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Baseline

Integrated assessment of major and trace elements in surface and core sediments from an urban lagoon, China: Potential ecological risks and influencing factors

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ABSTRACT

Marine sediments serve as a sink for contaminants of anthropogenic origin. Here, 25 major and trace elements were determined in surface and core sediments from an urban lagoon (Yundang Lagoon), China. The median concentrations of Pb, Cd, Cu, and Zn in both surface and core sediments exceeded global and crustal averages. Principal component analysis for the elements and ecological impact of the heavy metals indicated spatial heterogeneity in core sediments from different lagoon areas; however, no such pattern was observed in surface sediments. Geodetector analysis indicated spatial locations of lakes, pH, N%, C%, and S% as the major factors influencing the heterogeneity of potential ecological risk index, a cumulative measure of the ecological impact of heavy metal. The interaction detector indicated nonlinear and bivariate enhancement between different physicochemical parameters. Besides, a depth profile of the elements in different samples was also elucidated.

Coastal lagoons account for 13% of the global coastline and play a significant role in supporting productivity, biodiversity conservation, and socioeconomic and cultural activities (Audouit et al., 2019). The intensive anthropogenic disturbances like industrial operations, aquaculture, and sewage discharge result in the release of tremendous amounts of toxic pollutants into the aquatic environment (Peter et al., 2020). The major portions (90%) of heavy metals get associated either with suspended particles or sediments (Zhang et al., 2014) making them major sinks (Peter et al., 2020). Conversely, pH changes, redox, and salinity cause sediments to release these contaminants to act as secondary sources of pollution (Algül and Beyhan, 2020).

The biomagnification and irreversible nature of major and trace elements cause deleterious effects on water quality, aquatic organisms, human health, and the entire biodiversity (Peter et al., 2020). Hence, they are categorized among the most pernicious environmental pollutants by the United States Environmental Protection Agency (USEPA) and the International Agency for Research on Cancer (IARC) (Tadesse et al., 2018).

Generally, the status and fate of metal and nonmetal elements have been investigated in surface sediments (Peter et al., 2020; Zhang et al., 2014). However, several previous studies have demonstrated the usefulness of core sediments in understating the historical perspective of environmental contaminants and for the evaluation of pollutant mitigation measures and environmental management (Chen et al., 2010; Luo et al., 2012).

In this study, 25 major and trace elements were studied in surface and core sediments of an urban lagoon (Yundang Lagoon), Southeast China, by using inductively coupled plasma mass spectrometry (ICP-MS), multiple ecological risk assessments, and multivariate statistical techniques. It was aimed to: (i) profile major and trace elements in surface and core sediments; (ii) assess the ecological risks associated with these elements; and (iii) elucidate the influence of physicochemical factors on the spatial heterogeneity of potential ecological risks of heavy metals.

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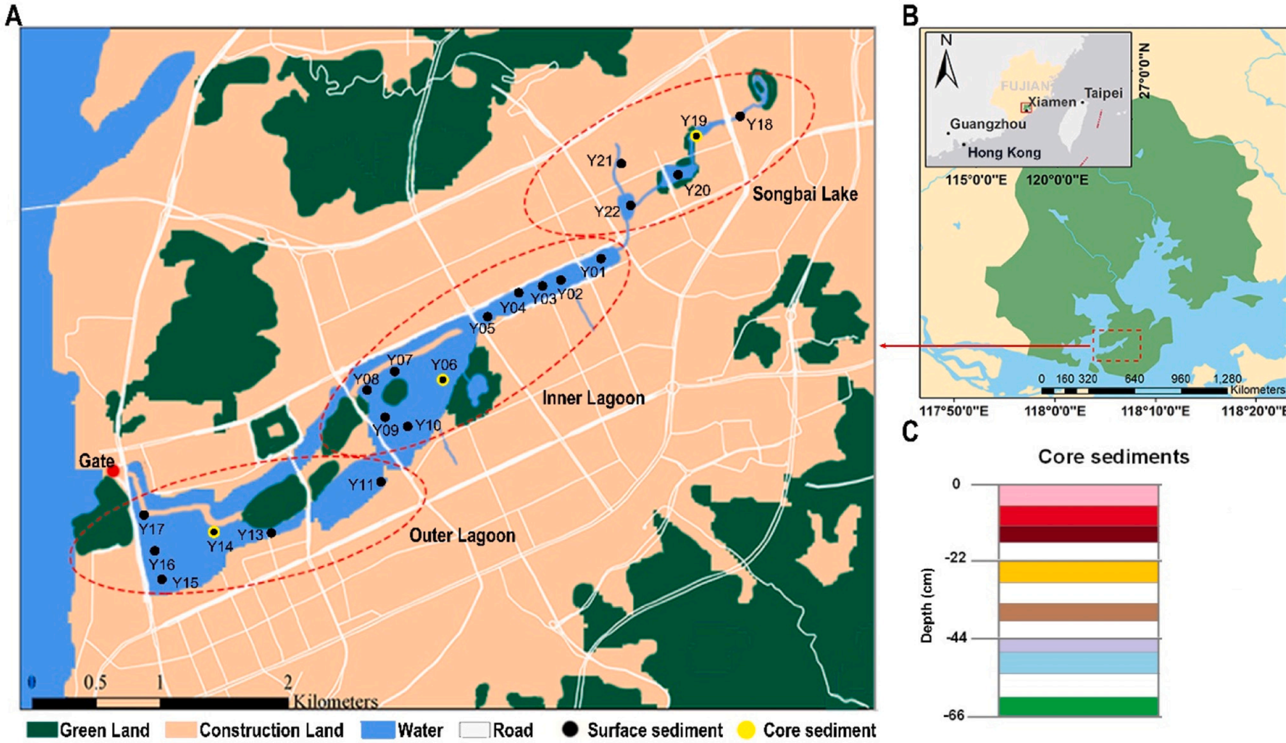

Fig. 1. Sampling area with station location in Yundang Lagoon.

The Yundang Lagoon is an artificially managed subtropical urban lagoon on the western coast of Xiamen city, China (24°28′47.4024″N and 118°5′21.9264″E). It has been under strong anthropogenic disturbances, owing to large reclamation and development (including the construction of wastewater interception system, retaining walls, afforestation, dredging, and water exchange) by the local government, since 1988 (Chen et al., 2010). Its area (~1.7 km^2) comprises Outer Lagoon, Inner Lagoon, and Songbai Lake (Fig. 1). A water control gate enables water exchange (110,000 m^3/day) between the lagoon and Xiamen Bay. Rapid urbanization and industrialization in Xiamen city have led to additional land-based pollution influx into the lagoon, raising concerns about the success of the restoration program and a need for constant monitoring and management of the Yundang Lagoon (Wang et al., 2020).

Surface sediment samples were collected by using Van Veen grab sampler at the downstream (Outer and Inner Yundang Lagoon, 16 sites) and Songbai Lake (upstream 5 sites) of the Yundang Lagoon on 27th and 28th July 2017 (Fig. 1). The core sediment samples up to 66 cm depth were collected from Outer Lagoon (Y14), Inner Lagoon (Y06), and Songbai Lake (Y19) by using an Eijkelkamp Agrisearch sampler (Giesbeek, Netherlands). Each core sediment sample was subdivided as follows: A (0–4 cm), B (4–6 cm), C (6–8 cm), D (8–10 cm), E (10–14 cm), F (14–18 cm), G (18–22 cm), H (22–26 cm), I (26–30 cm), J (30–34 cm), K (34–38 cm), L (38–42 cm), M (42–46 cm), N (46–50 cm), O (50–54 cm), P (54–58 cm), Q (58–62 cm), and R (62–66 cm) (Fig. 1C).

Sediment sample aliquot (50 g) was sequentially frozen at −80 °C for 48 h, freeze-dried (Beijing Boyikang Laboratory Instrument Co., Ltd. Beijing China), ground, sieved (<2 mm), and stored at 4 °C for further analysis. The physicochemical parameters namely, electric conductivity (EC), pH, total carbon (C%), total nitrogen (N%), and total sulfur (S%) were determined (Peter et al., 2020), whereas dissolved inorganic nutrients including ammonia (NH_4-N), nitrate (NO_3-N), and phosphate (PO_4-P) were measured by using a spectrophotometric method (Hernández-López and Vargas-Albores, 2003). The sediment particle composition was analyzed by a laser diffraction particle size analyzer (Mastersizer 2000, Malvern, UK).

Sediment samples were digested by following a method (Nkinahamira et al., 2019) for the determination of 25 elements (Na, Mg, Al, P, K, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb, Sr, Cd, Ba, Tl, Pb, Ti, Nb, Ru, Pd, and Au) by using inductively coupled plasma mass spectrometry (ICP-MS) (Agilent 7500CX, Agilent Technology, Santa Clara, CA, USA). QA/QC was ensured by using reference standards (GBW07309, GSD-9) and procedural blanks. The accuracy of the method ranged from 70% to 120% (Table S1).

The physicochemical parameters of core and surface sediments are summarized in Table S2. Generally, the EC levels were higher (median 24.75 mS/cm) in surface sediments compared to Y14 (12.82 mS/cm), Y06 (24.12 mS/cm), and Y19 (15.42 mS/cm) core sediments. Core sediment Y19 was relatively richer in C%, N%, and S% contents than other core and surface sediment samples. Clay particles were relatively higher in Y14 and Y06 than in Y19 and surface sediments. The NH_4-N, NO_3-N, and PO_4-P also varied among different core and surface sediments. Surface sediments demonstrated the highest median concentration of NO_3-N (18.4 mg/kg) followed by Y06, Y19, and Y14 core samples.

The major and trace elements detected from the surface and core sediments are given as box and whisker plots in Fig. 2a and b, respectively. The elements in both sediment types followed the order of magnitude Al > Fe > K > Na > Mg > Ti > P > Ca > Ba > Mn > Zn > Sr > Pb > Rb > V > Cr > Cu > Ni > Nb > Co > Tl > Cd > Pd > Au > Ru. Comparison of the element concentrations with crustal average, world average, and other parts of the world suggests anthropogenic sources of their origin (Table S3).

Spatial variation in the distribution of elements in surface and core sediments of Yundang Lagoon was studied by principal component analysis (PCA) using primer v7 (Quest Research Limited Auckland, New Zealand) (Fig. 3a and b). PCA for the surface sediments explained 61.5% variability with 36.4% and 25.1% contributions from PC1 and PC2, respectively. Moreover, PCA for the core sediments explained 61% variability with 42.5% and 18.5% contributions from PC1 and PC2,

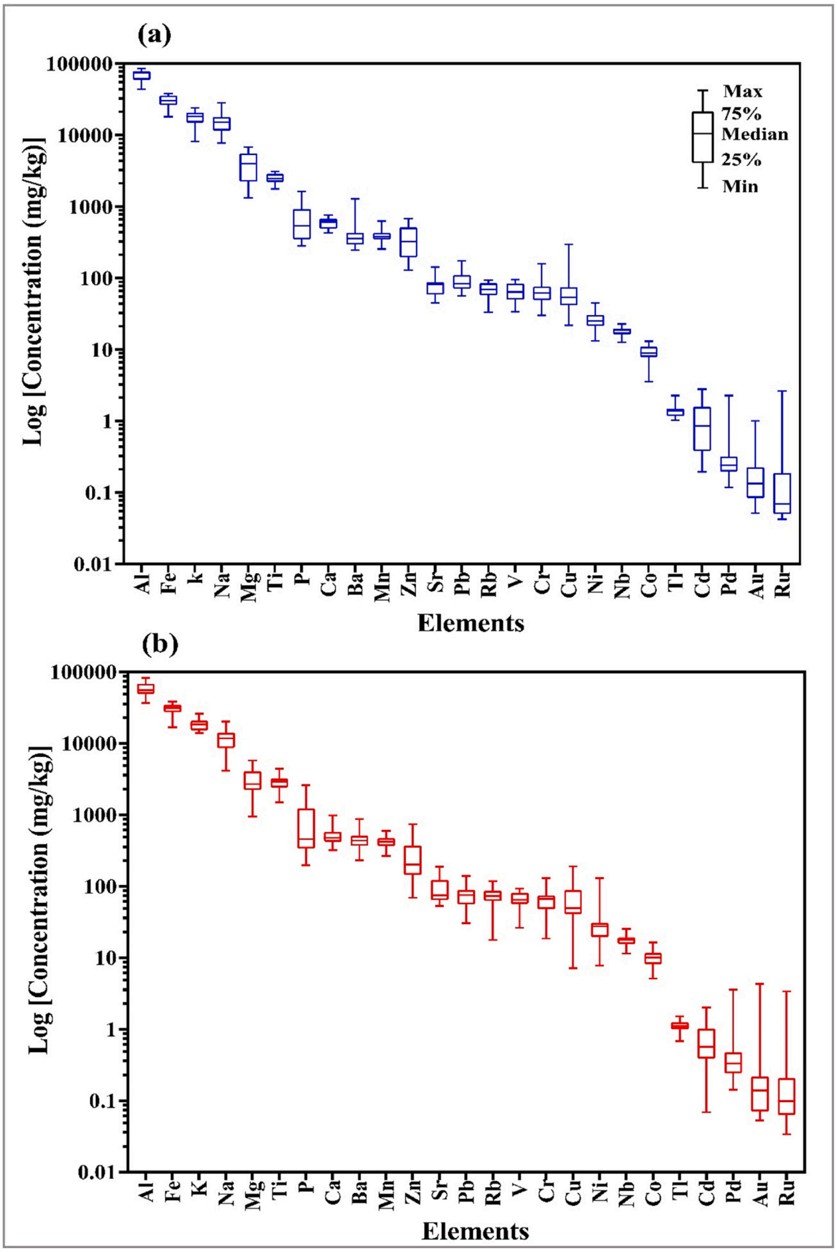

Fig. 2. Box plot and whisker plot for major and trace elements in (a) surface sediments and (b) core sediments of Yundang Lagoon.

respectively. The surface sediments did not exhibit a clear spatial pattern; however, it was rather pronounced in the core sediments. The vectors for K and Rb indicated an association with Y14; those of Co, Fe, Tl, Al, V, Nb, and Mg revealed an association with Y06; and Pb, Ni, Cu, Zn, and Cd, indicating their associations with Y19 core samples. These results suggest a heterogenic distribution of elements in core sediments.

The geo-accumulation index (I_{geo}) categorized in Table 1 was calculated by using Eq. (1), where C_n and B_n are metal concentrations in sediment sample (n) and earth crust, respectively, whereas factor 1.5 is the background matrix correction factor for lithogenic effects and rock weathering (Muller, 1979).

$$I_{geo} = log_2 \frac{C_n}{1.5B_n} \quad (1)$$

I_{geo} categorized, Al, Fe, K, Na, Mg, Tl, P, Ca, Ba, Mn, Zn, Sr, Rb, V, Cu, Cr, Ni, Nb, and Co as class 1; Zn, Pb, and Cd as class 2; and Ti and Au as class 3 (Fig. S1 a & b). In core sediments, the top layers of Y06 (4 to 30 cm), Y14 (4 to 34 cm), and Y19 (4 to 46 cm) core sediments harbored Au, Tl, Pb, and Cd of class 3, indicating moderate to strong pollution than the underlying portion. Generally, higher I_{geo} values for different elements in Y06 and Y19 core indicated relatively polluted upper layers than those at depth.

The enrichment factor (EF) categorized in Table 1 was calculated (Martin et al., 2012) by using Al as a reference element by using Eq. (2) (Taylor and Mclennan, 1995).

$$EF = \frac{X/Al_{sample}}{X/Al_{background}} \quad (2)$$

where, X/Al_{sample} and $X/Al_{background}$ are the sample and earth crust concentration of the metal, respectively. The EF values in surface sediments ranged from 0.01 to 264.76 (Fig. S1c). The highest EF value was observed for Au (14.26 to 264.08), followed by Ti (31.39 to 76.15) indicating very high to extremely high enrichment. The EF values of a

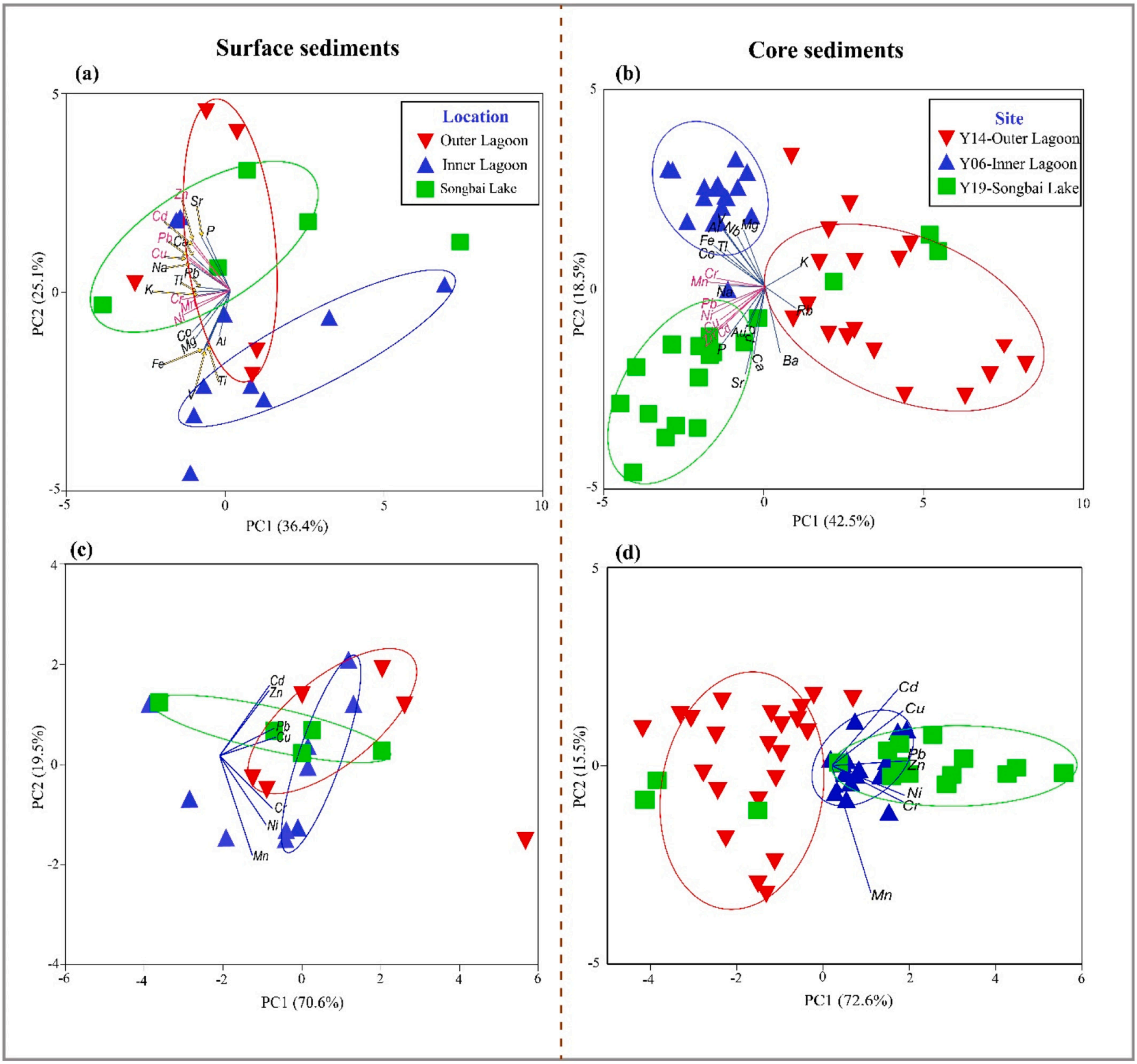

Fig. 3. Principal component analysis (PCA) plots for spatial variation based on major and trace elements in (a) surface sediments, (b) core sediments; and based on ecological risk index (Ei_m) in (c) surface sediments, (d) core sediments. Vectors indicate prominent major and trace elements responsible for spatial variations.

majority of elements namely Na, Mg, P, k, Ca, V, Cr, Mn, Fe, Co, Ni, Sr, Cu, Rb, Ba, and Nb were <2, indicating a deficiency to minimal enrichment. The high EF values for the majority of elements at Y19 core can be attributed to industrial effluents, agricultural activities, and domestic wastes from the vicinity (Huang et al., 2019a; Yan et al., 2016). In a spatial perspective, the EF followed a generalized sequence Songbai Lake > Outer Lagoon > Inner Lagoon. The high EF values for Zn, Cd, Tl, Pb, Au, and Ti suggest their environmental significance in Yundang Lagoon (Fig. S1d). The enrichment of Cd, Zn, and Pb in both surface and core sediments and soil were attributed to municipal sewage wastes and other anthropogenies (Fu et al., 2013; Huang et al., 2019a; Tadesse et al., 2018; Yan et al., 2016; Zhang and Liu, 2002). However, Ti and Au exhibited extreme enrichment indicating the influence of discrete external sources. According to Zhang and Liu (2002), an average EF between 0.5 and 1.5, indicates a metal emanation from lithogenic effect/rock, whereas EF values greater >1.5 suggest an anthropogenic impact. In this study, the average EF for Zn, Cu, Cd, Ti, Pb, Tl, and Au were beyond 1.5, suggesting strong anthropogenic impacts.

The contamination factor of metals (Cf_m) and degree of contamination (DC) described in Table 1 were used to assess multimetal contamination in sediments by using Eqs. (3) and (4), respectively (Hakanson, 1980).

$$Cf_m = \frac{C_S}{B_n} \quad (3)$$

$$DC = \sum Cf_m \quad (4)$$

where, C_S and B_n are sample and earth crust concentrations of element "m", respectively. Cf < 1 indicated no contamination by Al, Fe, K, Na,

Table 1
The classification of environmental risk assessment indices.

Index	Category	Description	Reference
I_{geo}	Class 1, 0-1	Unpolluted to moderately polluted	Muller, 1979
	Class 2, 1-2	Moderately polluted	
	Class 3, 2-3	Moderately polluted to strongly polluted	
	Class 4, 3-4	Strongly polluted	
	Class 5, 4-5	Strongly polluted to extremely polluted	
	Class 6, >5	Extremely polluted	
EF	EF < 2	Deficiency to minimal Enrichment	Hamdoun, 2015
	2 < EF ≤ 5	Moderate enrichment	
	5 < EF ≤ 20	Significant enrichment	
	20 < EF ≤ 40	Very high enrichment	
	40 < EF	Extreme high enrichment	
CF	CF < 1	Low contamination	Hakanson, 1980
	1 ≤ CF < 3	Moderate contamination	
	3 ≤ CF < 6	Considerable contamination	
	CF ≥ 6	High contamination	
DC	DC ≤ 6	Low degree of contamination	Hakanson, 1980
	6 ≤ DC ≤ 12	Moderate degree of contamination	
	12 ≤ DC ≤ 24	Considerably degree of contamination	
	DC >24	Very high degree of contamination	
Ei_m	$Ei_m < 40$	Low risk	Huang et al., 2019a, b
	$40 \leq Ei_m < 80$	Moderate risk	
	$80 \leq Ei_m < 160$	Considerable risk	
	$160 \leq Ei_m < 320$	High risk	
	$Ei_m \geq 320$	Very high risk	
PERI	PERI < 65	Low risk	Yan et al., 2016
	65 ≤ PERI < 130	Moderate risk	
	130 ≤ PERI < 260	Considerable risk	
	PERI ≥ 260	Very high risk	

Mg, Tl, P, Ca, Ba, Mn, Zn, Sr, Rb, V, Cu, Cr, Ni, Nb, and Co (Fig. S1e). However, Zn, Cd, Tl, Pb, Ti, and Au exhibited high levels of contamination, owing to anthropogenic activities such as sewage effluent and others (Huang et al., 2019a; Yan et al., 2016). Among core sediments, Cf for Y19 core was relatively higher than Y06 and Y14 core sediments (Fig. S1f).

DC indicated the cumulative Cf of all elements in surface and core sediments (Fig. S2). Almost similar DC was observed for surface and core sediments from Outer and Inner Lagoons; however, DC was significantly higher in the Y19 core than the surface sediments of Songbai Lake. Overall, a high degree of contamination (DC > 24) was observed in both surface and core sediments of the Yundang Lagoon, suggesting significant levels of pollution than those indicated by EF and I_{geo}, separately. The cumulative effect of multiple elements may pose higher toxicity because of the metal interactions (Fu et al., 2013).

Ecological risk index (Ei_m) and potential ecological risk index (PERI) categorized in Table 1 were used to assess the ecological impacts of heavy metals by using Eq. (5) and Eq. (6), respectively (Huang et al., 2019b). These indices were calculated for heavy metals namely, Cd, Cr, Cu, Mn, Ni, Pb, and Zn by using their respective toxic response factor (Tr_m) (Yan et al., 2016). However, PERI provides comprehensive information regarding synergy, toxic level, concentration, and the ecological effect of heavy metals.

$$Ei_m = Tr_m \times Cf_m \quad (5)$$

$$PERI = \sum_{m=1}^{n} Ei_m \quad (6)$$

The $Ei_m < 40$ for heavy metals in almost all surfaces and core sediments samples from the three locations indicated low risk by Cr, Mn, Ni, Cu, and Zn (Fig. 4). However, intersite variations existed for all heavy metals. In general, Pb posed a low risk in both surface and core sediments; however, moderate risk ($Ei_m = 44$) was observed in Outer Lagoon surface sediments. Cd indicated serious ecological concerns that were relatively higher in the surface sediments than in core sediments. The cumulative ecological risk (PERI) of heavy metals varied among locations and also between sediment types (Fig. S3). Generally, the values of PERI were higher for surface sediments than core sediments. According to PERI, core sediment Y14 exhibited low risk, whereas Y06 and Y19 exhibited considerable risk, but surface sediments from the Inner Lagoon posed considerable risk than those from the Outer Lagoon and Songbai Lake, which posed a very high risk because of heavy metals.

PCA biplot for spatial variation owing to Ei_m of heavy metals in surface and core sediments (Y14, Y06, and Y19) is given in Fig. 3c and d, respectively. PCA explained 90.1% variability with 70.6% and 19.5% contributions from PC1 and PC2, respectively, for Ei_m in surface sediments. However, PCA explained 88.1% variability with 72.6% and 15.5% contribution from PC1 and PC2, respectively, for Ei_m in the core sediments. PCA indicated spatial homogeneity of Ei_m in surface sediments, whereas distinct heterogeneity was observed for the three core sampling sites.

An excel-based open-source software, geodetector, (http://www.geodetector.cn/) was used to detect the influence of sediment physicochemical parameters namely, spatial location of lakes, sampling depth (cm), pH, EC, N%, C%, S%, clay, silt, sand, NO_3-N, NH_4-N, and PO_4-P on the spatial heterogeneity in Ei_m, and to quantify the influence of driving forces in core sediments. This was achieved by using PERI as cumulative Ei_m for heavy metal in core sediments. The geo detector is based on the power of determinant (PD) or *q*-value, expressed as Eq. (7) (Wang et al., 2010).

$$q = 1 - \frac{1}{N\sigma^2} \sum_{i=1}^{L} N_i \sigma_i^2 \quad (7)$$

where, "q" is the explanatory power of one physicochemical parameter on change in PERI; i is the number of partitions of Y (PERI) on factor X (single physicochemical parameter); N and N_i are the number of units in all spatial units and at "i", respectively. Similarly, σ and σ_i are the variance of Y for overall spatial units and at "i", respectively. The physicochemical parameters (X) were transformed into categorical variables by using Jenks natural breaks function in Real Statistics (Zaiontz, 2020) as given in Table S4. The value of q ranges from 0 to 1 indicating no to stronger heterogeneity, respectively (Text S1).

The factor detector indicated that the spatial locations, pH, C%, N%, and S% were the most significant ($\alpha \leq 0.05$) physicochemical factors responsible for the spatial heterogeneity of PERI (Table S5). According to q-statistics, N% was the highest contributing factor (61.0%), followed by C% (52.0%), lake locations (26.0%), pH (23.0%), and S% (20.0%) in the spatial heterogeneity. Our findings are similar to an earlier study where pH, organic matter, soil texture, NH_4-N, NO_3-N, and spatial locations were the major influencing factors for the spatial heterogeneity of heavy metals in soils from the Yangtze River Delta (Zuo et al., 2018). The results of the ecological detector and interaction detector are given in Fig. 5. The ecological detector indicated significantly higher ($\alpha \leq 0.05$) effects of N% and C% compared with lake locations, sampling depths, pH, and EC. Whereas, the results of the interaction detector indicated that most of the variable pairs nonlinearly enhanced each other [$q(X_1 \cap X_2) > q(X_1) + q(X_2)$]. However, N% and C% contents demonstrated enhanced bivariate [$q(X_1 \cap X_2) > \mathrm{Max}(q(X_1), q(X_2))$] effect with most of physicochemical factors. N% in a mutualistic interaction with lake locations, sampling depths, pH, EC, S% clay, sand, silt, NH_4-N, and NO_3-N resulting in an enhanced (66.0%–76%) effect on PERI heterogeneity. Similarly, C% contributed enhancement (54% to 67%) of PERI heterogeneity in mutualistic interaction with lake locations, sampling depth, pH, EC, N%, S%, clay%, sand%, and NH_4-N.

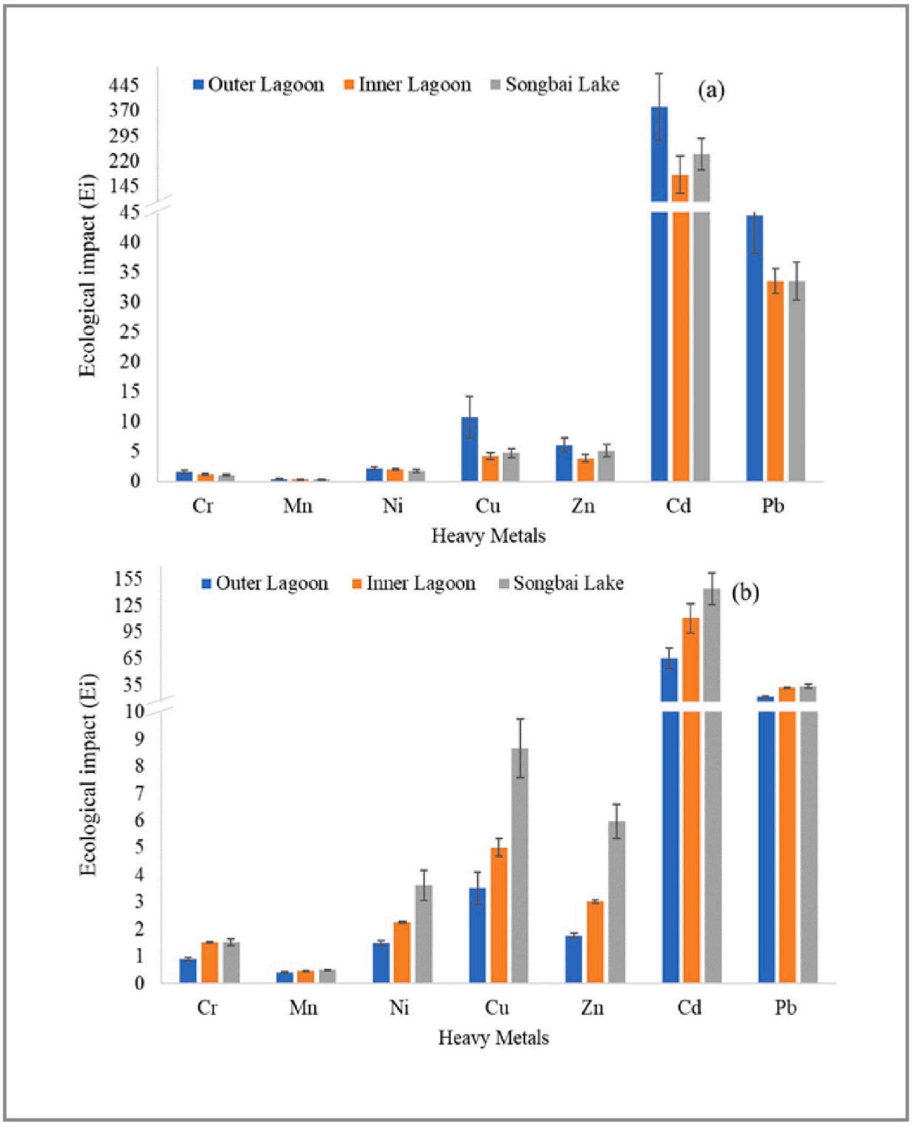

Fig. 4. Ecological impact (Ei_m) of heavy metals in (a) surface, and (b) core sediment samples from Outer Lagoon, Inner Lagoon, and Songbai Lake.

These results suggest that N% and C% were the major driving forces for spatial heterogeneity in ecological risks by heavy metals.

The risk detector explained the effect of changes in different physicochemical parameters on PERI in core sediments (Fig. 6). Among the lakes, the Outer Lagoon and Songbai Lake posed considerable risks, whereas the Inner Lagoon posed moderate risks because of heavy metals. PERI was low to moderate in the deeper layers (>50 cm) that reached a considerable level in the upper sediment layers. A decrease in PERI with an increase in pH indicated the deposition of heavy metals under acidic pH. According to Hu et al., reducing environmental conditions at low pH prevent the fixation of heavy metals (Hu et al., 2015). On the contrary, PERI increased with an increase in salinity and the maximum level of PERI was observed at 28.8–34.4 mS/cm. A consistent increase in PERI was observed with an increase in both N% and C%. According to Hu et al. (2015), N% and C% contents from the decomposition of living organisms may act as sinks of heavy metals and cause their concentration in sediments (Hu et al., 2015). A similar trend was observed for S%, where PERI decreased initially from 0.49 to 0.71%, but subsequently, increased with an increase in the S%. In case of nutrients, the maximum level of PERI was observed at 15.02–19.49 mg/kg, 58.01–100.75 mg/kg, and 10.56–15.46 mg/kg concentration of NO_3-N, NH_4-N, and PO_4-P, respectively. Sand and silt particles exhibited almost similar effects and an increase in PERI was observed with an increase in these particles; however, PERI decreased with increasing clay content. Maximum levels of PERI were observed at 25.08–30.38% clay, 23.92–26.40% silt, and 26.21–33.79% sand particles.

The depth distribution of major and trace elements was studied in relation to the surface sediments by using the stratification ratio (SR) (Franzluebbers, 2002). The SR approach was initially used for soil organic carbon at different soil depths; however, later it was also used for other soil and sediment quality parameters (Li et al., 2018; Qu et al., 2020). SR was calculated as the ratio of soil properties and elements in the surface sediments A (0–4 cm) and those in the deeper sediment layers (4–66 cm depth) in Y14, Y06, and Y19 core sediment samples by using Eq. (8).

$$SR = \frac{Concentration\ at\ surface\ (0-4\ cm)}{Concetration\ at\ deeper\ layers\ \rangle 4\ cm)} \tag{8}$$

The value of SR = 1 indicates similar concentrations, whereas SR > 1 and SR < 1 indicate greater and smaller concentrations at depth compared to surface sediments, respectively.

The SR for different elements in core sediments from Y14 (Outer

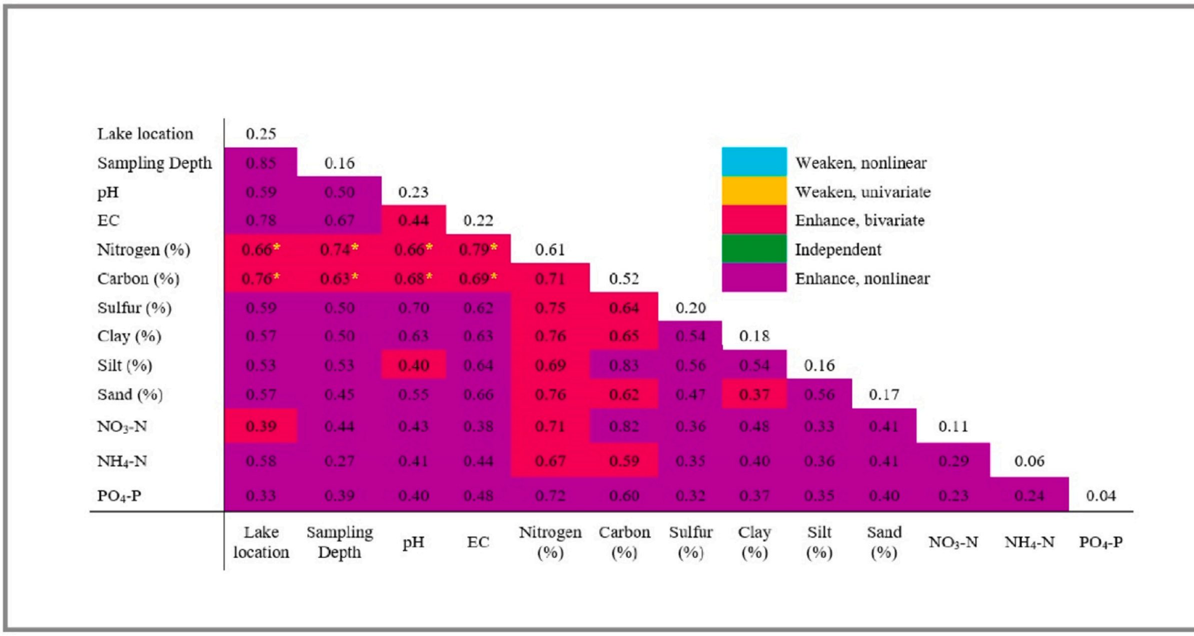

Fig. 5. Effect of interaction between different physicochemical parameters in influencing potential ecological risk index (PERI) determined by Interaction Detector. The values with "*" indicate the significant difference ($\alpha = 0.05$) between two factors for their effects on PERI determined by an ecological detector.

Lagoon), Y06 (Inner Lagoon), and Y19 (Songbai Lake) is given in Fig. 7. The SR for Na indicated a decline in concentration with an increase in the depths in the three core sites. Levels of Mg decreased with depth in Y06, whereas an increase in the Mg concentration from 8 to 30 cm depths and subsequent decline at further depths was observed in Y19. However, Mg levels increased at depths beyond 54 cm in Y14. The concentrations of Al, K, Co, Pb, Ba, Tl, Fe, Ti, and Nb remained almost the same throughout the depths in the three core sites. Generally, the concentration of P declined with an increase in depth; however, higher concentrations were observed from 10 to 22 cm followed by a decline at depths in Y19. SR indicated a similar trend in Ca and Sr concentrations in the three core sediments with a general decline when the depth increases. The concentration of V remained almost the same at depths in Y06 and Y14; however, after an initial decline from 5 to 22 cm, an increase in V concentration in Y19 was observed. The concentrations of Cr, Ni, Zn, Cu, Pb, Cd, and Mn either remained the same or increased slightly immediately below the surface, but decreased beyond 25 cm depth in the Y19 core sample. This indicated deposition of relatively higher heavy metal contents in the upper layers of Y19. These higher levels of metal contaminants near the surface could be attributed to housing clusters, exposure to sewage effluents, low hydrodynamic changes, and seawater dilution in the Songbai Lake (Chen et al., 2010). The concentrations of Ni and Mn remained the same in the Y06 core; however, Cr, Zn, Cu, Pb, and Cd concentrations tended to increase beyond 35 cm depth. This increase was profound for Cd in the deeper layers. The behavior of heavy metals in Y14 and Y19 were similar to earlier reports for core sediments from different aquatic environments (Li et al., 2012; Versporten et al., 2018). Our results conform with earlier findings, where a decline in a majority of elements in the upper layers and surface sediments were attributed to hydrodynamic changes caused by artificial seawater dilution in the Yundang Lagoon (Chen et al., 2010). The concentration of Ru, Pd, and Au increased 2, 4, and 70 times at 6–8 cm depth, but declined consistently with an increase in depth in all three cores to indicate their deposition near the surface. Au, Pd, and Ru are precious metals, extensively used in industry and as automobile catalytic converters that can be drained from roadsides into the Yundang Lagoon through sewage water (Westerhoff et al., 2015).

This study suggested the influence of different anthropogenic activities on the sediment quality of the Yundang Lagoon. Relatively higher stratification ratios in the subsurface sediments suggested recent deposits, despite the conservation measures in the Yundang Lagoon. Generally, surface sediments had relatively higher levels of major and trace elements as compared to core sediments. I_{geo}, EF, CF, DC, and PLI assessment generally classified Yundang Lagoon as moderate to extremely contaminated by Cu, Zn, Tl, Cd, Pb, Ti, and Au – for both surface and core sediments. The high enrichment of some heavy metals in the core sediments in this study might be attributed to their persistent nature and high leeching capacity, and thus, they percolate to the lower layers of the sediment strata. Furthermore, it can be concluded that physicochemical parameters can be used to predict the potential ecological risk posed by heavy metal contaminants. This study thus provides important information to the protection agencies and public and aquatic system researchers, who aim to understand the distribution pattern of metals pollution in anthropogenic lagoon systems, especially with that of core sediments.

CRediT authorship contribution statement

Philomina O. Peter: Formal analysis, Visualization, Methodology, Software, Data curation, Writing – original draft. **Azhar Rashid:** Conceptualization, Methodology, Validation, Writing – review & editing. **François Nkinahamira:** Formal analysis, Methodology, Visualization, Software, Data curation. **Hongjie Wang:** Investigation, Methodology. **Qian Sun:** Investigation, Resources. **Mahmoud Gad:** Methodology, Software. **Chang-Ping Yu:** Resources, Supervision, Funding acquisition. **Anyi Hu:** Conceptualization, Investigation, Resources, Data curation, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

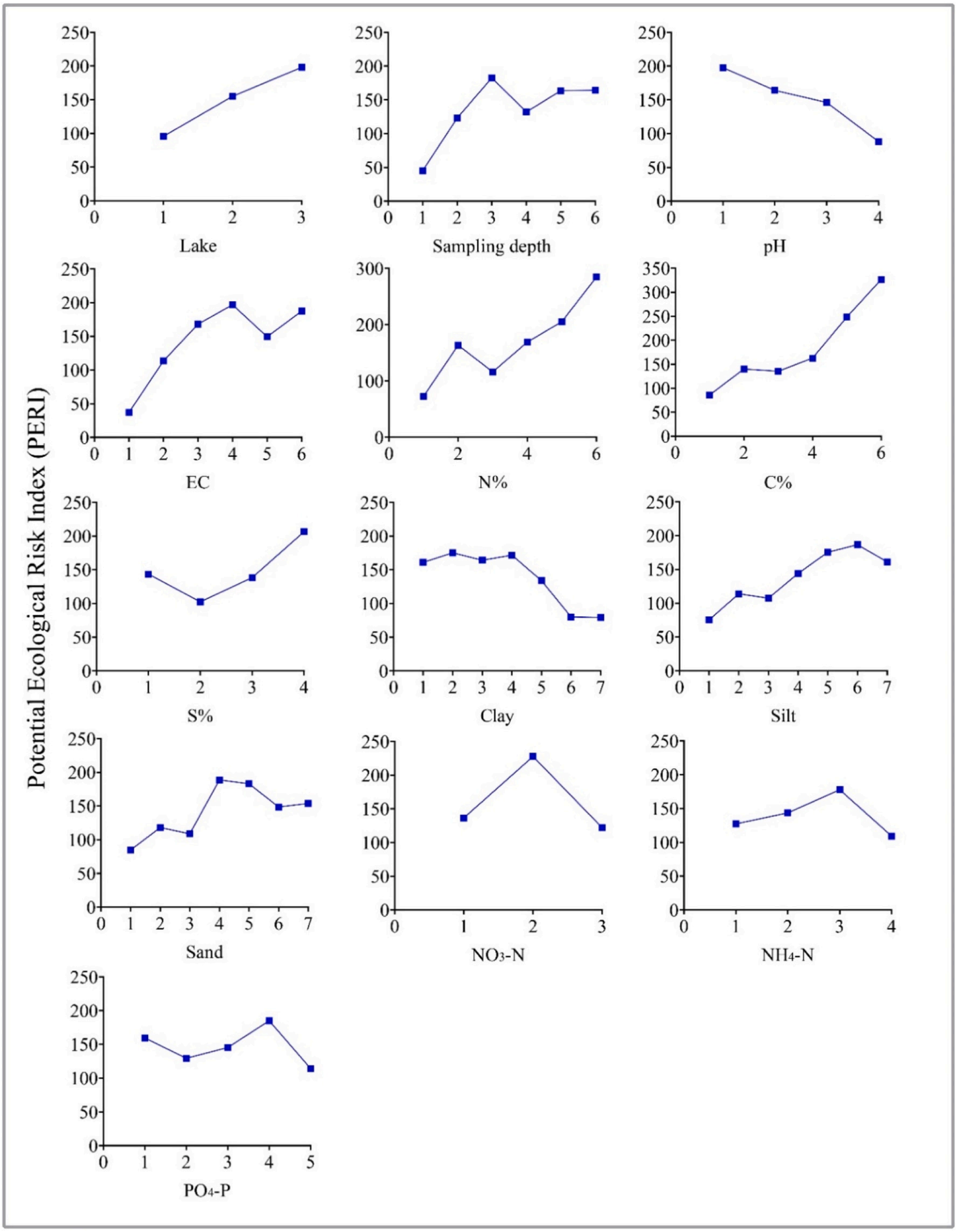

Fig. 6. Variations in PERI at different categories of the physicochemical parameters. The categories are explained in Table S2.

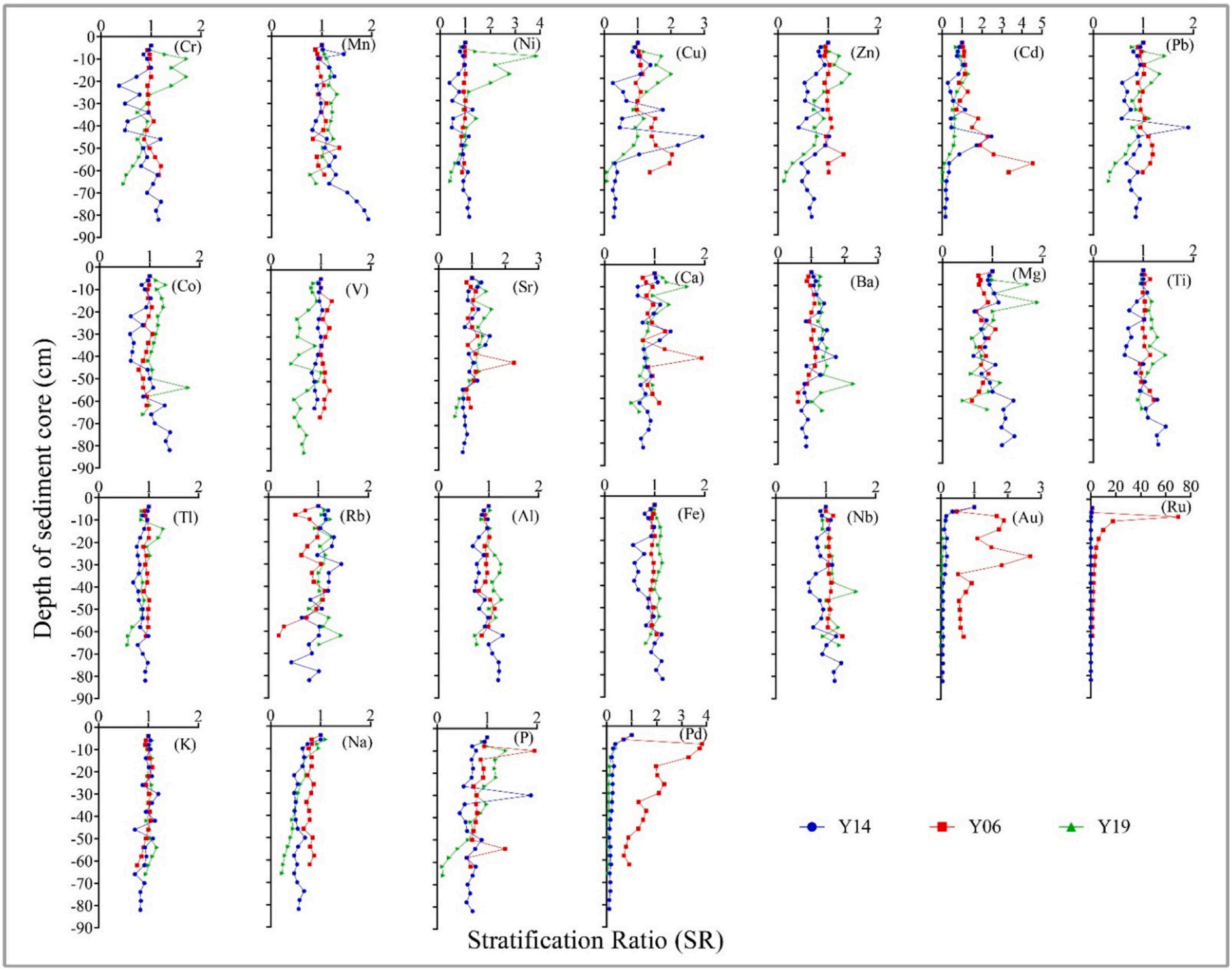

Fig. 7. Stratification ratio of major and trace elements at different depths of core sediment from Outer Lagoon (Y14), Inner Lagoon (Y06), and Songbai Lake (Y19). The underlined elements are heavy metals with major environmental concerns.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.112651.

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