

# Heavy metals in the sediments of the Nile Delta: Anthropogenic-induced hydrologic changes

Ahmed Awad Abdelhady (✉ [ahmed.abdelhady@mu.edu.eg](mailto:ahmed.abdelhady@mu.edu.eg))

Minia University <https://orcid.org/0000-0003-4438-8572>

**Salem Ghonamy Salem**

National Institute of Oceanography and Fisheries

**Mahmoud Khalil**

Minia University

---

## Research Article

**Keywords:** Environmental pollution, Anthropogenic disturbance, Heavy metals, Hydrodynamics, Nile–Delta.

**Posted Date:** February 15th, 2021

**DOI:** <https://doi.org/10.21203/rs.3.rs-183247/v1>

**License:** © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

---

# Abstract

Aquatic ecosystems act directly or indirectly as sinks for heavy metals, which persists for longer times in the biogeochemical cycle and poses high ecological risks and thus, it represents a major worldwide concern. To evaluate the metal contamination in the Nile Delta, twenty sites along both Rosetta and Damietta branches were investigated. Most heavy metals concentrations are above the sediments quality guidelines. The Contamination Factor (CF), Pollution Load index (PLI), and geo-accumulation index ( $I_{geo}$ ) indicated that the sediments are moderately to extremely polluted by Ni, Cd, Cr, Cu, Pb, and Zn. A trend of increasing metals concentration towards the Mediterranean was observed and attributed to historical sinking of heavy metals in the sediment, where many agricultural drains bringing mixed wastewater. Cluster analyses support the latter and indicated that the heavy metals, which clustered together, may have the same source (i.e. anthropogenic). Non-metric Multidimensional Scaling, Analysis of Similarity (ANOSIM), and Partial Least Square (PLS) regression confirmed that the distance along the river is the major predictor of the observed metal concentrations, while sediment grain-size has no or very minor effect. The lower hydrodynamics associated with the construction of Aswan High-Dam in 1964 and the developed agricultural system in addition to arid climate with scarce rainfall, all leave no chance for natural annual flooding. Therefore, freshening up of the sediments was prohibited. The marinating of well-controlled flooding may erode the upper contaminated portion of river sediments, dilute the metal concentrations, and improve the sediments quality.

## 1. Introduction

The heavy metal contamination persists for longer times in the biogeochemical cycle and poses high ecological risks and thus, it represents a major worldwide concern. Anthropogenic activities (agricultural, domestic, and industrial) are the main source for higher concentrations of these metals (Dean et al., 2007, Kalantzi et al. 2014), which usually discharged into aquatic environments (Abdelhady et al. 2019), suspended in water column, sinking in the sediment, and entering the food chain (benthic organisms, fish and humans, Rainbow and Phillips 1993, Rainbow 1995). Polluted sediments are good indicators for water pollution (Förstner and Wittmann 1981). Although water quality may be improved due to current global polices, underlying sediments may release these metals again into the water column due to any physicochemical environmental change (e.g., temperature, pH, and hydrodynamics). Therefore, metal concentrations in the sediments have to be regularly monitored at different spatiotemporal scales (Branica et al. 1985, Schropp et al. 1990).

The Nile runs for more than 6000 km from Ethiopia in the south to the Mediterranean Sea in the North. For thousands years ago, it has enabled settlement of the old Egyptian, where one of the most ancient civilizations initiated (Dumont 2009). The annual flooding of the world's longest river has been delivered both water and good soil required for agriculture. The Nile is fundamental source of freshwater in Egypt, which share about 55.5 BCM (billion cubic meters)/year (MWRI, 2010). The Nile Delta is situated in the middle of the Egyptian Mediterranean coastline of approximately 1,000 km (Fig. 1). The Nile Delta was occupied for at least the five thousand years, where it has been intensively farmed (Dumont, 2009). The Nile Delta represents only 2% of Egypt area but it hosts 41% of the country's population (one of the top 5 densely populated agricultural areas in the world, Hereher, 2010). Intensive agricultural practices in the past decades, occasionally after the construction of the Aswan High-Dam, were resulted in a gap between water supply and demand. To overcome this problem, drainage water was reused since the 1980s (Khater, et al. 2014). The usage of phosphate-rich sewage water with partial or without any treatment in agriculture has increased the metals concentration in sediments of the Nile Delta (Karatat et al. 2006). During the past Century, the regulation of the Nile flooding by constructing dams, development of complicated agricultural systems, and increasing water exploitation due to rapid population growth, may have left dramatic changes in the hydrologic cycles.

Oczkowski and Nixon (2008) indicated that the Nile Delta lakes (Mariut, Edku, Burullus, and Manzala) are polluted at different levels by heavy metals. A result, which has been clearly demonstrated by many others in the past decade (e.g., Chen et al. 2010, Gu et al. 2013, Abdelhady et al. 2018, 2019a). The closed or semi-closed system of these lakes may be the main cause for such higher concentrations of heavy metals. To test if the hydrologic/hydrodynamics is a main source for heavy metal sinking in the sediments, the heavy metals in the sediments of the two branches, Rosetta and Damietta, of the Nile Delta were analyzed. Herein, we aim to assess the distributions of the both metals in the sediments along Nile Delta branches to

quantify their sensitivity to location of the pollution source, water energy (i.e. hydrodynamics), and other physicochemical variables (i.e. sediment grain-size). Therefore, we propose to address the following research questions: 1) What are the main sources of the heavy metals in the Nile delta? 2) Is there any gradient of heavy metal pollution in the sediments? 3) Why the metals (if any present, concentrated in the sediments? 4) is there any proper method to overcome/reduce the pollution intensity? The spatial distribution of these metals in the river can enable tracing their sources and assess the pollutants mobility for better management in the future.

## 2. Study Area

The Nile delta is suitable for intensive agriculture and it supports 63% of the country's agricultural and represents more than 80% of the fishing industry. The Nile Delta is part of one of the world's most important migration routes for birds. Every year, millions of birds pass between Europe and Africa along the East Africa Flyway, and the wetland areas of Egypt are especially critical stopover sites. The Nile Delta is subjected also to shoreline changes resulting from erosion and accretion, subsidence, and sea level rise (SLR) resulting from climate change (Fishar 2018). The Nile has two branches starts at Cairo and ends at two promontories (estuaries) at Damietta on the east or Rosetta in the west (Fig. 1a).

Damietta branch, as shown in Fig. 1, located at the eastern part of the Nile Delta. Its length is about 241 km, average width 280 m with an average depth 11 m and average elevation 2 m. The Rosetta branch extends for more than 239 with shallow depths (2 to 4 m) and average of 180 m width (Negm et al. 2017). Mixed domestic, industrial, and agricultural wastes disposed to the Rosetta branch through a drainage network starting from Cairo and extends to the north with only partial or without any treatments. El-Barbary et al. (2008) indicated that 900 MCM of wastes discharges monthly in the Rosetta branch. The main drains include El-Rahawy, Sabal, El-Tahrir, El-Tahdi, and Tela (Abdo 2002, El-Bouraie et al. 2010, Ezzat et al. 2012). The water of the two branches is negatively affected and therefore, the environmental conditions have become extremely harsh for fauna (Appendix A, Fig. 2).

## 3. Material And Methods

### 3.1. Sampling and granulometry

Samples of sediments were collected in two replicates from twenty sites in the Nile Delta from February to April of 2014 using 20\*20 cm Ekman grab (Fig. 1a, Table 1). In the laboratory, sediment samples were air-dried and then sediment grain-size analysis was done using an electric shaker for 100 gram of the sediments (sieves openings are 2, 1, 0.5, 0.25, 0.125, and 0.063 mm). The percentages of the different size classes were calculated (Quintino et al. 1989). Percentage of fine sediments (silt and clay) obtained by wet sieving method. The mm calculation transformed to phi scale ( $\phi$ ) and the main features of the sediments grain-size (mean, standard deviation, skewness, and kurtosis) were used for statistical analyses (Table 1).

Table 1  
Univariate statistics of sediments grain-size in the Nile Delta.

Branch	Station number	Station name	Latitude	Longitude	Sediment grain-size			
					Mean ( $\phi$ )	Standard deviation	Skewness	Kartosis
Rosetta	El-Kanater	30°10'48.72"N	31° 7'30.83"E	5.7	1.7	0	1.2	
	El-Rahawy	30°13'8.42"N	30°58'47.06"E	2.7	1.4	-0.2	1.4	
	Tamalay	30°30'19.79"N	30°49'52.94"E	1.3	0.6	-0.1	1.6	
	4	Sabal	30°35'45.78"N	30°48'33.23"E	2.1	0.5	-0.3	1.2
	5	Kom Hamada	30°46'0.78"N	30°45'15.71"E	1.7	1	-0.3	1.5
	6	Kafr El-Zayat	30°49'33.39"N	30°48'23.70"E	3.5	1.6	0.9	2.9
	7	Desuq	31° 8'7.60"N	30°37'58.80"E	0.9	1.9	0	0.7
	8	Fowa	31°11'52.20"N	30°34'19.01"E	3.6	2.2	0.5	1.9
	9	Rosetta city	31°20'51.40"N	30°27'20.57"E	2.4	0.8	0.2	0.5
	10	Rosetta estuary	31°27'36.49"N	30°22'18.60"E	2.4	0.5	-0.1	1.2
Damietta	1	Benha	30°27'16.25"N	31°10'23.62"E	3.7	1.3	0.6	1.2
	2	Zefta	30°43'0.17"N	31°15'0.85"E	3.8	1.9	0.3	1.2
	3	Talkha	31° 4'4.04"N	31°24'12.97"E	4.4	2.1	0.5	1.1
	4	El-Serw	31°11'16.01"N	31°30'33.81"E	3.3	2.6	0.2	1.1
	5	South Faraskour	31°16'28.83"N	31°39'37.54"E	3.2	1.5	0.6	1.3
	6	North Faraskour	31°19'40.59"N	31°42'36.20"E	3.6	2.3	0.5	1.3
	7	Damiatta	31°23'47.95"N	31°46'3.88"E	2.2	2.3	-0.2	1.7
	8	El-Khayata	31°26'32.06"N	31°47'51.79"E	-0.5	1.2	0.8	1.7
	9	El-Ratma	31°28'58.43"N	31°49'30.21"E	3.9	2	0.3	1.2
	10	Ezpt El-Bourg	31°31'16.10"N	31°50'37.83"E	3.8	1.2	-0.7	0.4

### 3.2. Geochemical analyses

The rest of samples were crushed with a ceramic pestle and mortar to pass through a 0.063 mm mesh screen. About 0.1 g of dried sediments and 1 ml of water aliquot was taken in a 50 ml beaker and then 3 ml of a concentrated mixture of HNO<sub>3</sub> and HCl (1:1) were added. Subsequently, all the treated samples were diluted to 10 ml with ultra-pure water (Milli-Q). Then the samples were filtrated for 5 minutes through a centrifuge to split the solids from the solution. We focused on the dissolved filtrate fraction, which is more likely to have measurable biological effects on aquatic organisms (Di Toro et al. 2000). Eight metals including Zn, Cd, Cr, Pb, Cu, Fe, Mn, and Ni) were analyzed using the Atomic absorption spectroscopy (Perkin Elmer 400) in Nationalinstitute of oceanography and fishery (NIOF), Cairo, Egypt. In order to ensure the quality of the analyses, strict laboratory regulations and procedures regarding cleaning, calibration, and duplicates measurements were followed. The

applied analytical method was continuously checked using a certified reference material to ensure the quality of the performed analyses. The certified reference materials were analyzed every 10 samples. The errors in all measurements were less than 5 %. In addition, analysis of heavy metals in many samples was repeated. The Relative Percent Differences (RPD) between the duplicate and the sample ranged from 0.1 to 3 %. The practical quantitation limits (PQLs) of the metals analyses were in the range of 0.01–0.05 ppm.

### 3.3. Data analyses

*Contamination Factor (CF)*, the concentration of metal in the sediments divided by background base value, was used to evaluate the sediments quality, where pollution intensity can be estimated as follows,  $CF < 1$ , low pollution,  $1 < CF < 3$ , moderate pollution,  $3 < CF < 6$  is considerable pollution, and  $CF > 6$  as high pollution. Pollution load index (PLI) was also used to comment on the overall pollution intensity by different metals, where  $PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{1/n}$ , Where (n) is the number of metals and CF is the contamination factors. In addition, the geo-accumulation index ( $I_{geo} = \log_2 (cn/1.5 * bn)$ ), where (cn) is the measured concentration of examined element (n) in the sediment sample and (bn) is the geochemical background for the element (n), was also implemented, where pollution intensity is quantified based on as scale from 0 to 6.

The grain-size and metals concentrations data were normalized using Euclidean transformation to give the same importance to all variables included in the statistical analyses and to comment on the co-linearity (Theodoridis and Koutroumbas 2008, Abdelhady 2019). Pearson correlation, RMA (reduced major axis) linear/exponential regression models, and hierarchical clustering were used for assessing the relationships. We tested the significance for all correlations at significance level ( $p < 0.01$ ). Sequential Bonferroni correction was applied to multiple correlations. In addition, metal concentrations were compiled for non-metric Multidimensional scaling (NMDS, Zhang et al. 2009, Gu et al. 2013). The non-parametric Analysis of the Similarity (ANOSIM) test was used to test the significance of the relationships among the examined metals. Furthermore, Partial Least Squares (PLS) regression was implanted, where the strength of the fitted model (Q2) and the loadings or the VIPs (Variable Importance for the Projection) were used to quantify the effect of each physicochemical parameter on the metals concentrations (Carrascal et al. 2009, Zelditch et al. 2012).

## 4. Results

### 3.1. Sediment grain-size

Grain-size analyses indicated a gentle gradient of the river toward the Mediterranean Sea, where Skewness, kurtosis, and standard deviation decreases in both branches of the Nile (Table 1, Appendix A, Fig. 2A-B). Mean grain-size also gradually decreases in both branches (Appendix A, Fig. 2C-D). The gradual decrease in coarse-grain proportion of the sediments and the decrease in variation may attribute to gentle sloping, where the elevation of northern parts of the Delta is about 2 m (see Fig. 1b). Fin-grain nature and high variance in the sediments of southern sites in addition to the platykurtic curve indicate ill-sorting fabric and point to the dominance of the suspended mode of transportation (immature) and/or different sources of the sediments (i.e. mainstream, erosion of the river banks, agricultural drains). Reduced Major Axis (RMA) regression revealed non-significant relation between distance along the branches and the sediment grain-size (Appendix A, Fig. 2C-D). The non-significant decreasing trend in grain size may be attributed to random discharge from agricultural drains that carry usually muddy water. Most sites are composed mainly of sand size sediments (Table 1), while mean grain-size increases northward and reaches gravel size at station 8 on Damietta branch (Appendix A, Fig. 3D). Most of the samples are slightly skewed with polymodal distribution and platykurtic distribution, which reflects the immaturity of these sediments and that they were transformed for only short-distance/time and thus, may be related to agricultural drains and their source is not the main course of the river.

### 3.2. Metal concentrations

The average concentrations within the samples arrange the metals in the sediments of both branches in the following descending order ( $Fe > Mn > Zn > Cr > Cu > Pb > Cd$ , Table 2). The metal concentrations show a gradual increase from the south to the north (Table 2, Fig. 4) and this is true for most metals of Rosetta branch (Appendix A, Fig. 3A-H). In contrast, the

Damietta branch only a similar trend was found for Mn, Cu, and Zn but not Ni, and Pb (Appendix A, Fig. 4). There is a strong significant exponential correlation between the distance to capital city (Cairo) and most of the heavy metals concentrations in sediments of Rosetta branch include Ni, Cu, Pb, and Zn (Appendix A, Fig. 3,  $R^2 > 0.27$ ,  $P < 0.001$ ). Fe, Mn, Cd, and Cr show chaotic distribution and have no clear trends and thus, they may have generated from other sources (see below).

Table 2

Metal concentrations in core samples at 10 cm intervals. Effective Range Low (ERL) and Effective Range Medium (ERM) according to Long and Morgan (1990), metals in Earth Crust according to Taylor (1964), reference concentrations are from Goher et al. (2014). Shaded cells are  $> ERM$ . Values in ppm unless stated.

	<b>Fe%</b>	<b>Mn</b>	<b>Ni</b>	<b>Cd</b>	<b>Cr</b>	<b>Cu</b>	<b>Zn</b>	<b>Pb</b>
<b>Rosetta</b>	4.8	1124.9	59.6	5.4	127.2	39.5	87.6	56.4
	4.96	1280.1	80.9	9.5	140.4	79.6	126.4	31.6
	9.92	600.1	76.6	8.8	93.2	65.5	208.7	84.1
	4.88	801.6	38.4	11.9	409.2	50.5	170.6	34.5
	4.93	1709.7	76.3	9.3	390.3	70.7	220.6	85.3
	5.03	920.7	87.6	10.3	227.9	40.5	156.6	54.4
	4.83	1450.7	76.6	10.6	442.9	79.6	310.6	148.2
	4.92	1107.6	66.8	71.9	162.9	250.7	134.5	185.6
	4.72	1125.2	91.2	61.3	145.5	88.8	348.8	332.6
	4.66	924.6	130.6	7.5	130.6	230	520.3	87
<b>Damietta</b>	4.81	138.3	70	9.5	292.6	22.8	65.1	18.7
	4.08	1267	82.2	11.9	128.3	64.7	243.9	82.3
	4.91	750	76	7.7	128.7	60.5	226	34.5
	4.83	800.4	76.6	9.3	130.7	68.3	148.6	60.7
	4.77	1189	73	61.3	106.1	77.3	240.6	46.9
	4.96	1702.6	78.3	9.8	114.4	65.9	152.8	38.2
	4.97	2488	38.1	6.6	118.8	125.5	404.2	47.5
	4.95	613.2	82.1	12.2	99	214.4	317.8	62.9
	9.93	830.2	86.3	8.7	168	145.4	287.7	51.8
	4.69	742.6	66.3	6.1	116.5	99.3	1200	17.1
<b>Earth Crust</b>	<b>563</b>	<b>850</b>	<b>75</b>	<b>0.15</b>	<b>100</b>	<b>55</b>	<b>70</b>	<b>12.5</b>
<b>Goher et al., 2014</b>	<b>11.3</b>	<b>279.6</b>	<b>20.22</b>	<b>0.175</b>	<b>30.79</b>	<b>21.78</b>	<b>35.38</b>	<b>10.91</b>
<b>ERL</b>			<b>20.9</b>	<b>1.2</b>	<b>81</b>	<b>34</b>	<b>150</b>	<b>110</b>
<b>ERM</b>			<b>51.6</b>	<b>9.6</b>	<b>370</b>	<b>270</b>	<b>270</b>	<b>218</b>

The northernmost stations of Rosetta branch have lower values of most metals (Appendix A, Fig. 3). This may result from wave/tide actions, where seawater intruded into the estuary during high tide and erode the substrate sediments and thus, dilute the metal. Only Concentrations of Ni are above the Effective Range Medium (ERM) at all station (Table 1, Long and

Morgan, 1990). In addition, concentrations of Cd, Pb, Zn, and Cu, are also above ERM at northern stations in both branches (Table 2). According to CF, most stations are moderately to very highly polluted (Appendix A; Table 1). PLI indicated that all stations are polluted at different levels (Appendix A; Table 1). *I*geo indicated that the stations are extremely polluted by Cd at both branches and moderately polluted by Pb and Zn (Appendix A; Table 1). For the Rosetta branch, CF increases northward for all metals (Appendix A; Table 1, Fig. 2A), which is not the case in Damietta branch (Fig. 2B). Similarly, and according to *I*geo, pollution intensity increases also northward in Rosetta stations (Fig. 2C). A trend which is not observed in the stations of the Damietta branch (Fig. 2D). PLI indicated a strong positive exponential correlation along the Rosetta branch (stations 1:10, Fig. 2E). In contrast, PLI show negative correlation (Fig. 2F). In general, the metal concentrations were consistently higher at northern stations of Rosetta branch (Appendix A, Fig. 3). Furthermore, most of the examined metals in Rosetta branch showed a consistent increasing trend, which reflect a steady increase in the anthropogenic input.

### 3.2. Source of pollution

To identify the source of the different metals in the sediments of the Nile Delta, Pearson correlation and hierarchical clustering were applied. A significant positive correlation was found between Ni and Cr ( $r = 0.63$ ,  $p < 0.001$ , Appendix A; Table 2) and also between Cd and Pb ( $r = 0.63$ ,  $p < 0.001$ , Appendix A; Table 2), which may indicate that they originated from the same source. To better characterize their relationships, cluster analysis was applied to the concentration data matrix. The dendrogram showed that Cd is slightly behaved differently from the other heavy metals (See also Appendix A, Fig. 3) and in the same time is clustered with Fe, which may point to same source or may be their accumulation is governed by different physicochemical factors. In contrast, other heavy metals (Ni, Cr, Cu, Zn, and Pb) were clustered together (Fig. 3A). A slight difference between Mn and Zn is seen from metal concentrations in the Damietta branch (Fig. 3B). However both still clustered with the rest of the heavy metals, which may point to another possible source for both Mn and Zn.

The stations of both branches divided into two groups, north and south stations. Differences between the two groups of stations are no significant (ANOSIM test,  $P < 0.001$ ). The latter may result from the fact that metals concentrations are gradual without sharp change in the concentration between northern and southern stations. The variation between both groups of the metal concentrations is well characterized on the 2D NMDS plot, where both groups of stations are well overlapped (Fig. 3C). Moreover, the variation in the metal concentrations is highly variable among the measured metals (Fig. 3D). Ni and Cd have the lowest concentrations with narrower range of variation among the studied stations. In contrast, Cr and Zn show wider range of variation (Fig. 3D).

To test the effect of sediment grain-size on the metal concentration, PLS regression was applied to the dataset including both metal concentrations as observations and sediment grain-size parameters in addition to distance from Cairo as predictors. The first three components comment on 99% of the variation (Fig. 4A). The VIPs loading showed that the distance from the stations on the two Nile Delta branches to Cairo is the main predictor (0.99). In contrast sediment grain size parameters (mean grain size, standard deviation, skewness, and kurtosis) have no or very minor effect (Fig. 4B).

## 5. Discussion

### 5.1. Pollution levels and source evaluation

The PLI indicates progressive deterioration of most stations, occasionally those to the north, where metals concentrations are usually exceed their baseline levels many times (Tables 2 and 3). For the Damietta branch, the results indicated a negative exponential correlation, where the pollution levels decreased with increasing distance from the source (Cairo and megacities at the mouth of the Nile delta). In contrast, a positive correlation was found and attributed to a steady discharge from five main agricultural drains and not only a single drain as in case of Rosetta branch. The source of Cd may be differing from other metals (Appendix A, Fig. 4). Probably, Cd is originated from industrial activities as well as from lithogenic sources as do Fe. Fe may have generated from lithogenic origin such as the volcanic rocks in the first distributaries of the Nile in Ethiopia. The later explain why both metals were clustered together (Fig. 2A-B). Pb, Cr, and Cu may have mixed sources (i.e. traffic and industrial practices).

The combined domestic, industrial, and agricultural wastes brought by five main drains in Rosetta branch (i.e. El-Rahawy, Sabal, El-Tahadi, El-Tahrir, and Tala) have had significant influences on the distribution of the metal concentrations and are the main source for pollution of the sediments in the Nile delta. As the topography is of very gentle slope (Fig. 1b), river is no longer strong enough to carry out these metals to the sea and hence, they sink to the ground. The reduction of the water quantity that discharges to the sea after the construction of Aswan high-Dam in 1964 exaggerated the heavy metal sinking (Gu et al. 2013). The sediments recorded higher values may be more than in polluted water itself as it represent historical value for metal that have accumulated for years ago (Abdelhady et al., 2019a, Fig. 5A). It is known that sediments close to the drains enriched with metals by two main mechanisms, the high content of the metals from industrial, domestic, and agricultural sources in addition the modification of physicochemical conditions include but not limited to high pH, high organic-rich mud, and associated dysoxia (Dean et al. 2007, Kalantzi et al. 2013). A possible solution for the heavy metal accumulation in the sediments may be the maintaining of (controlled) high-intensity floods, which may erode the upper portion of the bottom sediments, where heavy metals accumulated, and leaching them to the sea (Fig. 5B). The Hydrodynamic changes associated with the construction of Aswan high-Dam, the development of complex agricultural system, reduction in water flowing to the sea, all have attributed to the accumulation of the heavy metals in the sediments of the Nile branches in the Nile Delta.

## 5.2. Temporal changes and ecological risk

Cu and Zn are essential micronutrients in all aqueous habitats (Simkiss and Taylor 1989). Anthropogenic activities, related to agriculture are significantly altered the biogeochemical cycle of the trace metals and enhance their bioavailability (Garrels et al. 1975). Elevated concentrations of certain trace metals (e.g., Cd, Cr, Cu, Hg, Ni, Pb) may be extremely toxic, and harm biota (Radix et al. 2000). Contamination entering in the aquatic ecosystem also arrived to the human food chain.

Abbassy et al. (2018) found that water of the Rosetta estuary contain persistent organic pollutants. Heavy metals may be absorbed in the suspended clay particles and deposited in the sediments, and thus, their concentrations in the water may be decreased (Keshta et al. 2020). Pollutants in both water and sediments will be enter the geochemical cycle, absorbed by the benthic fauna and hence, reached fishes and humans (Dean et al. 2007, Ryu et al. 2011, O'Brien and Keough 2013, Chariton et al. 2015). Pollution of aquatic environment possess a high risk to the biodiversity (Rodrigues et al. 2017, Abdelhady et al. 2019a, Mosbahi et al. 2019)

A fundamental problem of the trace metals is their resistance to biodegradation and once entered the aquatic environment they are redistributed throughout the water column, accumulated in sediments and consumed by biota (Abdelhady et al. 2019b, Long et al. 1996, Fichet et al. 1998). Spatial distribution of the trace metals is critical for differentiating natural concentrations from introduced anthropogenically (Galloway 1979, Long et al. 1996, Hatje et al. 2001, Korfali and Davies 2003).

## 6. Conclusion

Analysis of the grain-size and the concentrations of eight metals in 20 sediment samples from the two branches of the Nile Delta revealed the following:

- The sediments are mainly of coarse grain sands, and grain size increases northward, while the concentrations of most of the heavy metals increases in northward (sea) direction.
- The concentrations of most heavy metals are above the ERM and exceeding their base level values many times. The sediments quality indices (i.e. CF, PLI, and I<sub>geo</sub>) indicated that the sediments are highly polluted by Ni, Cu, Pb, and Zn and the pollution intensity, occasionally in the Rosetta branch increasing exponentially in northward direction.
- The spatial variation in the metals concentrations was interpreted to be a consequence of the source (drains) location and intensity/quantity of wastewaters discharged to both branches. The main agricultural drains located along both branches (i.e. El-Rahawy, El-Tahadi, El-Tahrir, Sabal, Tala, and Omar-bek) discharge huge amount of heavy metals-rich wastewaters.

- The PLS regression revealed that the distance from Cairo to the stations in the two Nile Delta branches is the main predictor (0.99). In contrast sediment grain-size (mean grain size, standard deviation, skewness, and kurtosis) have no or very minor effect.
- The hydrodynamic changes associated with the construction of Aswan High-Dam, the development of complex agricultural system, reduction in water flowing to the sea, all have contributed to the accumulation of the heavy metals in the sediments of the Nile branches in the Nile Delta.
- The sediments recorded higher concentrations of heavy metals, which may exceed their concentration in the polluted water itself, as it represents historical accumulated of the metals. A controlled high intensity floods may erode the upper portion of the bottom sediments, where heavy metals accumulated, and leaching them to the sea.

## Declarations

### Acknowledgments

For numerous useful suggestions and for providing a literature review, we are grateful to Dr. John Huntley (University of Missouri, Columbia, USA).

### Ethics approval and consent to participate

Not applicable

### Consent for publication

Not applicable

### Availability of data and materials

All data generated or analysed during this study are included in this published article [and its supplementary information files].

### Competing interests

The authors declare that they have no competing interests

### Funding

This research received no fund

### Authors' contributions

AA analyzed, interpreted, and wrote the manuscript. SS collected the samples, analyzed sediment grain-size, and interpreted the data. MK draw the figures, interpret the data, and edited the references,. All authors read and approved the final manuscript

## References

Abbassy MMS (2018) Distribution pattern of persistent organic pollutants in aquatic ecosystem at the Rosetta Nile branch estuary into the Mediterranean Sea, North of Delta, Egypt. *Mar. Pollut. Bull.* **131**, 115-121.

<https://doi.org/10.1016/j.marpolbul.2018.03.049>

Abdelhady AA, Abdelrahman E, Elewa AMT, Fan J, Zhang S, Xiao, J (2018) Phenotypic plasticity of the gastropod *Melanoides tuberculata*: A pollution-induced stabilizing selection. *Mar. Pollut. Bull.* **133**, 701-710.

<https://doi.org/10.1016/j.marpolbul.2018.06.026>

Abdelhady AA, Khalil MM, Ismail E, Mohamed R, Ali A, Snousy M, Fan J, Zhang S, Yanhong L, Xiao, J (2019a) Potential biodiversity threats associated with the metal pollution in the Nile-Delta ecosystem (Manzala lagoon, Egypt). *Ecol. Indic.* 98, 844-853. <https://doi.org/10.1016/j.ecolind.2018.12.002>

Abdelhady AA, Khalil MM, Ismail E, Fan D, Zhang S., Xiao J (2019b). Water chemistry and substrate type as major determinants for molluscan feeding habit and life-mode in lagoon sediments. *Estuar. Coast. Shelf Sci.* 220, 120-130. <https://doi.org/10.1016/j.ecss.2019.02.019>

Abdo MH (2002.) Environmental studies on Rosetta branch and some chemical applications at the area extend from El-Kanater El-Khyria to Kafr El-Zayt city. Ph.D. Thesis, Faculty of Science, Ain Shams University, Egypt, 187 pp.

Branica M, Peharec Ž, Kwokal Ž (1985) Concentrations of Zn, Pb, Cd and Cu in the surface waters of the Adriatic Sea (1980 cruise of the R/V „Andrija Mohorovičić“). *Rapp. Comm. int. Mer médit. (Monaco)*. Rapport du 29e Congres de la CIESM. CIESM, Monaco, pp. 109–110.

Carrascal LM, Galvan I, Gordo O (2009) Partial least squares regression as an alternative to current regression methods used in ecology. *Oikos* 118, 681–690. <https://doi.org/10.1111/j.1600-0706.2008.16881.x>

Chariton AA, Stephenson S, Morgan MJ, Steven AD, Colloff MJ, Court N, Hardy CM (2015) Metabarcoding of benthic eukaryote communities predicts the ecological condition of estuaries. *Environ. Pollut.* 203,165-174. <https://doi.org/10.1016/j.envpol.2015.03.047>

Chen Z, Salem A, Xu Z, Zhang W (2010) Ecological implications of heavy metal concentrations in the sediments of Burullus Lagoon of Nile Delta, Egypt. *Estuar. Coast. Shelf Sci.* 86, 491–498. <https://doi.org/10.1016/j.ecss.2009.09.018>

Cooper J (2014) *The Medieval Nile: Route, Navigation, and Landscape in Islamic Egypt*. The American University in Cairo Press. p. 76

Dean RJ, Shimmiel TM, Black KD (2007) Copper, zinc and cadmium in marine cage fish farm sediments: an extensive survey. *Environ. Pollut.* 145, 84-95. <https://doi.org/10.1016/j.envpol.2006.03.050>

Di Toro DM, McGrath JA, Hansen DJ (2000) Technical basis for narcotic chemicals and polycyclic aromatic hydrocarbon criteria. I. Water and tissue. *Environ. Toxicol. Chem.* 19(8), 1951-1970.

Dumont HJ (2009) A description of the Nile Basin and a synopsis of its history, ecology, biogeography, hydrology, and natural resources. In: Dumont HJ (ed), *The Nile: Origin, environments, limnology, and human use*, Ghent: Springer pp. 1–21. [https://doi.org/10.1007/978-1-4020-9726-3\\_1](https://doi.org/10.1007/978-1-4020-9726-3_1)

El-Barbary AA, El-Bouraie MM, Yehia MM (2008) Evaluation of organochlorine pesticides (OCPs) in surface water and bed sediment samples from the River Nile at Rosetta branch. *J Appl Sci Res*, 4, 1985–1993.

El Bouraie MM, El Barbary AA, Yehia MM, Motawea EA (2010) Heavy metal concentrations in surface river water and bed sediments at Nile Delta in Egypt. *Suoseura* 61, 1–12.

Ezzat SM, Mahdy HM, Abo-state MA, Abd El-Shakour EH, El-Bahnasawy MA (2012) Water quality assessment of River Nile at Rosetta branch. Impact of drains discharge. *Middle-East J Sci Res* 12(4):413–423. DOI: 10.5829/idosi.mejsr.2012.12.4.1694.

Fichet, D., Radenac, G., Miramand, P., 1998. Experimental studies of impacts of harbour sediments resuspension to marine invertebrates larvae: bioavailability of Cd, Cu, Pb and Zn and toxicity. *Mar. Pollut. Bull.* 36, 509-518. DOI: 10.1016/S0025-326X(97)00190-2.

- Fishar M (2018) Nile Delta (Egypt). In: Finlayson C, Milton G, Prentice R, Davidson N (ed) *The Wetland Book*. Springer, Dordrecht. [https://doi.org/10.1007/978-94-007-4001-3\\_216](https://doi.org/10.1007/978-94-007-4001-3_216).
- Förstner U, Wittmann GTW (1981) *Metal Pollution in the Aquatic Environment*. 2<sup>nd</sup> ed. Springer-Verlag, Berlin.
- Galloway JM (1979) Alteration of trace metals geochemical cycles due to the marine discharges of wastewaters. *Geochim. Cosmochim. Acta*, 43, 207-218.
- Garrels RM, Mackenzie FT, Hunt C (1975) *Chemical Cycles and the Global Environment - Assessing Human Influences*. W. Kaufman, Inc., Los Altos, USA.
- Gu J, Salem A, Chen Z (2013) Lagoons of the Nile delta, Egypt, heavy metal sink: with a special reference to the Yangtze estuary of China. *Estuar. Coast. Shelf Sci.* 117,282–292. <https://doi.org/10.1016/j.ecss.2012.06.012>
- Hatje V, Birch GF, Hill DM (2001) Spatial and temporal variability of particulate trace metals in Port Jackson Estuary, Australia. *Estuar. Coast. Shelf Sci.* 53, 63-77. <https://doi.org/10.1006/ecss.2001.0792>
- Hereher ME (2010) Vulnerability of the Nile Delta to sea level rise: an assessment using remote sensing. *Geomatics, Nat. Hazards Risk* 1:4, 315-321. <https://doi.org/10.1080/19475705.2010.516912>
- Kalantzi I, Shimmield TM, Pergantis SA, Papageorgiou N, Black KD., Karakassis I (2013) Heavy metals, trace elements and sediment geochemistry at four Mediterranean fish farms. *Sci. Total Environ.* 444:128–37. <http://dx.doi.org/10.1016/j.scitotenv.2013.10.020>
- Kalantzi I, Papageorgiou N, Sevastou K, Black KD, Pergantis SA, Karakassis I (2014) Metals in benthic macrofauna and biogeochemical factors affecting their trophic transfer to wildfish around fish farm cages. *Sci. Total Environ.* 470–471,742–753. <https://doi.org/10.1016/j.scitotenv.2013.10.020>
- Karatas M, Dursun S, Guler E, Ozdemir C, Emin AM (2006.) Heavy metal accumulation in wheat plants irrigated by wastewater. *Cellulose Chem. Technol.*, 40 (7): 575-579.
- Keshta AE, Shaltout KH, Baldwin AH, Sharaf El-Din AA (2020.) Sediment clays are trapping heavy metals in urban lakes: An indicator for severe industrial and agricultural influence on coastal wetlands at the Mediterranean coast of Egypt. *Mar. Pollut. Bull.* 151, 10816. <https://doi.org/10.1016/j.marpolbul.2019.110816>
- Khater AE, Kitamura Y, Shimizu K, Somura H, Abou El Hassan WH (2014) Improving water quality in the Nile Delta irrigation network by regulating reuse of agricultural drainage water. *J. Food Agric. Environ.* 12 (3&4), 329-337.
- Korfali SI, Davies BE (2003) A comparison of metals in sediments and water in the River Nahr-Ibrahim, Lebanon: 1996 and 1999. *Environ. Geochem. Health*, 25, 41-50.
- Long ER, Morgan LG (1990) The potential for biological effects of sediment-sorbed contaminants tested in the National Status and Trends Program. NOAA Tech. Memo. NOS OMA 52. US National Oceanic and Atmospheric Administration, Seattle, Washington, 175 pp.
- Long ER, Robertson A, Wolfe DA., Hameedi J, Sloane GM (1996) Estimates of the spatial extent of sediment toxicity in major US estuaries. *Environ. Sci. Technol.* 30, 3585-3592.
- Mosbahi N, Serbaji MM, Pezy J, Neifara L, Dauvin J (2019) Response of benthic macrofauna to multiple anthropogenic pressures in the shallow coastal zone south of Sfax (Tunisia, central Mediterranean Sea). *Environ. Pollut.*, 253, 474-487. <https://doi.org/10.1016/j.envpol.2019.06.080>

MWRI (2010) Water Resources Development and Management Strategy in Egypt – 2050, in Arabic, Ministry of Water Resources and Irrigation, Cairo, Egypt.

Negm AM, Saavedra O, El-Adawy A (2017) Nile Delta Biography: Challenges and Opportunities. In: Negm, A (ed) The Nile Delta, The Handbook of Environmental Chemistry, Springer: Cham, Switzerland, 55, pp. 1–16. DOI: 10.1007/978-3-319-56124-0.

O'Brien AL, Keough MJ (2013) Detecting benthic community responses to pollution in estuaries: A field mesocosm approach. *Environ. Pollut.*, 175, 45-55. <https://doi.org/10.1016/j.envpol.2012.11.038>

Oczkowski A, Nixon S (2008) Increasing nutrient concentrations and the rise and fall of a coastal fishery, a review of data from the Nile Delta, Egypt. *Estuarine, Shelf Coastal Sci.* 77, 309–319. <https://doi.org/10.1016/j.ecss.2007.11.028>

Quintino V, Rodrigues AM, Gentil F (1989) Assessment of macrozoobenthic communities in the lagoon of Óbidos, western coast of Portugal. *Sci. Mar.* 53, 645–654.

Radix P, Leonard M, Papantoniou C, Roman G, Saouter E, Gallotti-Schmitt S, Thiebaud H, Vasseur P (2000) Comparison of four chronic toxicity tests using algae, bacteria, and invertebrates assessed with sixteen chemicals. *Ecotoxicol. Environ. Saf.* 47, 186-194. DOI: 10.1006/eesa.2000.1966.

Rainbow PS, Phillips DJH (1993) Cosmopolitan biomonitors of trace metals. *Mar. Pollut. Bull.* 26, 593-601. [https://doi.org/10.1016/0025-326X\(93\)90497-8](https://doi.org/10.1016/0025-326X(93)90497-8).

Rainbow PS (1995) Biomonitoring of Heavy Metal Availability in the Marine Environment. *Mar. Pollut. Bull.* 31, 183-192. [https://doi.org/10.1016/0025-326X\(95\)00116-5](https://doi.org/10.1016/0025-326X(95)00116-5)

Rodrigues SK, Abessa DM, Rodrigues APDC, Soares-Gomes A, Freitas CB, Santelli RE, Freire, AS, Machado W (2017) Sediment quality in a metal-contaminated tropical bay assessed with a multiple lines of evidence approach. *Environ. Pollut.* 228, 265-276. <https://doi.org/10.1016/j.envpol.2017.05.045>

Ryu J, Khim JS, Kang SG, Kang D, Lee CH, Koh CH (2011) [The impact of heavy metal pollution gradients in sediments on benthic macrofauna at population and community levels](https://doi.org/10.1016/j.envpol.2011.05.034). *Environ. Pollut.* 159(10), 2622-2629. <https://doi.org/10.1016/j.envpol.2011.05.034>

Schropp SJ, Graham Lewis F, Windom HL, et al. (1990) Interpretation of metal concentrations in estuarine sediments of Florida using aluminum as a reference element. *Estuaries* 13, 227–235. <https://doi.org/10.2307/1351913>

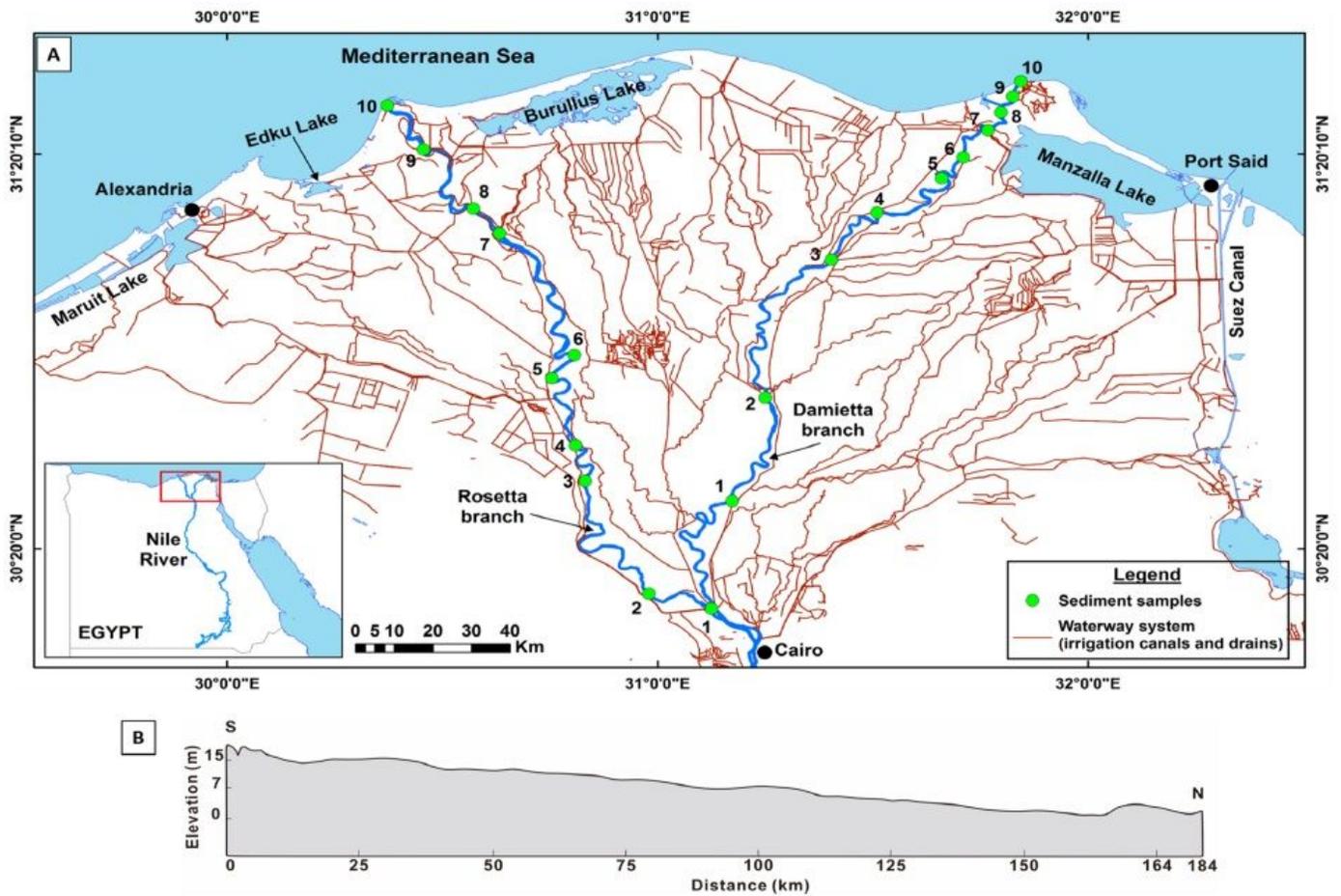
Simkiss K, Taylor MG (1989) Convergence of cellular-systems of metal detoxification. *Mar. Environ. Research* 28, 211-214.

Theodoridis S, Koutroumbas K (2008) *Pattern Recognition*. Academic Press (4<sup>th</sup> ed.), Elsevier.

Zelditch ML, Swiderski DL, Sheets HD (2012) *Geometric Morphometrics for Biologists: A Primer*. Elsevier Academic Press, London.

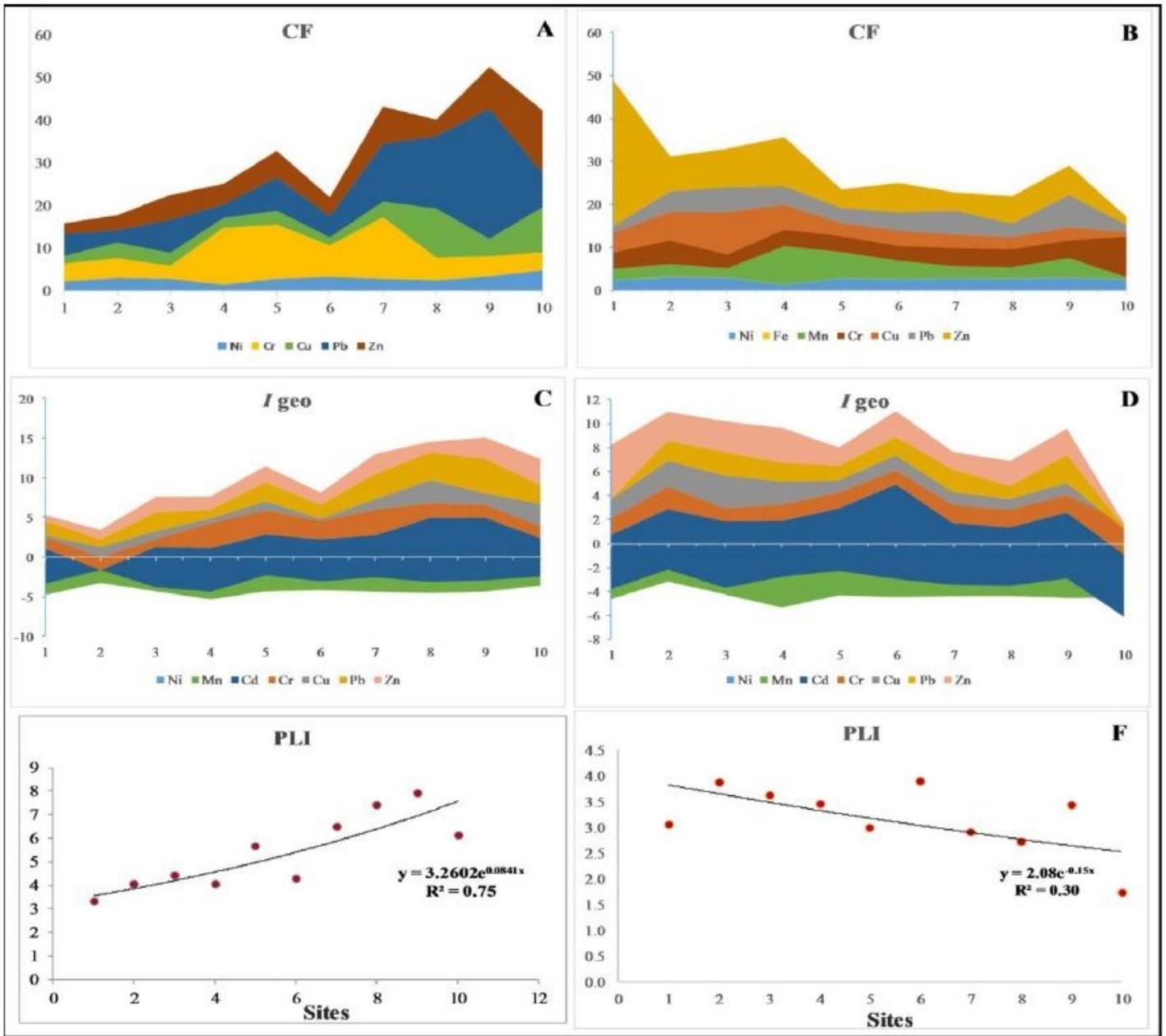
Zhang WG, Feng H, Chang J, Qu JG, Xie HX, Yu LZ (2009) Heavy metal contamination in surface sediment of Yangtze River intertidal zone: an assessment from different indexes. *Environ. Pollut.* 157, 1533–1543. <https://doi.org/10.1016/j.envpol.2009.01.007>

## Figures



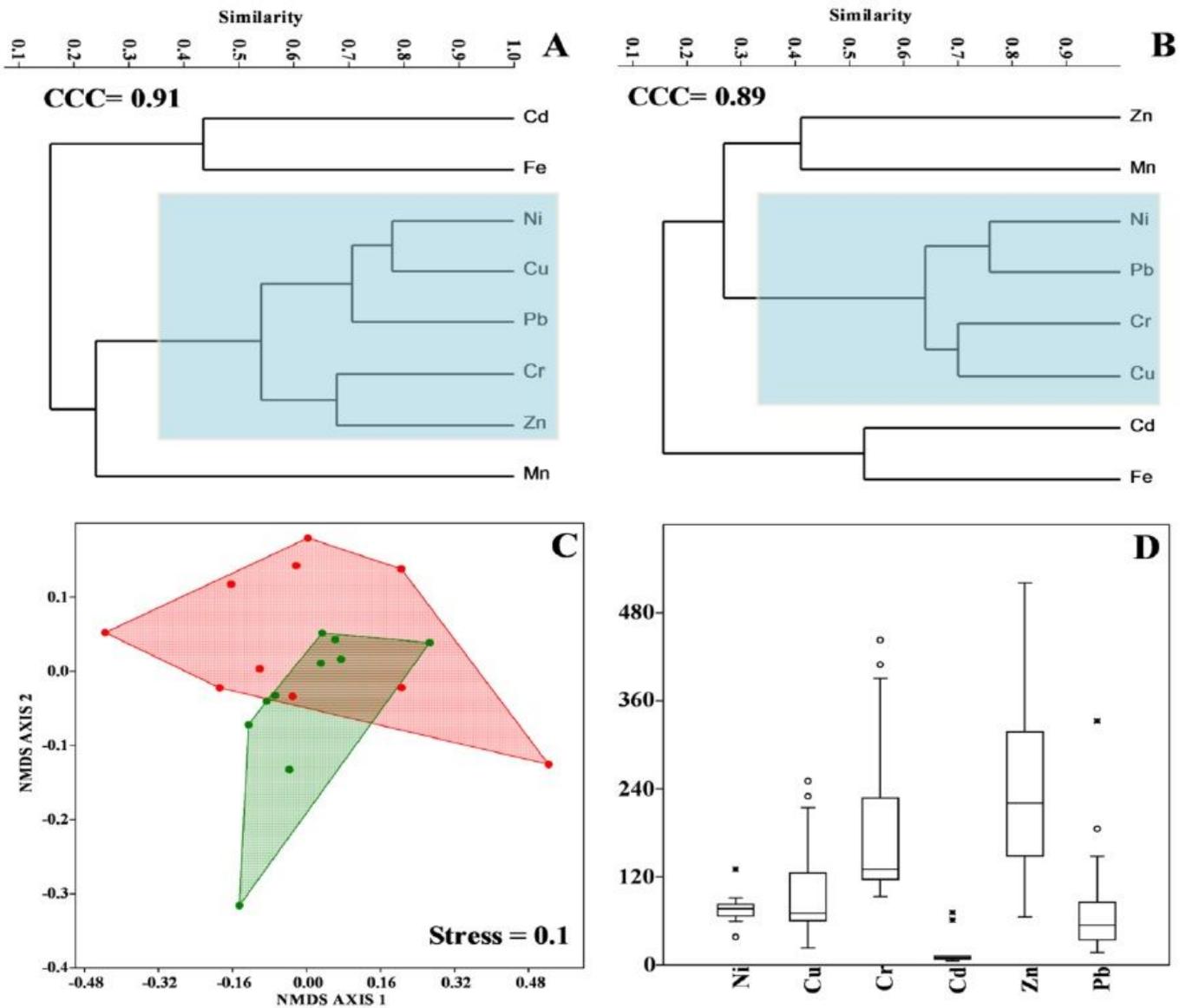
**Figure 1**

A map of the Nile Delta showing the coastal lakes, the two main branches (Rosetta and Damietta) of the Nile, the intensive irrigation canals and drains, and location of the analyzed stations (A), and the main river gradient along Damietta branch from the delta apex, at Cairo, to the Mediterranean coast (B).



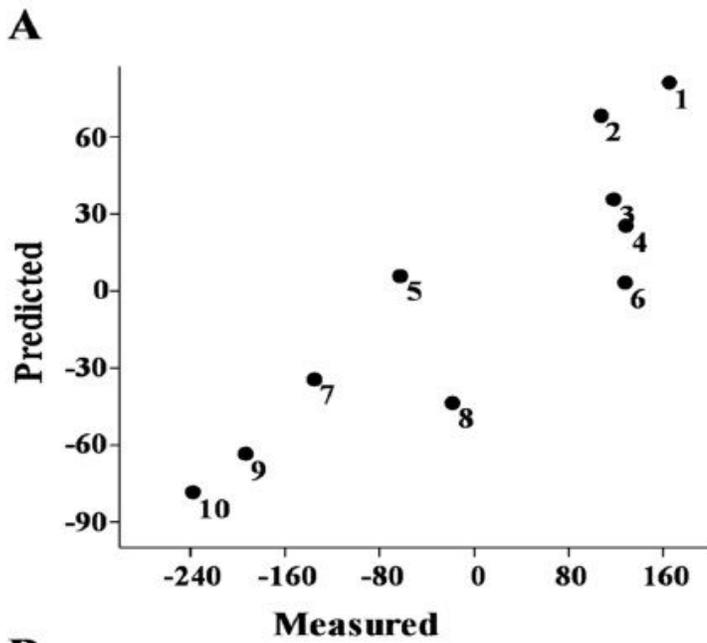
**Figure 2**

Pollution level (pollution indices) along the sampling sites, A) Contamination Factor (CF) along Rosetta branch, B) Contamination Factor (CF) along Damietta branch, C) Index of geo-accumulation (*I* geo) along Rosetta branch, D) Index of geo-accumulation (*I* geo) along Damietta branch, E) Pollution Load Index (PLI) Exponential regression models between the distance of stations along Rosetta branch to the capital city, F) along Damietta branch.



**Figure 3**

A) UPGMA clustering dendrogram show the associations of metals according to their concentrations in the sediment samples of Rosetta Branch, B) of Damietta branch, C) 2D-NMDS plot of the samples coded according to their distance (near/far) from the source (capital city) for all 20 stations analyzed, D) Box-plot of the 5 heavy metals based on their concentrations in the Nile Delta (both branches).

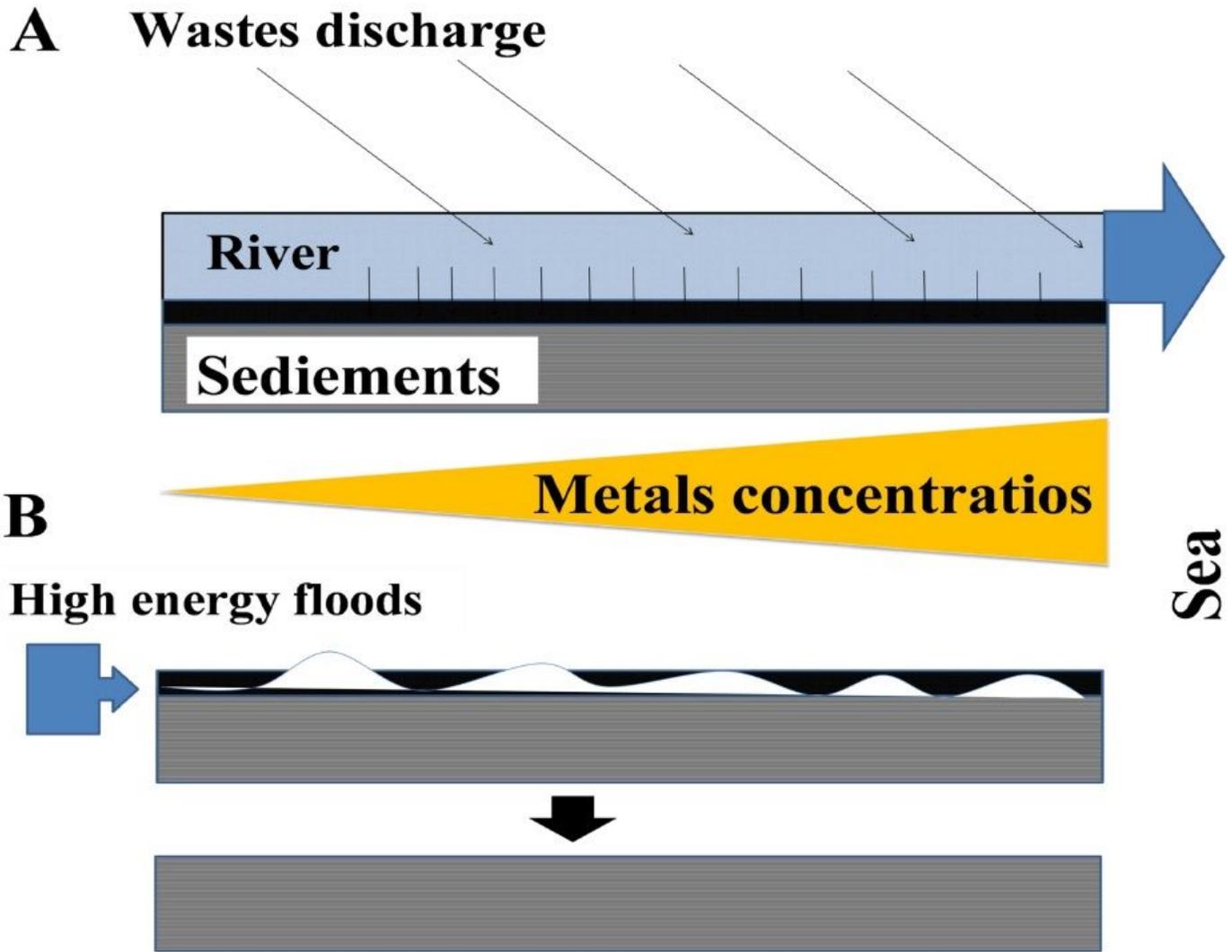


**B**

	Loading		
(VIP)s	Axis 1	Axis 2	Axis 3
<b>M</b>	0.01	-0.67	0.69
<b>sd</b>	0.00	0.58	0.70
<b>Sk</b>	0.00	-0.24	0.03
<b>K</b>	0.01	-0.40	-0.17
<b>Distance</b>	<b>-1.00</b>	<b>-0.01</b>	<b>0.01</b>

Figure 4

PLS regression model summary between the metal concentrations in sediments (observations) and the physicochemical traits (sediment grain-size/distance, predictors), A) predicted vs. measured concentrations in the sediments of the Rosetta branch ( $Q^2 = 56.4$ ), B) Variable importance for Projection (VIPs).



**Figure 5**

A model explaining the process of heavy metal sinking in the Nile Delta (A) and a possible solution for leaching them to the sea (B).

### Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [AppendixA.docx](#)