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Potential biodiversity threats associated with the metal pollution in the Nile–Delta ecosystem (Manzala lagoon, Egypt)

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ABSTRACT

Metal pollution may pose a high risk to the ecosystem stability. To evaluate the impact of the metal pollution on the biodiversity, metals concentrations in sediments, water, and molluscan shells were analyzed at sixteen sites in the Manzala lagoon, which is the largest in the Nile–Delta. The samples were collected along a gradient from the main agricultural drain, which brings mixed industrial, domestic, and agricultural wastes. An exponential trend of increasing metals concentration towards the main agricultural drain was observed. For sediment and faunal samples this trend was statistically significant in most cases, however, this trend was not found for all metals in water samples except for Zn. Partial Least Square (PLS) model confirmed that the distance to the drain is a second major predictor of the observed metal concentrations after sediment grain–size, while other physicochemical parameters have minor effects. Moreover, a significant correlation was found between most metals in the fauna and their respective sediments. In contrast, neither sediment nor faunal metal concentrations did correlate with water samples. Collectively, all pollution indices (enrichment factor, contamination factor, and geo–accumulation index) indicate high pollution by Cd and Pb and moderate pollution by Zn. UPGMA clustering and non–metric Multidimensional scaling (nMDS) classified the sites in the lagoon into three main categories: 1) highly polluted southeast corner around the drain, 2) moderately polluted northeastern corner, where the newly widened and deepened sea–outlet occur, 3) unpolluted northwestern part, which located away from the drain. Multiple regression analysis showed that the distance to the pollution source, salinity, and water depth are significantly predict the faunal diversity. Furthermore, the Pollution Load index (PLI) was significantly correlated with the diversity indices. Lower diversity and dominance of opportunistic taxa in the polluted sites are interpreted to be negative consequences of the metal pollution.

1. Introduction

Natural environments are currently under raising threats of heavy metal pollution from different sources including industrial, agricultural, and domestic wastes, which may generate other toxic pollutants such as the volatile organic compounds or other non–conventional pollutants such as ammonia (Dean et al., 2007; Kalantzi et al., 2014). The huge parts of these wastes usually find a way to the aquatic ecosystems. Effective ecosystem management requires valid tools to assess the spatial extent of the contamination and their potential sources (Schropp et al., 1990).

The metals concentrations in the natural aquatic environments, which are highly sensitive to the anthropogenic inputs, are depending mainly on their water sources, sediment characteristics, and the surrounding soil, where monitoring the spatiotemporal changes is extremely important (Branica et al., 1985). In addition, understanding the distribution and mobility of these heavy metals between the sediment and water is of great importance (Förstner and Wittmann, 1981). Moreover, metals in both sediments and water column can be transferred to the fauna during their feeding and respiration (Rainbow and Phillips, 1993; Rainbow, 1995). Although metal contamination can be assessed by sets of different compartments such as water, sediments,

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and different fauna, integrating multiple sources may give a more robust conclusion.

The Nile–delta lakes are a vital aquacultural base for millions of people in Egypt. The rapid rise of the human population, petrochemical refineries, and agriculture in the Nile Delta have resulted in intense heavy metal and nutrient pollution of the delta's four major lagoons (Oczkowski and Nixon, 2008; Chen et al., 2010; Gu et al., 2013). According to Arnous and Hassan (2015), Manzala lagoon was considered a high-risk area, which is contaminated with heavy metals, where periodic monitoring and evaluation is highly recommended. Bahr–El–-Baqar, which is anoxic drain with mixed wastes, is the main source of the pollution in the Manzala lagoon (Elkady et al., 2015).

The negative impacts of this degradation are becoming well known in the upper portions of the trophic web (e.g., humans and fish; Oczkowski and Nixon, 2008), but are less characterized among the benthic primary consumers (mollusks). We aim herein to assess the spatial variation in the metal concentrations and their mobility in the surface sediments, water, and benthic fauna in the Manzala lagoon, trace their sources, and delineate the influences of the physicochemical factors. This may provide a better understanding of the environmental risks and possible management policies. Therefore, we aim to answer the following research questions; 1) what is the degree of metal pollution in the Manzala lagoon? 2) Can the metals concentrations among different ecosystem elements (i.e. sediments, water and fauna) be correlated? 3) How it depends on the distance from the potential source? 4) Has it negative consequences on the faunal diversity?

2. Material and methods

2.1. Field sampling

Samples of sediments, water, and molluscan shells were collected in three replicates from sixteen sites in the Manzala lagoon from February to April of 2017 along a gradient from the main agricultural drain (Bahr-El-Baqar, Fig. 1) by 20*20 cm Ekman grab. Water samples were stored in polypropylene bottles, which is precleared ultra–pure HNO_3. The physicochemical variables, which may affect the dissolved metals such as Electric conductivity (EC), total dissolved solids (TDS), hydrogen level (pH), and water depth were measured at each site during sampling using *Xplorer* GLX – PS–2002 (Table 1). Sediment grain size was also calculated at each site (Table 1).

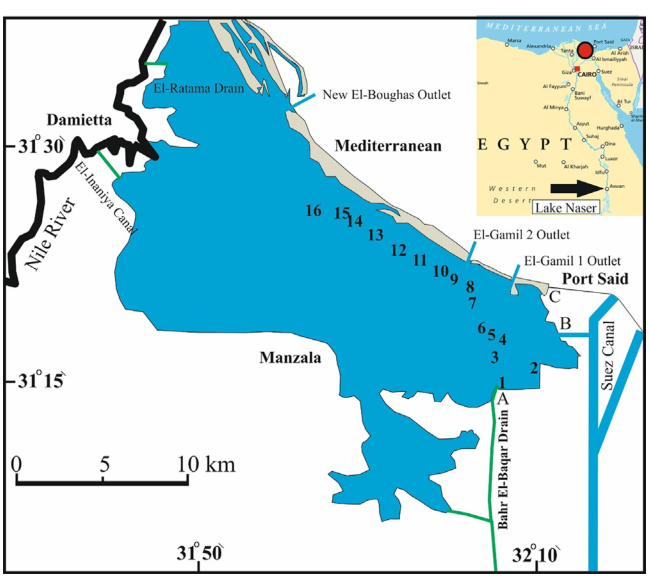

Fig. 1. Sampling location in Manzala lagoon show the main possible pollution sources; Bahr–El–Baqar Drain (A), industrial discharge (B), and the sewage plant (C).

2.2. Geochemical analyses

In the laboratory, sediment grain–size analysis was done using an electric shaker for 100 g 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 and grouped together to represent the fine–grain sediments (i.e. shales) for statistical analyses (see Table 1). Molluscan shells were picked from a separated portion of the sediment (200 g), which were washed and sieved through a 0.5 mm mesh screen. Only shells of live individuals were used in the analyses.

The sediment samples were air–dried and crushed with a ceramic pestle and mortar to pass through a 0.063 mm mesh screen. The selected shells were washed and the soft tissues were separated from the shells with a glass rod. The shells were cleaned with a toothbrush to remove fine organic or inorganic particles and dried at the room–-temperature. Each shell was crushed and sieved also through a 0.63 mm mesh screen. In a 50–ml beaker, 0.2 g of dried sediments/shells and 1 ml of water aliquot was taken and then 3 ml of a concentrated mixture of HNO_3 and HCl (1:1) were added. Subsequently, all the treated samples were diluted to 10 ml with ultra–pure water (Milli–Q). Then the shell/sediment samples were filtrated for 5 min 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 Al were analyzed using inductively coupled plasma optical emission spectrometry (ICP–OES) at the Institute of Geology and Geophysics, Chinese Academy of Sciences (Beijing, China).

2.3. Quality assurance

In order to ensure the quality of the analyses, strict laboratory regulations and procedures regarding cleaning, calibration, and duplicates measurements were followed. Metal concentration was done using inductively coupled plasma optical emission spectrometry (ICP–OES; IRIS Advantage). The applied analytical method was continuously checked using a certified reference material (GSB04–1767–2004) to ensure the quality of the performed analyses. The certified reference materials were analyzed every 10 samples. The detection limits of the procedure were equal to 3sd. The errors in all measurements were < 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% for sediment samples, 1–5% for shells samples, and 2 and 5% for water samples. The practical quantitation limits (PQLs) of the metals analyses were in the range of 0.01–0.05 ppm.

2.4. Pollution and diversity calculations

For better assessment of the pollution risk, the Contamination Factor (CF), geo–accumulation index, and the Enrichment Factor (EF) were calculated for sediment samples and integrated in the interpretations. Contamination Factor (CF), calculated as metal content in the analyzed sediment to a background level, is the easiest and has been continuously implemented. However such simplification is very sensitive to the selected reference (Goher et al., 2014). Similarly and although it has been frequently applied, the geo–accumulation index ($Igeo = \log2 (cn/1.5 * bn)$, where (cn) is the measured concentration of examined element (n) in the sediment sample and (bn) is the geochemical background for the element (n), may not be adequate as grain size effects may vary considerably among different localities and cannot be simply resolved by the 1.5 'safety factor'. The Enrichment Factor (EF), calculated as (CM/CX sample)/(CM/CX Earths), where CM is the content of metal studied and CX is the content of immobile element, is

Table 1
Location and physicochemical data of the sites and their distance to the main agricultural drain.

Sampling sites	Distance (km)	Grain size (%)							Water chemistry				Species number
		Gravel	course sand	medium sand	Fine sand	Total sand	Silt	Clay	EC (mS/cm)	TDS (ppt)	pH	Water depth (m)	
1	1.2	1.2	19.4	13.9	9.9	16.3	59.5	24.0	16.5	31.7	18.1	8.2	0
2	2.7	2.7	13.7	15.3	11.6	22.0	62.6	21.8	15.7	36.0	20.5	8.1	0
3	4.2	4.2	5.9	17.1	11.7	29.1	63.8	14.5	21.7	14.5	8.3	8.5	7
4	5.2	5.2	5.9	17.1	11.7	29.1	63.8	14.5	21.7	9.0	5.2	8.3	11
5	7.0	7.0	12.8	17.6	15.8	34.1	80.3	9.5	10.2	20.7	11.8	9.2	0
6	7.9	7.9	16.2	21.6	21.6	27.0	86.5	10.8	2.7	10.2	5.8	9.8	8
7	8.7	8.7	58.9	24.5	2.3	12.6	98.3	1.4	4.0	40.3	23.0	8.9	3
8	10.7	10.7	58.8	24.5	2.3	12.6	98.2	1.3	6.0	44.1	25.2	8.6	6
9	11.9	11.9	60.4	25.1	1.8	4.5	91.7	5.2	3.1	35.4	20.2	9.0	6
10	11.9	11.9	27.0	9.9	36.5	23.0	96.5	3.3	0.3	40.3	23.0	9.1	5
11	13.9	13.9	51.0	26.0	6.5	13.3	96.8	2.2	1.0	62.5	25.6	8.3	0
12	15.8	15.8	21.7	13.5	20.1	41.8	97.1	0.2	2.7	8.1	4.6	7.8	7
13	15.9	15.9	55.7	26.8	0.0	14.9	97.4	2.1	5.0	37.4	21.3	8.3	4
14	17.3	17.3	58.8	24.0	2.4	12.5	97.7	2.3	0.0	42.1	24.0	9.0	4
15	18.9	18.9	58.8	24.5	1.1	12.3	96.8	2.2	1.0	44.1	25.2	8.7	7
16	19.2	19.2	87.0	11.0	0.5	0.0	98.5	1.2	0.3	42.9	24.4	8.9	4

computed relatively to both an immobile element in addition to abundance in the Earth's crust (Sinex and Helz, 1981), therefore, it can provide a convenient measure of geochemical trends and is used for making robust comparisons among areas. In addition, the Pollution Load Index (PLI), which calculated as the nth root of contamination factor (CF) of each metal, where n is the number of metals analyzed, was also calculated (for details about calculations and assessment criteria see Goher et al., 2014). Background data was taken from Nasser Lake (Goher et al., 2014), Al reference value has been taken from El Bouraie et al. (2010). To minimize/downplay the grain–size effect, Coefficient of Determination (R^2), calculated from the linear regression model between the metal concentrations and the shale percentage, was used to normalize the CF and the PLI.

For assessing the biodiversity in the lagoon, the specimens were identified down to the species level using the available literature (e.g., Barash and Danin, 1982; Reinhardt et al., 2000; Galil, 2004; Lotfy and Lotfy, 2015). Diversity indices (e.g., Shannon, Simpson, Species Richness, Dominance, Abundance, and Evenness were calculated for each site. All of the analyses were carried on PAST version 2.17 (Hammer et al., 2001).

2.5. Statistical analyses

To give the same importance to all variables included in the statistical analyses, the variables were divided by the Euclidean norm (i.e. chord transformation; Theodoridis and Koutroumbas, 2008). This type of data transformation will also resolve the effect of the multicollinearity and/or the heteroscedasticity of the data if any present. Pearson correlation and regression models were used for assessing the relationships among metal concentration in different compartments (sediments, water, and shells). We tested the significance for all correlations at the significance level ($p < 0.001$).

In addition, metal concentrations in sediments were compiled for non–metric Multidimensional scaling (nMDS) and UPGMA clustering (Zhang et al., 2009; Gu et al., 2013). Integrating both analyses is highly-recommended (for details see Abdelhady and Fürsich, 2014, 2015). Although Euclidian is usually used as a similarity measure in both clustering and nMDS, it is a unit independent and as the scale of the major metals (e.g. Al, Fe, and Mn) differ greatly from the trace ones (e.g., Cd, Pb, and Zn), the clustering result will be related to the scale and not to the real patterns of the data. Therefore, correlation similarity may provide more accurate clustering. Correlation similarity is a weighted type of Euclidean distance, which differs from the Pearson correlation coefficient r. The results based on the different similarity measures were included for comparison. In addition, the strength of the clustering or what is known as the cophenetic correlation coefficient (CCC; a measure of how a dendrogram preserves the pairwise distances between the original data points) was used to assess the resulted dendrograms; see Abdelhady and Fürsich, 2015).

A multiple linear regression analysis was carried out to test if the distance to the source/ physicochemical parameters significantly predicted the diversity Shannon index. The data was normalized by the standard deviation. In order to quantify the effect of each physicochemical parameter, Partial Least Squares (PLS) model was implanted. According to Bloemsma et al. (2012), PLS models of geochemical and grain–size data can drive robust proxy information for the environmental traits. The strength of the fitted model (Q^2) 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. PLS model is more reliable than other techniques when identifying relevant variables and their magnitudes of influence, especially in cases of small sample size. Unlike other regression methods, the PLS model can be used when the predictor variables are highly collinear (multicollinearity; see Carrascal et al., 2009; Zelditch et al., 2012).

3. Results

3.1. Metals concentrations

Comparing metal concentrations in all samples show that sediments have higher concentrations followed by shells, while water samples have the lowest concentrations (Fig. 2; Appendix S1). The average concentrations within the samples arrange the metals in the sediments in the following descending order (Fe > Al > Mn > Pb > Zn > Cu > Cr > Cd). Shells have the same trend but only Cr concentrations are higher than Cu. Concentrations in water are slightly different and the metal concentration is as following Fe > Al > Cr > Zn > Mn > Cu > Pb > Cd (Appendix S1). Concentrations of Cd, Cr, and Cu, is above the Effective Range Low (ERL) in some cases, while Pb, and Zn are above the Effective Range median (ERM; Long and Morgan, 1990; Appendix S1).

Furthermore, Pearson correlation between metals concentrations in the shell samples and their respective sediments showed that concentrations of all trace metals (Cd, Cu, Cr, Pb, and Zn) in addition to Al were positively correlated, while both Fe and Mn have no significant correlations (Appendix S2). In addition, metals concentrations in Cd, Cu, Pb, and Zn are significantly correlated between the sediments, shell,

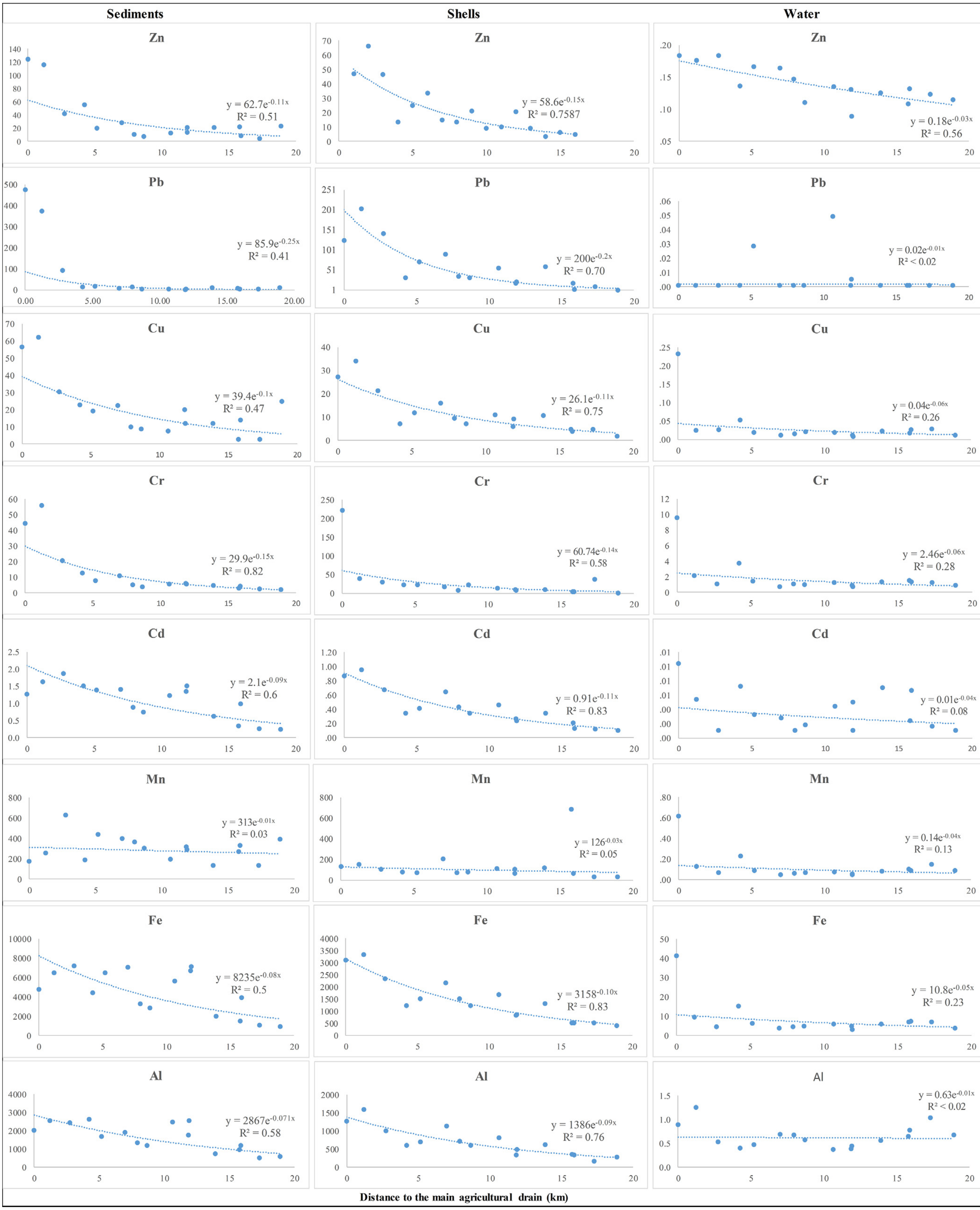

Fig. 2. Exponential regression models between metals concentrations (y-axis) and the distance to Bahr–El–Baqar Drain (x-axis), concentrations in (μg/g) for sediments/shells samples and in (μg/l) for water samples.

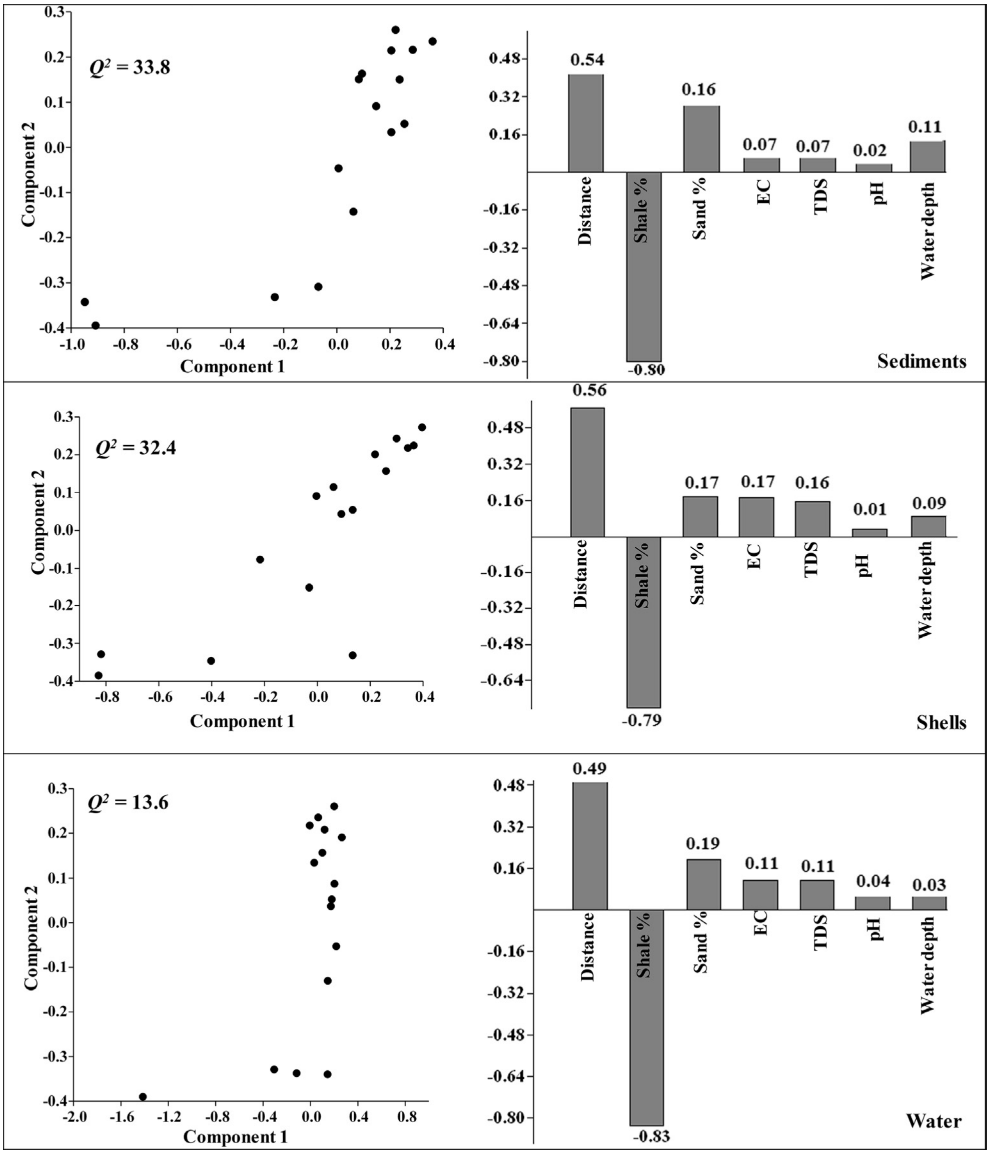

Fig. 3. PLS model (Component 1 and 2 plot and VIPs loading) between the metal concentrations in sediments (observations) and the physicochemical traits (predictors).

and water samples ($p < 0.01$), which may indicate that they originated from the main source or they are highly exchangeable among the analyzed components. In general, the metal concentrations in all of the examined materials were consistently higher at Bahr Al–Baqar (Figs. 1, 2). There is a strong significant exponential correlation between the distance to Bahr El–Baqar Drain and most metals concentrations in sediments and shells except for Mn (Fig. 2). Although most metals concentrations in water samples decreasing also significantly with distance from the Bahr–El–Baqar Drain, Zn is the only metal that shows a significant correlation (Fig. 2).

3.2. Physicochemical traits

A PLS model was conducted to predict the metal concentrations from the physicochemical parameters and distance to the source. The PLS model is well fitted (Q^2 = 33.8%; Fig. 3), where the first component represents 0.98% of the total covariance Plots of the VIPs indicate that shale percentage (grain-size) is the first main contributor to the metal variability, while the distance to the drain is a second and final major predictor of the total variability in the metal concentrations (0.8 and 0.5 respectively; Fig. 3). In contrast, all other physicochemical traits comment on a minor proportion of the metals variability.

3.3. Pollution levels and source evaluation

According to the EF, the sediments near the drain are modestly polluted by Cd and Fe and significantly polluted by Pb (Fig. 4). In addition, CF indicated that the sediments are moderately–polluted by Cu and Zn, moderately to considerably polluted by Al, considerably to very highly polluted by Fe, Cd, and Pb (Fig. 4, Appendix S4). Moreover and according to the I*geo*, the sediments are moderately polluted by Zn, moderately to highly–polluted by Cd, and highly to extremely–polluted by Pb (Fig. 4 and Appendix S4). Furthermore, the PLI indicates progressive deterioration of the sites 1 and 2, while all other sites characterize by baseline levels of pollution. The results indicated a negative exponential correlation, where the pollution levels decreased with increasing distance to the drain. The northwestern side, where the main outlets are located and away from the pollution sources, have the lowest pollution levels (Fig. 4).

In addition, Cluster analysis grouped the stations located under same types of stress, a pattern well characterized in nMDS plot (Fig. 5A). Clustering shows that sites 1–12 can be arranged within a

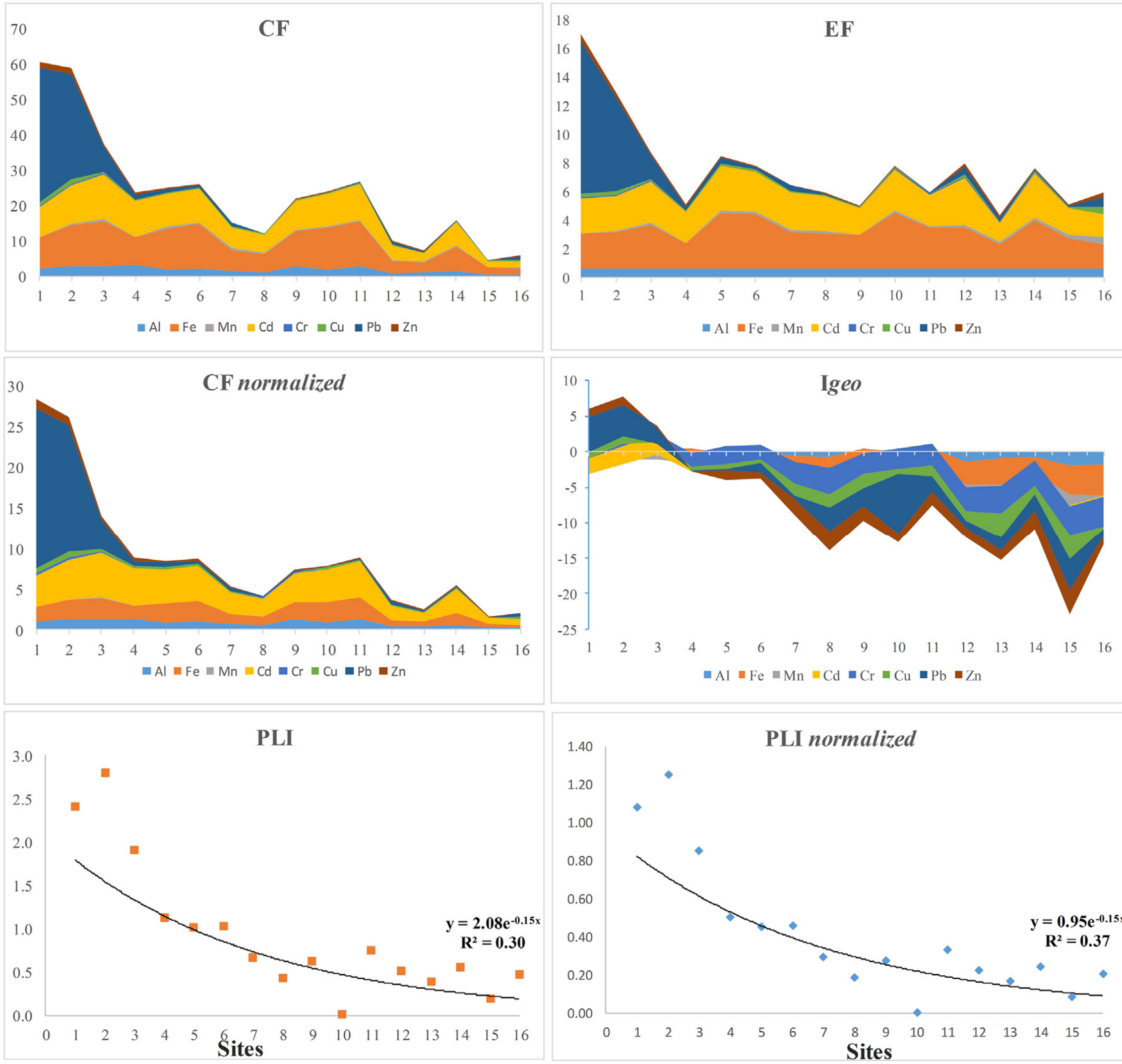

Fig. 4. Pollution level (pollution indices) along the sampling sites. Note the gradual decrease of the pollution levels away from the source (Bahr–El–Baqr Drain). Contamination Factor (CF), Enrichment Factor (EF), Index of geo–accumulation (*Igeo*), Pollution Load Index (PLI). Normalization of both CF and PLI was done by dividing the estimated values by the Coefficient of Determination (R^2) based on the linear regression between the metals concentrations and the shale percentage.

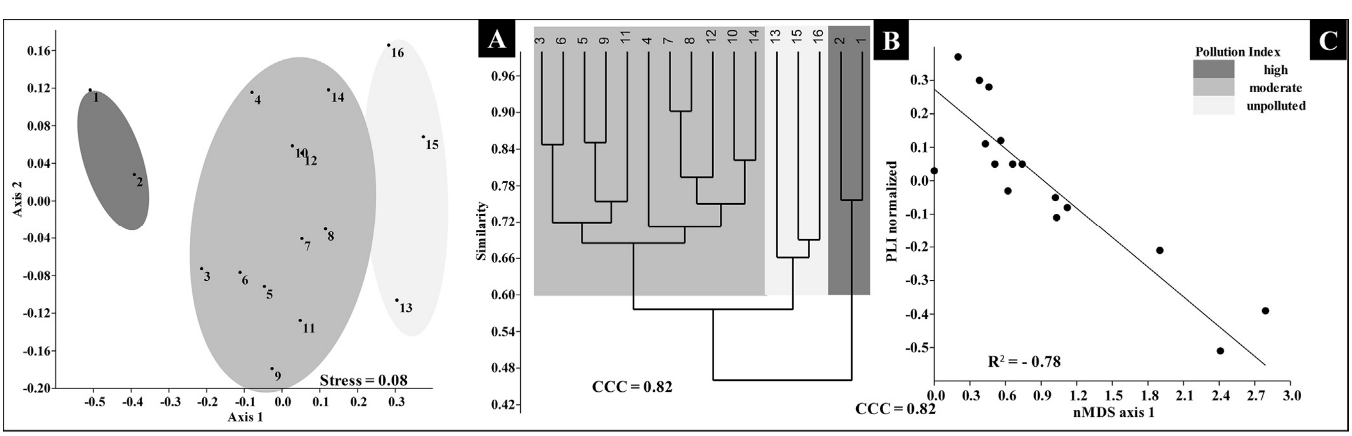

Fig. 5. Sample classifications according to metal concentrations in sediment samples. A) Plots for Euclidian-based nMDS, B) UPGMA clustering, and C) linear regression model between nMDS axis 1 and PLI.

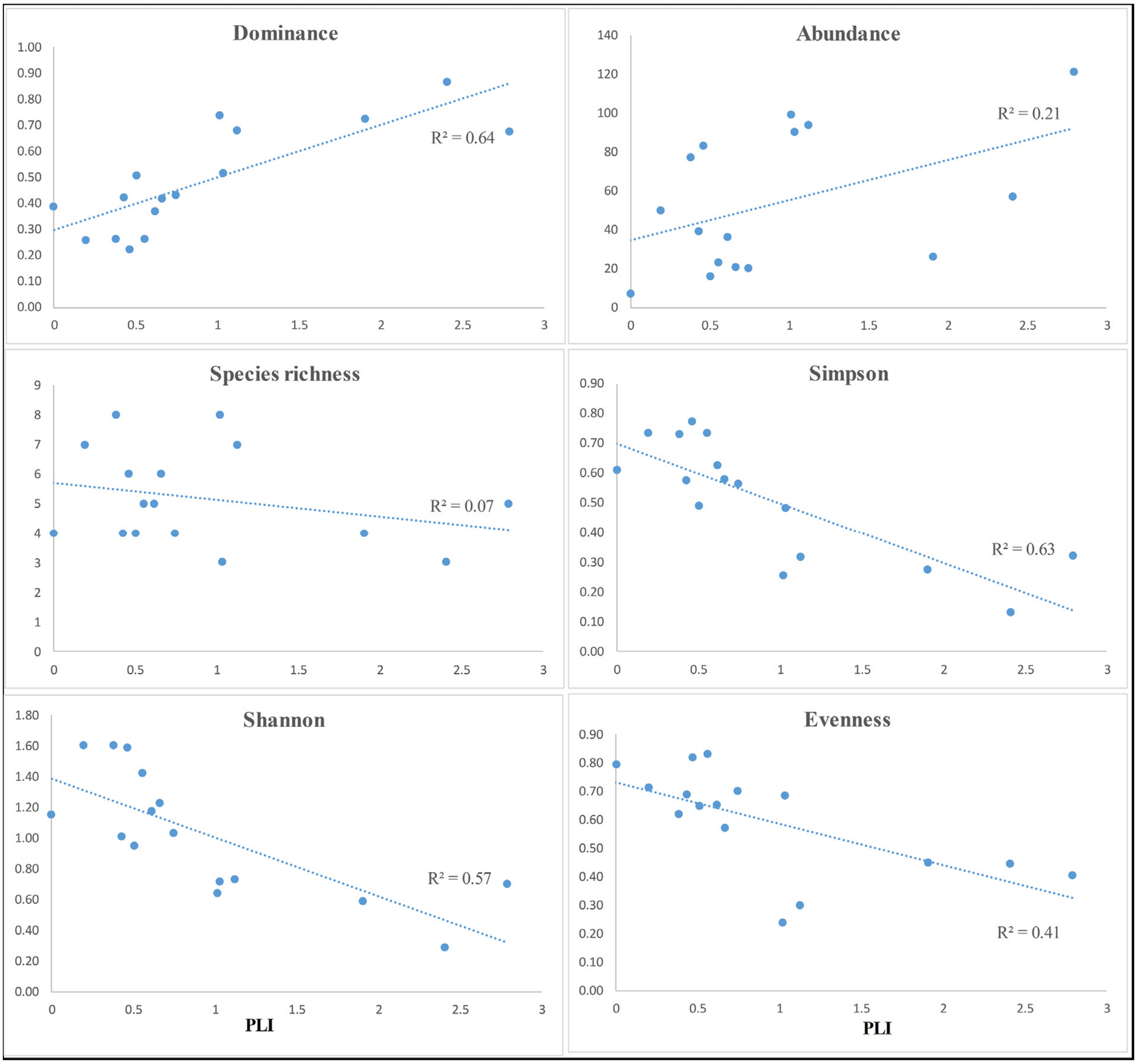

Fig. 6. Linear regression models between the PLI and the diversity indices.

Table 2
Multiple Regression Model coefficients between the physicochemical parameters/distance to the pollution source and the Shannon diversity index.

Independent variables	Coefficient	P-value
Distance	0.06862	0.0001
pH	0.09515	0.0715
Shales	0.009621	0.0546
TDS	0.01653	0.0005
Water depth	0.1345	0.0080
	R^2 = 0.9611	
	R^2-adjusted = 0.9416	
	P-value = 0.0004	

single cluster (polluted, Fig. 5B). A second main cluster includes sites 13–16, which lies far from the agricultural drain (unpolluted sites). Furthermore, the polluted cluster can be further subdivided into two sub-clusters, one including sites 7, 8, 12, and 14 (moderately polluted), and the second including sites 1–6, 9, 10, 11, and 13 (highly polluted, Fog. 5B). Comparing the PLI to the nMDS axis one indicate a strong and significant negative correlation (R^2 = 0.8, Fig. 5C).

3.4. Biodiversity

To determine the impact of the metal pollution mentioned above on the benthic biodiversity, all of the six diversity indices (Appendix S5) were correlated to the PLI (Fig. 6). The results show a strong and significant positive correlation between the PLI and the Dominance (R^2 = 0.6). In addition to a strong and significant negative correlation between the PLI and all of Simpson, Shannon, and Evenness (R^2 between 0.6 and 0.4). In contrast, Abundance and Species Richness show no significant correlation. As polluted sites have lower diversity and higher dominance of specific (i.e. opportunistic) taxa, metal pollution is interpreted to be a major threat for biodiversity, at least in the Manzala ecosystem. As the lower diversity at the polluted sites could be related to some physiochemical parameters, a multiple regression analysis was conducted to predict the diversity Shannon index from the physicochemical parameters and distance to the source. The results (Table 2) show that the overall quality of the fit is very good (R2 = 0.96, $p < 0.001$). The distance to the pollution source, water depth, and TDS, all are statistically significant ($p < 0.001$), while other physicochemical parameters such as EC, and pH have no significant effect.

4. Discussion

4.1. The spatiotemporal trend in metals concentrations

The research hypothesis herein about the potential pollution source was supported by the fact that most of the metals show an increasing trend toward Bahr–El–Baqar Drain (i.e. the drain is the main source for metal pollution in the lagoon). Although this gradient is not obvious in water samples, the stations close to the drain have also very high concentrations of most metals (Fig. 2). Collectively, pollution indices indicate a high pollution for Cd, Pb and moderate pollution by Zn, and Cu. In general, the historical values for most metals are two to ten times more than those reported three decades ago (Appendix S6). Indeed, Cu, Zn and Pb have the most consistent increasing trend and point to a steady increase in the anthropogenic input. Partially or even untreated sewage discharge from Cairo and Port–Said cities in the past three decades through Bahr–El–Baqar and other minor drains is probably the main factor behind this trend. Exponential regression models between the metal concentrations/pollution indices and the distance to the mouth of the Bahr–El–Baqar Drain support this hypothesis. The Exponential correlation with the distance to the source and the metals concentrations was earlier indicated (see also Feng et al. 2006; Wang et al., 2014).

4.2. Mobility and distribution of the metals

It is well-known that metals are associated with smaller grain–size particles (Whitney, 1975; Wang et al., 2017). In addition, the amount of metal exchanged with biological organisms (bioavailability) is another important criterion (Vangronsveld and Cunnihgham, 1998). The mobility and bioavailability of metals are depending not only on the binding strength of the elements to sediments but also on the water characteristics such as pH, oxygen level, and salinity (Filgueiras et al., 2004). Moreover, metals concentrations are highly affected by the metabolism of organisms. PLS model herein indicates that physicochemical factors play no or minor role in metal concentrations. Bivalves and gastropods, accumulate metals more than in water column and thus they were continuously implemented as bioindicators (see Abdelhady, 2016; Abdelhady et al., 2018; Chakraborty et al., 2014). Therefore, mollusks were considered a good biomonitoring tool (Protasowicki et al., 2008; Rainbow and Phillips, 1993; Zuykov et al., 2013). However, its value in bioaccumulation is highly variable as it depends on the specific relationship between the species and the environmental compartment (Gundacker, 2000). The stronger significance correlations with the distance from pollution source obtained herein indicate that molluscan shells may be more useful in determining the spatial trend of the metals as they are not affected by grain–size. However, the results obtained herein may be influenced by other hidden environmental parameters, occasionally as there are many environmental gradients in the study area. Therefore, future research evaluating pollution-biodiversity relationship is highly acknowledged.

The results obtained herein indicate also that most trace metals concentrations in the molluscan shells increase with increasing their values in respective sediment in agreement with many others (e.g. Mtanga and Machiwa, 2007; Davydkova et al., 2005; Farag et al., 2007). In contrast, major cations (Al, Fe, and Mn) do not correlate, which means that the fauna may control the major but not the trace metals (see Abdelhady, 2016). The correspondence between metals concentrations in the shells and respective sediments may be related to their diet mode and life habit. Metals can be accumulated in molluscan animals during feeding either through water (suspension–feeders) or sediments (deposit feeders; Rainbow and Phillips, 1993; Rainbow, 1995).

Comparing metal concentrations in shells revealed that they vary greatly at both temporal and spatial scales (e.g. El-Sorogy et al., 2013; Appendix S6), and also vary from those measured in the Arabian Gulf (i.e. Heidari et al. 2013). The possible explanations for these high concentration patterns may be answered by the experiment of Lopes–Lima et al. (2012), who found that the exposure to toxic heavy metals may result in deregulation of metals. Indeed, essential metals like Cu and Zn are closely regulated, whereas the nonessential metals such as Pb and Cr increase to very high levels in the freshwater bivalves *Anodonta cygnea* after exposure to high metal concentrations.

Metals concentrations increased significantly in the water samples near the Drain, however, no correlations were found with other sediment or shell samples or with distance from the source except for Zn. The metal concentrations in water samples are very low and Cd and Zn in almost samples fell below the detection limits. Although the detection limits did not allow accurate comparison, the dissolved metal concentrations were lower than the range observed in the Nile–Delta or nearby areas for most metals (Arnous and Hassan, 2015; Youssef et al, 2016; Appendix S6). Only Cr value is higher than those previously documented in Manzala lagoon, however, it still lower than the value recorded from the Red Sea and Arabian Gulf (Heidari et al. 2013; Youssef et al, 2016; Appendix S6).

The metals variability among sediments and their respective water samples may be explained by the nature of occurring of these metals and may be related to the partition coefficients (Kd). Most heavy metals in water are present mainly as suspended colloids or fixed by organic matters and cannot exist in soluble forms for a long time, therefore, they accumulated in the bottom sediment. Moreover, metal concentrations in the water phase of stormwater ponds and similar shallow water bodies have a rapid short-term variability due to the intermittent nature of the pollutant load (see Hvitved-Jacobsen et al., 2010). The later may explain why water samples are excluded from some metal assessments studies in the aquatic ecosystem (e.g., Stephansen et al., 2014).

A large project by the Egyptian government for deepening and widening of El–Gamil Outlet (Fig. 1), which started in 2016 and will end by 2018 with a total cost of 220 Million EGP, may explain the better quality of the current water. Dilution by seawater may have lowered the metal concentrations. This may be supported by the high salinity of the northernmost sites (Table 1). Similarly, Richardson et al. (2001) found a decrease in the concentration of metals in the North Sea with the subsequent decline of wastewaters dumping.

4.3. Ecological threats

The Pollution Load index (PLI) was significantly correlated with the diversity indices, where benthic fauna was more diverse away from the main pollution source. This agrees with Stephansen et al. (2014), who compared the diversity of different fauna and flora with the pollution level and found that only mollusks diversity can be correlated to the pollution. This indicates that molluscan diversity and community structure can be used as an early warning indicator for biodiversity loss. Rosenberg et al. (2004) found that opportunistic species are usually abundant in low diversity communities while equilibrium species are normally found in high diversity ones (for details see Abdelhady and Mohamed, 2017). The high dominance of the opportunistic or the pollution–tolerant taxa (e.g. *Melanoides tuberculate, Corbicula fluminalis,* and *Fulvia fragilis*) in most polluted sites herein agree with Rosenberg et al. (2004). These well–known pollution indicators are able to tolerate variations in environmental conditions in polluted environments (see McMahon, 2002; Farani et al., 2015). In contrast, higher diversity and low dominance in the unpolluted sites is associated with equilibrium taxa such as *Mactra lilacea, Bullia annulata*, *Nassarius arcularia*, and *Tritia mutabilis* (Appendix S5). These taxa are found in environments with stable environmental resources (Kalantzi et al., 2014). Without proper management of the pollution levels in the lagoon, these taxa may suffer further declining or even disappear in the future. Moreover, the high metal content of this benthic fauna, which constitutes the lower trophic levels, may transfer their metals upward to higher trophic level and to the human.

Although nutrients and other organic pollutants were not included in the analyses, they may have another important role in the diversity pattern of the benthic fauna in the Manzala lagoon. Nutrient enrichment (eutrophication) of the lake, occasionally the southern parts, was earlier indicated (Oczkowski and Nixon, 2008). Eutrophication of the lake can be indirectly indicated by the abundance of the freshwater plants and fine grain sediments (Abdelhady et al., 2018). As other physicochemical parameters such as water depth, and TDS have a statistically significant correlation with the Shannon diversity index, the consequences of the metal pollution on the biodiversity should be further tested, occasionally in environments characterized by low variation in the physicochemical conditions.

5. Conclusion

In the present study, the metals concentrations in the molluscan shells in addition to sediments and water from sixteen sites in the Manzala Lagoon were assessed. The role of physicochemical factors on the accumulation process was also quantified. We can conclude the following;

- The sediments and the faunal samples of the mollusks were correlated to the distance to the main pollution source (Bahr–El–Baqar Drain), which is an anoxic drainage canal carry most wastes from Cairo and other megacities in the Delta. A strong and significant correlation between the metals concentrations and the sediment grain–size was found.
- Significant positive linear correlations were found between most of the metal concentrations in sediments and shell samples but not with water samples.
- PLS model indicated that a major proportion of the metal variability in the lagoon is explained by two main predictors; the shale content and the distance to the pollution source. In contrast, physicochemical traits explain the minor proportion of the variability.
- EF indicated that the sediments are moderately polluted by Cd and Fe and significantly polluted by Pb. In addition, CF indicated that the sediments are moderately–polluted by Cu and Zn, moderately to considerably pollute by Al, and considerably to very highly polluted by Fe, Cd, and Pb. Moreover and according to Igeo, the sediments are moderately polluted by Zn, moderately to highly–polluted by Cd, and highly to extremely–polluted by Pb.
- PLI indicated a progressive deterioration of the sites 1 and 2, while all other sites show a low concern for metal pollution. Cluster analysis grouped the stations located under same types of pollution level, a pattern became well–characterized also by nMDS.
- Simpson, Shannon, Dominance, and Evenness, all exhibit a strong and significant correlation with the PLI and point to biodiversity loss and highlight the threats of the metal pollution on the Manzala ecosystem.
- The consequences of metal pollution on the biodiversity should be further tested, occasionally in environments with low variation in the physicochemical conditions.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2018.12.002.

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