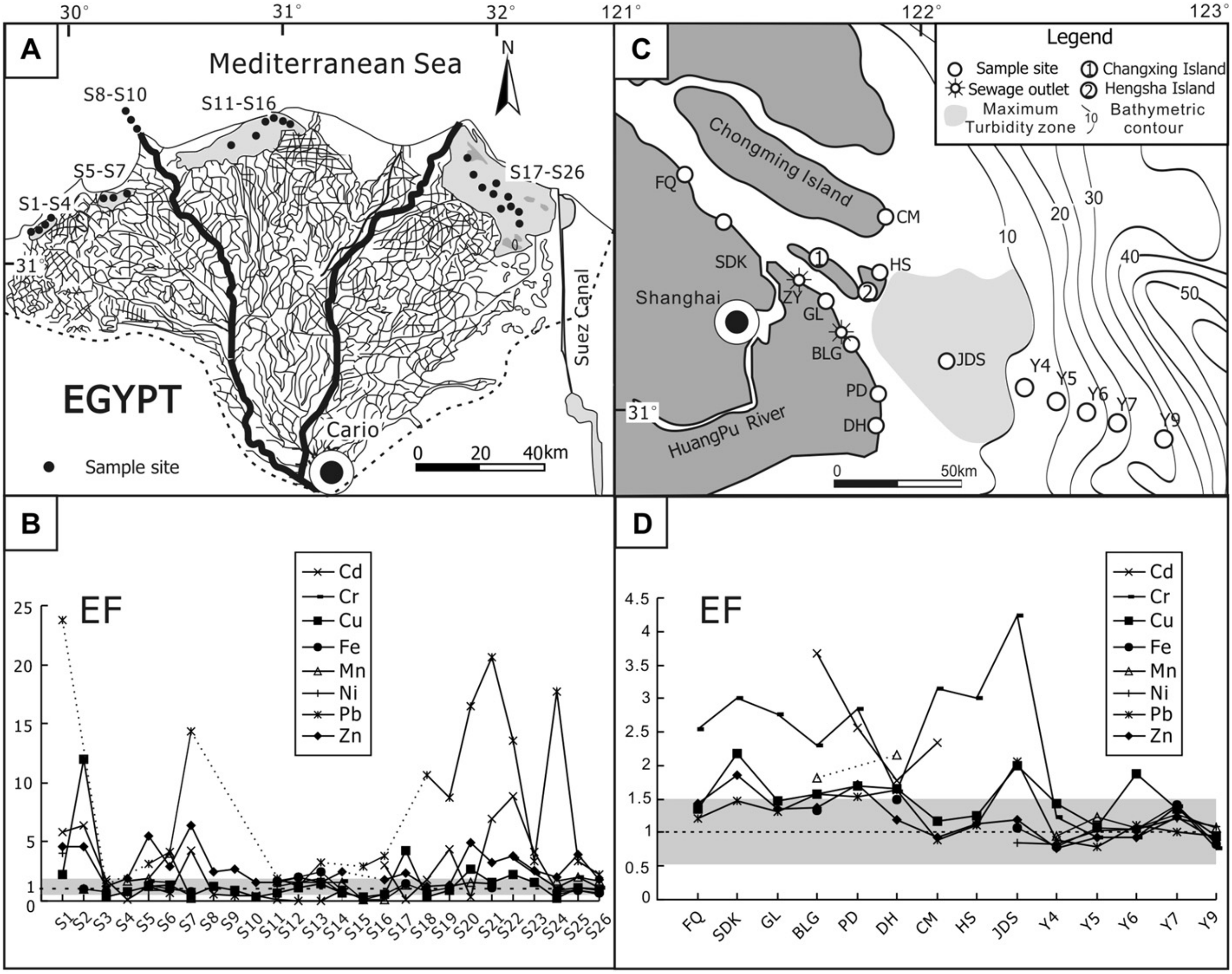

Fig. 7. (A) Sampling sites in the Nile delta; (B) EF of heavy metals derived from Manzala, Burullus, Edku and Mariut, and Rosetta estuary; (C) Sampling sites in the Yangtze estuary; (D) EF of heavy metals in the Yangtze estuary (EF is calculated by using heavy metal concentrations of the upper sediment sections, divided by the background values defined from B-4 in Burullus of the Nile delta, and Y7 off the Yangtze estuary (Chen et al., 2004)) (the criteria of EF ($0.5 < EF < 1.5$) is denoted by the gray zone in B and D).

than that of the Nile (4.5 km^3 a^{-1}) (Wahaab and Badawy, 2004; CWRC, 2006). However, EF of the Yangtze coast as established by the present study remains in general almost 3 times lower than the Nile case (Fig. 7B and D). We thus conclude that monsoon runoff into the sea (924 km^3 a^{-1}) and huge precipitation (1200 mm a^{-1}) in the lower Yangtze has played a critical role in diluting the concentration of heavy metals (Chen et al., 2004), although wastewater pre-treatment on the Yangtze delta coast has been ineffective in the past decades (Dai and Gu, 1990; Chen et al., 2000). In addition, there has not been any significant change in water discharge of the Yangtze River after the impoundment of TGD in 2003 (Yang et al., 2006), while the regular natural flood of the Nile River has been regulated into artificially slow-flowing water through the dense network of delta canals and drains linking to the lagoons (Stanley, 1996). Therefore, in contrast to the Nile delta since the AHD, there seems less significant increase in heavy metal pollution in the Yangtze delta after the TGD (Wang et al., 2008; Dong et al., 2009).

The two different heavy metal contamination scenarios of the two deltas presented in present study have provided us with some insights into the complex interaction between human intervention and local physical settings. It helps to indicate the need for careful evaluation of environmental responses in other deltas to any large-scale hydro-engineering upstream.

6. Conclusions

Using 6 short sediment cores recovered from the Nile lagoons, in this study we have examined the spatial and temporal distribution of heavy metals in the lagoonal sediments of the Nile delta. Furthermore, we have tried to differentiate the heavy metal sources in the three lagoons and to reveal the pollution processes in this arid climatic setting in comparison to that of humid zone Yangtze estuary.

The spatial distribution pattern of heavy metals shows highs in the eastern Manzala and western Edku lagoons, but an obvious low in the central Burullus lagoon. Most heavy metals show an increasing trend with time, especially in the upper part (10–15 cm) of the core sediments. Radiometric (^{210}Pb/^{137}Cs) analysis of the core sediment confirms the post-Aswan Dam source of these upper sediment sections.

Manzala is thought to be the most seriously polluted region, chiefly characterized by Mn, Pb, Zn, and Cd, etc. This lagoon is directly linked with the Greater Cairo metropolitan city, and also

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surrounded by several regional megacities, where pollution sources are linked with petroleum and chemical refining processes. Burullus on the central coast, although remaining relatively low in the metal concentration, shows an incremental increase in Mn and Pb. Farming and growing cities with populations greater than a million are contribute pollution through the existing drainage networks. Edku on the western Nile coast with high levels of pollution by Mn, Pb and Zn is being threatened by the pollution sources associated with Alexandrian wastewaters via littoral current transport, even though there is lower intensity of industrial activities nearby.

The Nile lagoons are becoming heavy metal sinks, since the limited discharge from the AHD has been diverted primarily through distributaries and dense drainage networks in the coast and estuary. In particular, because of the arid climate there is insufficient water to flush the lagoons. This is in contrast to the situation in the Yangtze estuary, where high monsoon precipitation on the delta and throughout the catchment provides abundant water to flush the coastal environment.

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