



Assessment of contaminants in the northwestern Bay of Bengal

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Abstract

The coastal sediments in the northern Bay of Bengal has undergone contamination due to the heavy metal contribution from rivers. To evaluate the status of contamination in the inner shelf region of the Bay of Bengal, a sediment core chronologically constrained using ²¹⁰Pb dating technique from the northwest Bay of Bengal was investigated for several trace elements. To assess sediment quality, enrichment factor (EF), geo-accumulation index (I_{geo}), and Modified Nemerow Pollution Index (MPI) were derived. The influence on ecology by individual contaminants and combined contaminants was evaluated using the potential ecological risk factor (Erⁱ) and modified ecological risk index (MRI). The single-element pollution indices indicated that the sediment has no significant pollution by individual elements. However, the multi-elemental approach shows slight pollution in the sediment core. The ecology is at low risk by contaminants present in the sediment. Comparison of the elemental values of shelf sediment with adjacent riverine and estuarine samples demonstrates the role of estuarine environment and/or high riverine flux of sediments causing either removal or dilution of trace elements during its transport from the river to the sea.

Keywords Bay of Bengal · ²¹⁰Pb dating · Trace elements · Pollution indices · Estuarine environment

Introduction

The last few decades have seen increasing concern of metal pollution due to rising anthropogenic contributions, especially in the aquatic ecosystem. Worldwide deterioration in water quality arises from both natural and anthropogenic processes, including soil erosion, mining, agricultural, industrial, transportation, and energy production-related activities (Duodu et al. 2016). Heavy metals in the marine environment have received much attention because they are toxic, non-biodegradable in the environment, easy to accumulate in organisms, and increases considerably due to the inputs of industrial waste, sewage, runoff, and agricultural wastes (Ebah et al. 2016). Heavy metals discharged into the marine environment by either natural or anthropogenic sources are distributed between the aqueous phase and sediments through

adsorption to clay, metal oxide/hydroxide, organic matter, hydrolysis, and co-precipitation or via biological uptake (Konhauser et al. 1997; Delshab et al. 2017). Pollutants get easily bound to marine sediment particles due to their relatively higher surface area and mineralogical characteristic (Herut and Sandler 2006). Sediments can also be a secondary source of pollution by releasing bound metals and other pollutants to overlying water and affect the marine environment (Goher et al. 2014). Sea receives more than 90% of sediments from the rivers, which include many anthropogenic contaminants (Liu 2018). The rising inputs of metal contaminants may cause significant risk to the marine ecosystem.

Several investigators have contributed towards estimation of the trace element contaminants in sea sediments (Loring et al. 1995; Rubio et al. 2000; Khan and Khan 2003; Selvaraj et al. 2004; Santos et al. 2005; Raj and Jayaprakash 2008; Fang et al. 2009). The study from the northeast coast of Bay of Bengal sediments reported Cd contamination from the untreated waste release from ship breaking industries (Khan and Khan 2003). Surface sediments from the southwest Bay of Bengal investigated to study the geochemical processes showed that the region is contaminated by Pb, Cd, Zn, and Cr, off Kalpakkam (Selvaraj et al. 2004). Raj and Jayaprakash (2008) who assessed sediments from the southwest Bay of Bengal (off Ennore) observed contamination by Cd, Cr, and Cu due to nearby heavily industrialised area. Studies on spatial

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variation in the surface sediments of the Mahanadi river reported contamination by Cr, Co, and Cd (Sundaray et al. 2014). River Ganga, the largest river system in India, has been reported by several researchers to be contaminated. Siddiqui and Pandey (2019) found a high geo-accumulation index for Cr, Cd, and Pb in the sediments of Kannauj, Rajghat, and Howrah regions of the Ganga river, with ecology at high risk in these regions. Pandey and Singh (2017) reported moderate to severe enrichment of Cd and Pb in the Ganga river sediments near the city of Varanasi. Sediments collected along the Hooghly (Ganga) river were found to be toxic for the benthic community due to As in the entire region and Cd particularly in the Calcutta region (Massolo et al. 2012).

Pollution in sediments from rivers contributing to the northern Bay of Bengal has increased concern about sediment quality of the Bay of Bengal and related threat to ecology. To assess the contamination in the Bay of Bengal, chronologically constrained sediment core from the shelf of the northwestern Bay of Bengal was investigated for assessing contaminant and their ecological impact using various pollution indices and ecological risk index.

Material and methods

Study area

During an oceanographic cruise on-board research vessel Sagar Manjusha (SM-24) conducted in July 2013, sediment core SM 24/14 (20° 33.2' N and 87° 13.2' E, water depth = 50 m, ~ 115 cm length) was collected from the northwest Bay of Bengal with the help of gravity corer (Fig. 1).

Sediments to the western Bay of Bengal (BOB) are contributed mainly by Himalayan rivers and peninsular rivers transported from the Indian sub-continent. Himalayan rivers like Ganga and Brahmaputra are major rivers delivering ~ 980

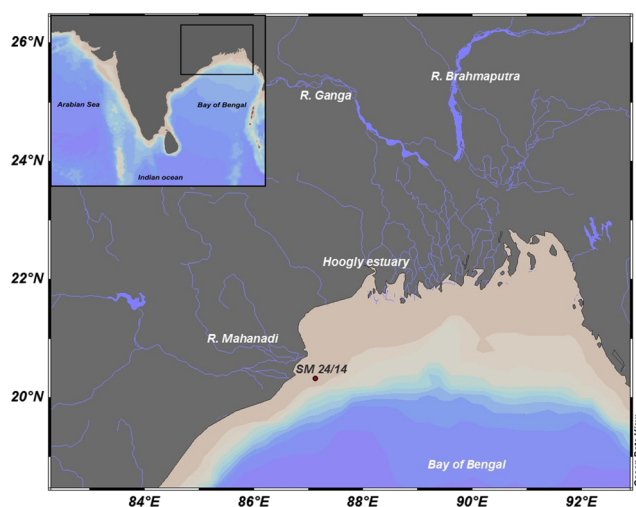


Fig. 1 Map showing core location of SM 24/14 sediment core

$\times 10^6$ tons/year of sediment to the Bay of Bengal (Wasson 2003). The present sediment core location is within the proximity of Mahanadi river estuary, which contributes $\sim 3.27 \times 10^6$ tons/year to the Bay of Bengal and ranks second among Indian peninsular rivers after river Godavari (Chakrapani and Subramanian 1990).

Sample preparation and analysis

Sediment core was sub-sampled at an interval of 1 cm using a non-metallic knife to avoid metal contamination. These samples were dried and crushed using an agate mortar and pestle to homogenise the sample and were stored in non-contaminated Ziploc bags. These samples were further used for the following geochemical analysis.

For sedimentation rate estimation, the ^{210}Pb dating technique was employed. ^{210}Pb is one of the decay products of the ^{238}U decay series. Lead being particle reactive is adsorbed and deposited with the settling particles in sediment. ^{210}Pb has two sources, one due to the decay of naturally occurring parent ^{226}Ra referred to as supported ^{210}Pb , which is in secular equilibrium. The other source is unsupported, a product of gaseous ^{222}Rn which has escaped the U-series decay nuclide from earth's surface through fissures and cracks and present in the atmosphere. Among the two components, it is only unsupported ^{210}Pb which decays, as supported ^{210}Pb is in secular equilibrium with ^{226}Ra . The activity of excess unsupported lead ($^{210}\text{Pb}_{\text{xs}}$) is calculated by subtracting the activity of ^{226}Ra from the activity of total lead. The sedimentation rate is derived based on $^{210}\text{Pb}_{\text{xs}}$ activity and depth distribution, which follows exponential decay as a function of depth with time (half-life of ^{210}Pb , 22.3 years), considering constant rate of ^{210}Pb supply (CRS) model (Turner and Delorme 1996; Somayajulu et al. 1999; Song et al. 2014). Nearly 3–5 g of finely ground homogenised samples was packed and sealed in plastic vials and stored for 20 days to allow the production of Radon gas without its escape to the atmosphere. The activity of ^{210}Pb and ^{226}Ra was assayed by the high-purity germanium (HPGE) detector (Somayajulu et al. 1999).

Total organic carbon analysis (C_{org})

For the estimation of organic carbon, ~ 0.5 g of sample was decarbonated using 0.6N HCl to remove inorganic carbon. Decarbonated samples were further dried and crushed for analysis. Twenty to 25 mg of decarbonated samples was packed in tin foil, and total organic carbon (C_{org}) was measured using Thermo Fisher Flash 2000 Elemental Analyzer. Deer River black shale was used as reference material, containing 2.53% C (Bhushan et al. 2001) to calibrate the instrument. The precision and accuracy of measurement were checked by analysing high organic sediment sample (HOSS, Elemental Microanalysis, Devon, UK). The accuracy of measurements was within $\pm 2\%$, and precision (1σ) was within $\pm 1\%$.

Trace element analysis

For trace element analysis, ~ 200 mg of sediment sample was treated with concentrated 4 ml HCl, 3 ml HNO₃, and 2 ml HF and digested using a microwave digestion system (Milestone, Ethos Easy) and were diluted in 50 ml 2% HNO₃. The aliquots were further diluted by a factor of 100 with a 2% HNO₃ solution for trace element measurement using Q-ICP-MS (Thermo-X series2). Ten percent indium solution was used as an internal standard to compensate for instrumental variation. To assess the quality of analysis, standard reference material SCO-1 (USGS reference material) was digested following a similar procedure as sediment samples. Accuracy for Ti, Mn, Co, Zn, and Pb was within ± 5%, and Ni and Cr were within ± 10%. The precision (1σ) of measurement for Ti, Co, and Zn was within ± 2% and for Cr, Mn, Ni, and Pb precision was within ± 7%. All acids used for digestion were sub boiling distilled in Teflon bottles. Double-deionised water (Milli-Q Millipore 18.2 MΩ/cm resistivity) was used for dilutions, and all apparatus and containers were acid-washed and deionised water rinsed prior to use.

Pollution indices

The pollution indices assess the level of contamination with respect to a background value of uncontaminated reference material. Background value is the concentration of an element in reference material that is uncontaminated by anthropogenic activities. The selection of background level plays an essential role in the assessment of contamination. In earlier studies of trace element contamination, the commonly used reference samples for background values were upper continental crust (Taylor and McLennan 1995), crustal average (Taylor 1964), and average shale value (Turekian and Wedepohl 1961). However, these reference samples do not include the natural and regional geochemical variability, which may result in misleading inference in the case of contamination assessment. The recent approach of using sediment core bottom of pre industrialisation period or uncontaminated sediment sample from a nearby region (in case of surficial samples) for selecting the reference sample for the background value has been adopted (Hornung et al. 1989; Faganeli et al. 1991; Siegel et al. 1994; Abraham and Parker 2008). Such samples will have similar chemical and mineralogical composition and are more reliable reference material both in terms of sediment matrix and background value.

In the present study, the average value of the pre-industrialisation period is considered for background value. The pollution indices and ecological risk index used in the present study are as follows.

Enrichment factor

Normalised enrichment factor is a single-element factor used to estimate the degree of enrichment or depletion of an element of interest relative to the background value. The

enrichment method involves normalisation either by the granulometric or geochemical method. The geochemical approach is considered better than granulometric, because it corrects both grain size differences and mineralogical composition, whereas granulometry minimises only grain size variability (Din 1992). The geochemical process involves normalisation of element by conservative element, which has negligible anthropogenic inputs and remains unaffected in the marine environment. To study the contribution of an element of interest from the terrestrial source, Al and Ti are generally used for normalisation. Iron can also be used for normalisation, considering that its natural abundance is so large that anthropogenic contribution will not have a significant increase (Abraham and Parker 2008). Aluminium may form an authigenic clay mineral and also gets scavenged on biogenic particle surface as hydroxides in the region of high productivity. Iron may get precipitated or remobilised with a change in redox condition. Unlike Al, Ti does not undergo any chemical weathering (Wei et al. 2003; Herut and Sandler 2006; Tribovillard et al. 2006). In the present study, enrichment factor was thus calculated using Ti for normalisation in the following equation:

$$EF = \frac{\left(\frac{Metal}{Ti}\right)_{Sample}}{\left(\frac{Metal}{Ti}\right)_{Background}}$$

It is a ratio of the normalised element in the sample by the same element normalised in the background reference sample. Enrichment factor value less than 1.5 indicates the source of sediment is detrital as weathering product and greater than 1.5 shows non-detrital sources (Zhang and Liu 2002; Karuppasamy et al. 2019; Siddiqui and Pandey 2019).

Geo-accumulation index

The geo-accumulation index is also a single-element pollution index proposed by Muller (1969) to assess contamination by comparing elemental concentration with background value or base value in uncontaminated sediment. The following equation defines the geo-accumulation index:

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 C_b} \right)$$

where C_n is the concentration of an element in the sample and C_b is the concentration of an element in background reference material. The concentration of an element in the background sample is multiplied by a factor of 1.5 to correct fluctuation in background values of metal. The classification of sediments is shown in Table 1.

Brady et al. (2015) reported logarithmic calculation results in low sensitivity for minor contamination. It is useful for only significant enrichment of element, and the factor of 1.5 multiplied with background value and does not take care of

Table 1 Muller’s classification for the geo-accumulation index

Igeo value	Class	Quality of sediment
≤ 0	0	Unpolluted
0–1	1	Unpolluted to moderately polluted
1–2	2	Moderately polluted
2–3	3	Moderately to strongly polluted
3–4	4	Strongly polluted
4–5	5	Strongly to extremely polluted
> 5	6	Extremely polluted

sediment interaction in a complex environment such as in the estuarine environment.

Modified Nemerow Pollution Index

The limitations of single-element pollution indexes led to the development of a multi-element pollution index. The most apparent limitation in the single-element pollution index is its consideration of only one element to determine the degree of contamination, which is not appropriate for the industrialised area where contamination can result due to one or more pollutants. Nemerow Pollution Index (PI) is a multi-element pollution index, one of the most widely accepted and increasingly used in recent years by researchers. It is calculated by the following equation:

$$PI = \sqrt{\frac{(CF_{average})^2 + (CF_{max})^2}{2}}$$

where $CF_{average}$ is average of contamination factors for all elements and CF_{max} is a single-element value having maximum contamination factor.

Brady et al. (2015) modified the Nemerow Pollution Index by using the enrichment factor instead of contamination factor due to the limitation of low index value for classification of sediment, resulting in false-positive contamination, and the fact that the use of contamination factor does not consider lithogenic fraction. The following equation calculates the modified pollution index:

$$MPI = \sqrt{\frac{(EF_{average})^2 + (EF_{max})^2}{2}}$$

The classifications based on the values of the Modified Nemerow Pollution Index are as follows:

- MPI < 1: unpolluted
- 1 < MPI < 2: slightly polluted
- 2 < MPI < 3: moderately polluted
- 3 < MPI < 5: moderately to heavily polluted
- 5 < MPI < 10: heavily polluted
- 10 < MPI: severely polluted

Modified ecological risk index

Ecological risk assessment is a quantitative assessment of the effect and sensitivity of ecology due to contaminants in sediment. Hakanson (1980) proposed a pollution ecological risk index. Pollution ecological risk index was further modified by replacing the contamination factor with an enrichment factor of elements that considers the complex nature of sediment (Duodu et al. 2016). Modified ecological risk index (MRI) is calculated by the following equation:

$$MRI = \sum_{i=1}^n Er^i = \sum_{i=1}^n Tr^i \times Ef^i$$

where Er^i is the potential ecological risk factor of an individual element, Ef^i is the enrichment factor for each element, and Tr^i is the biological toxic response factor for an individual element. The values of Tr^i for Pb, Zn, Mn, Co, Ni, and Cr are 5, 1, 1, 5, 6, and 2, respectively. The ecological grade for Er^i and MRI is shown in Table 2.

Results and discussions

Chronology

The sedimentation rate derived using ^{210}Pb technique varied from 0.22 to 0.68 cm/year (Fig. 2) with an average sedimentation rate of 0.36 cm/year. Based on the age-depth model, age was assigned to respective depths using variable sedimentation rate and sediment collection year. The depths beyond which Pb_{xs} is not detected were assigned chronology by extrapolation using average sedimentation rates. Industrialisation periods in India developed after 1850, and thus, the bottom 20 cm of sediment core was considered as the background reference sample, which corresponds to the year older than 1737, a period well before pre-industrialisation and can be considered as uncontaminated. The average concentration of uncontaminated core bottom was considered as background value for calculating pollution indices as it is uncontaminated and has similar mineralogical composition.

Table 2 Ecological grading standards for Er^i and MRI (Duodu et al. 2016)

Er^i	Ecological grade	MRI	Ecological grade
< 40	Low risk	< 150	Low risk
40–80	Moderate risk	150–300	Moderate risk
80–160	Considerable risk	300–600	Considerable risk
160–320	High risk	-	
> 20	Very high risk	> 600	Very high risk

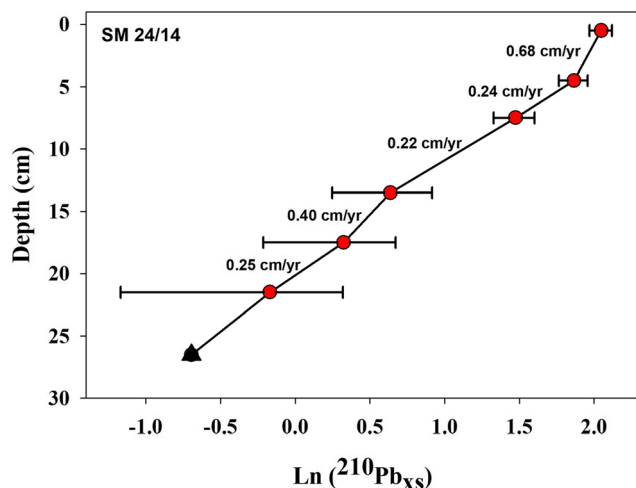


Fig. 2 Profile of $\text{Ln } ^{210}\text{Pb}_{\text{xs}}$ (black coloured triangle indicates the depth beyond which Pb_{xs} was not detected; the sedimentation rate is calculated by dividing decay constant with the slope of $\text{Ln } (^{210}\text{Pb}_{\text{xs}})$ vs. depth plot)

Down-core variation of metals in sediment core

The mean concentration of elements measured in studied sediment core shows following order $\text{Ti} > \text{Mn} > \text{Cr} > \text{Zn} > \text{Ni} > \text{Pb} > \text{Co}$, and no significant enrichment was observed (Fig. 3). Trace elements get incorporated into the sediment with either the detrital phase or organic matter. The relation between all concentrations of trace elements and organic carbon was analysed using Pearson's correlation. Pb, Zn, Mn, Co, Ni, and Cr show a good positive correlation with the detrital element, Ti ($r \geq 0.96$), and shows poor negative correlation with organic carbon (< 0.11) (Table 3). The positive linear correlation of the metals with Ti is indicative of the detrital source as the primary contributor of sediment to the study location. Thus, Ti can be considered

as a reference element for geochemical normalisation. In the present study, normalisation was done by Ti.

Pollution indices

Enrichment factor In this study, fluctuation in the enrichment factor for all elements was observed until 1862, followed by an increasing trend in enrichment value of Ni and Cr towards the present (Fig. 4). No significant variation in the enrichment factor of Co, Mn, and Pb was observed. The enrichment factor value of Zn shows considerable variation. The sediment corresponding to the year of 1960 and 1682 shows Zn enrichment of 1.57 and 1.52, respectively. Overall, the average enrichment factor value was less than 1.5 for all elements.

Geo-accumulation index The geo-accumulation index value for all elements was less than zero, indicating no contamination except for Zn (Fig. 5). The calculated value of Zn geo-accumulation index at depth corresponding to the years 1771, 1843, 1855, 1894, and 1960 had values 0.04, 0.02, 0.05, 0.03, and 0.24 respectively. Considering both enrichment and geo-accumulation index value, the depth corresponding to 1960 is slightly polluted by Zn.

Modified Nemerow Pollution Index The MPI was calculated by combining the values of Pb, Zn, Mn, Co, Ni, and Cr to evaluate if a combination of these elements pollutes the site. The values of MPI in the entire core ranged between 1 and 2, indicating sediment is slightly contaminated by combining elements.

Ecological risk factor Potential ecological risk factor (E_{rf}) for individual elements was less than 40, and the modified ecological risk index (MRI) by combining these elements was

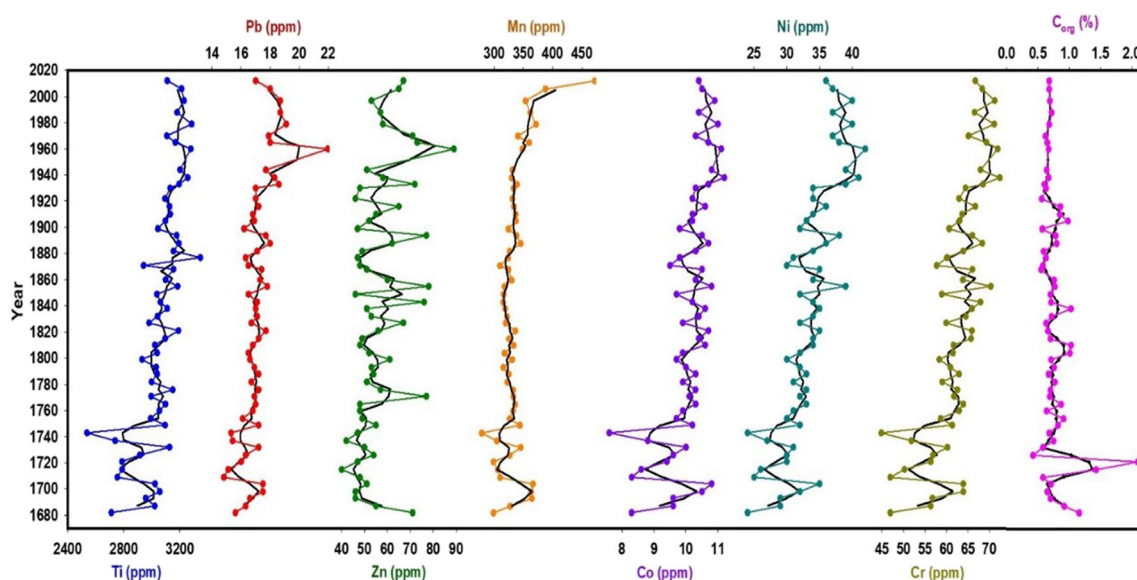


Fig. 3 Down-core variation of Ti, Pb, Zn, Mn, Co, Mo, and Ni in SM 24/14 core (black lines are 3 points running average)

Table 3 Inter-element correlation matrix

	Ti	Pb	Zn	Mn	Co	Ni	Cr	Org C
Ti	1.000							
Pb	0.996	1.000						
Zn	0.961	0.969	1.000					
Mn	0.990	0.990	0.959	1.000				
Co	0.998	0.997	0.963	0.991	1.000			
Ni	0.980	0.983	0.955	0.963	0.982	1.000		
Cr	0.990	0.990	0.959	0.975	0.992	0.996	1.000	
Org C	-0.098	-0.094	-0.083	-0.081	-0.083	-0.129	-0.116	1.000

less than 150 in the entire core. This indicates that the ecology in the present study location is at low risk by Pb, Zn, Mn, Co, Ni, and Cr present in the sediment. Although the MPI indicated slight pollution by a combination of elements under investigation, the ecology is below the risk threat level.

Despite the contamination reported in the Mahanadi river (Sundaray et al. 2014) and G-B river system (Massolo et al. 2012; Pandey and Singh 2017; Siddiqui and Pandey 2019), which are the main contributors to the northern Bay of Bengal, only slight pollution was observed in the sediment core from the inner shelf of the Bay of Bengal. To understand the possible controlling factor for the transport of contaminants from rivers to sea, a comparison was made between the average elemental concentration of adjacent riverine and estuarine sediments with the sea sediment under investigation.

Comparison of average metal concentration in the sediment of the nearby region

Estuaries are immediate recipient of sediments carried by rivers. Oxygen gradient in the estuarine region has a strong

influence on the biogeochemical cycling of trace elements and plays a significant role in binding and releasing trace metals in specific redox conditions (Hambrick et al. 1980; Chapman and Wang 2001). The estuary ecosystem is a highly productive region (Cloern 1987). High organic deposition causes reducing conditions at the sediment-water interface, which regulates the sink and release of the trace elements in the estuary (Conley 1999; Conley et al. 2009; Woodland et al. 2015).

Ni acts as a micronutrient and is delivered to sediment as organometallic complexes. The high content of Ni in sediment indicates high organic matter flux and reducing conditions during deposition (Tribovillard et al. 2006). Ni is also considered as a productivity proxy as it retains records of organic matter even after its partial or complete degradation by associating mainly with pyrite (Tribovillard et al. 2006). The average concentration of Ni in the sediment of the Mahanadi river to estuary increased from 9 to 27 ppm. Similarly, a higher concentration of Ni in Hooghly estuary (~ 34 ppm) when compared with that in Ganga river sediment (~ 20–27 ppm) was observed. The higher value of Ni indicates the

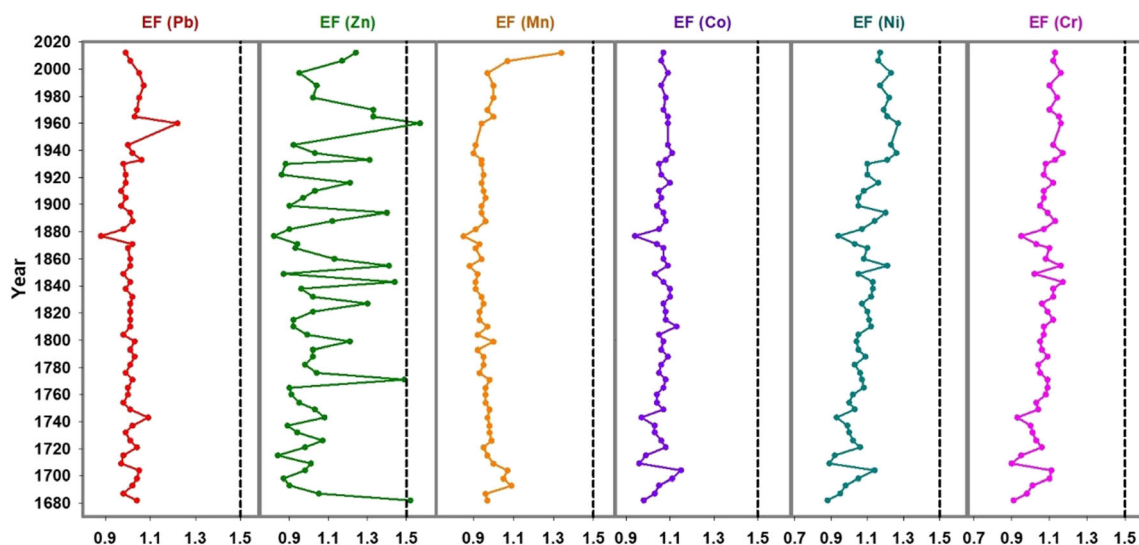


Fig. 4 Down-core variation of enrichment factor value in core SM 24/14; dashed line at 1.5 is the cut-off point for the detrital and non-detrital source (Zhang and Liu 2002)

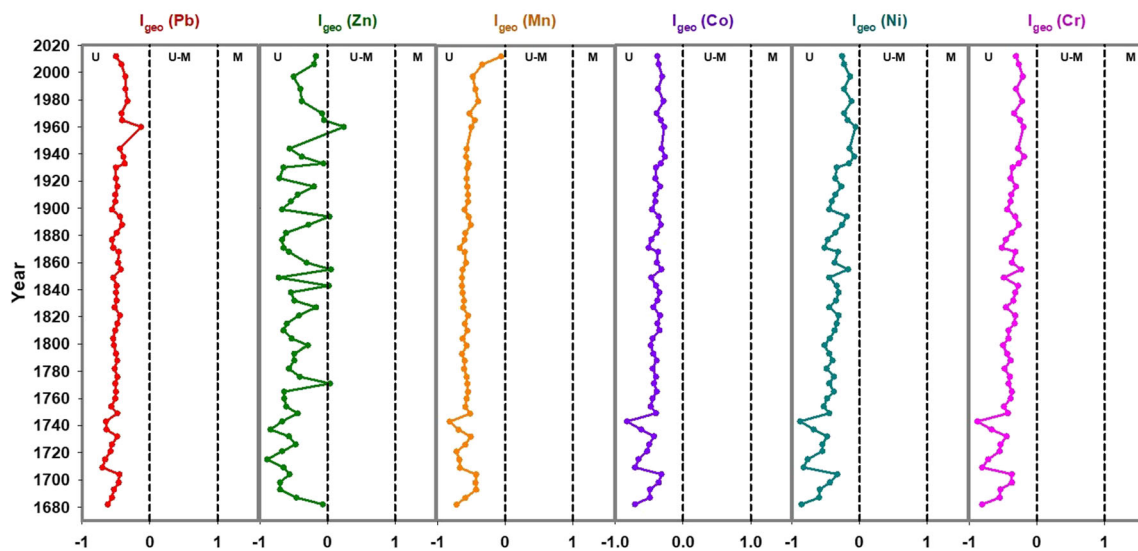


Fig. 5 Down-core variation of geo-accumulation index value in core SM 24/14; dashed lines are cut-off for Muller's I_{geo} classification (U, unpolluted; U-M, unpolluted to moderately polluted; M, moderately polluted)

estuarine regions of Mahanadi and Hooghly estuary have high productivity and can cause reducing conditions at the sediment-water interface.

Ti being a conservative element, its concentration in both river and shelf sediment is similar. Manganese being a redox-sensitive element forms solid Mn-oxyhydroxide in oxic conditions and scavenges trace elements such as Ni, Zn, Co, and Pb as cations and Mo, V, and Cr as ionic species. While under reducing condition, it forms soluble Mn (II) species and diffuses back to the water column and gets mobilised in water, thereby releasing trace elements associated with it (Tribovillard et al. 2006; McManus et al. 2012). With the traverse of sediments from the Mahanadi river to its estuary, Mn shows a decrease in average concentration from 2020 to 1096 ppm, which further reduces to 334 ppm in shelf sediments. The Mn value for G-B river sediment, Hooghly estuary, and shelf sediment also shows a similar decreasing trend (Table 4). Moreover, the average concentration of Pb, Co, and Zn, which are regulated by Mn-oxyhydroxide (Tribovillard et al. 2006), shows a similar decreasing trend while they transfer from rivers to sea (Table 4). Thus, the reducing condition which prevails in the estuarine region possibly resulted in dissolution and release of Mn and its associated elements from sediment to overhead water column, causing a decrease in the concentration from the river to shelf sediment.

Cr is adsorbed on Fe-Mn-oxyhydroxide under oxic conditions and is released upon the reductive dissolution of oxyhydroxide. Cr itself being redox-sensitive element precipitates as Cr (III) hydroxyl cations in reducing condition which can complex with humic/fulvic acids and gets enriched in sediment (Tribovillard et al. 2006). Cr shows higher value in shelf sediment as compared with the concentration in Hooghly and Mahanadi estuary, which further confirms the role of

reducing environment of the estuarine region which plays a significant role.

Comparing the elemental concentration in the shelf region sediment with the adjacent river and estuarine samples suggests that the highly productive region of estuarine environment can play a significant role in higher uptake of micronutrients thereby increasing the concentration in estuary sediments. Moreover, the oxygen gradients in the estuarine region can be responsible for altering the transport of redox-sensitive elements from the river to the sea. Thus, the estuarine region plays an important role in regulating the transfer of pollutant from the river to the sea, by either uptake into sediment or transfer to the water column by dissolution. The estuarine environment could be responsible for the low contamination in the northern Bay of Bengal shelf region, even though estuary and riverine sediments contributing to the present site have higher contamination. The assessment of water quality needs to be monitored to have clarity on marine ecological risk by pollutants. Additionally, detailed studies on the biogeochemistry of various trace elements in the estuarine region would provide insight into the role of estuary in their mobilisation/removal.

Conclusion

^{210}Pb -based chronologically constrained sediment core from the northwestern Bay of Bengal was investigated to study the anthropogenic inputs of various elements to the inner shelf sediments and to decipher their depositional behaviour as a function of their biogeochemical response while they traverse from the river to estuary to shelf sediments. The present core provides a depositional sediment record from the years 1682

Table 4 Comparison of average metal concentration of nearby rivers and estuary

Location		Average elemental concentration (ppm)						
		Ni	Mn	Pb	Co	Zn	Cr	Ti
River sediment	Ganga river ^a	26.7	372.0	26.6	-	67.8	69.9	-
	Ganga river ^b	20	400	25	22	46	52	3030
	Brahmaputra river ^b	47	644	13	31	47	100	3080
	Mahanadi river ^c	9	2020	60	-	125	15	-
Estuarine sediment	Hooghly estuary ^d	33.97	502.42	23.45	18.23	53.42	40.11	-
	Mahanadi estuary ^e	26.8	1095.6	48.9	26.1	101.2	45.2	-
Shelf sediment (northwestern BOB)	Present study	33	333.9	17.1	10.1	56	62.4	3062

^a Pandey and Singh (2017)

^b Subramanian et al. (1985)

^c Chakrapani and Subramanian (1990)

^d Banerjee et al. (2012)

^e Sundaray et al. (2014)

to 2012. Both enrichment factor and geo-accumulation index show no significant contamination of Pb, Zn, Mn, Co, Mo, Ni, and Cr. In contrast, multi-elemental assessment by Modified Nemerow Pollution Index (MPI) demonstrated slight pollution by a combination of elements under investigation. However, the ecological risk factor index showed that ecology is at low risk by individual elements and also by combining the effect of all elements under investigation.

Despite increasing contamination in the riverine system due to anthropogenic activities, the sediment of the northern Bay of Bengal (off Mahanadi basin) is not highly contaminated, and its ecology is also estimated to be at low risk. It has been noted that conditions in estuary play an essential role in regulating the dissolution and release of trace elements from the sediments due to its oxygen gradient and high productivity. The role of the estuarine environment and high sediment flux G-B river system could be the possible reason for the sediment of northwestern Bay of Bengal not being as contaminated as their riverine source, as they lead to either dilution or removal of certain trace elements in estuaries.

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