Distribution of Trace Metals in the Sediments of Estuarine-Mangrove Complex across the Indian Coast

9

Prabhat Ranjan, Namrata Priya, Alok Kumar, and AL. Ramanathan

Abstract

The present chapter reviews the current knowledge on trace metal distribution and their enrichment and ecotoxicity potential in sediments in Indian estuarine-mangrove complexes. Available literature suggests that the metals like Cd and Fe show very high contamination, whereas Co, Cr, Cu, Mn, Ni, Pb and Zn indicate moderate contamination in Indian mangroves [based on the pollution indices contamination factor (CF), pollution load index (PLI), enrichment factor (EF), geo-accumulation index (I-geo), potential ecological risk index (Eif) and potential toxicity response index (RI)]. The tsunamigenic sediments of Pichavaram mangroves of Southern India indicate very high enrichment of the metals. Low values for Al and As for all indices suggest low degree of risk with respect to these metals across the Indian estuarine mangroves. Cd shows higher enrichment in almost all estuarine-mangrove complexes in India except those at Muthupet and Sundarbans. Of all Indian mangroves, high risk is seen in the case of Pichavaram, Coringa-Gaderu, Manakudy estuary mangrove and Vellar estuary mangrove, while for Sundarbans, Muthupet and Goa, the risk is low. In the light of this, there is a need for effective management strategy for most of the Indian mangrove ecosystems.

P. Ranjan • N. Priya • AL. Ramanathan (✉)
School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India
e-mail: prabhatranjan.jnu@gmail.com; namratapriyarox@gmail.com; alrjnu@gmail.com

A. Kumar
Department of Environmental Science, Central University of Rajasthan, Kishangarh, Ajmer, Rajasthan, India
e-mail: alok_evs@curaj.ac.in

9.1   Introduction

Mangrove forests are one of the world's most productive tropical ecosystems confined to the coastal deltaic zones of tropics and subtropics, predominantly between 25° N and 25° S with an estimated total coverage of 1.7 to 2.0×10^5 km^2 (Borges et al. 2003). Mangroves are of much significance as they act as a barricade against cyclones, protect coastal erosion and provide habitat for a number of commercially important aquatic organisms (Kathiresan and Bingham 2001).

Pollution of the natural environment by trace metals is a worldwide problem because trace metals have toxic effects on living organisms when they exceed a certain concentration (Chakraborty et al. 2009; Dias and Nayak 2016). Trace metal toxicity holds greater significance as they tend to accumulate in the sediments as well as biota through various physical, chemical and biological processes (Leivouri 1998; Jonathan et al. 2010; Kumar and Ramanathan 2015). Increasing urbanization and industrialization has increased the release of higher domestic sewage, industrial effluents, trace metals and other toxic pollutants to coastal areas (Agoramoorthy and Hsu 2005; Ranjan et al. 2008). Mangrove plants have a special feature to store trace metals without being damaged even at higher concentration than terrestrial flora (MacFarlane et al. 2007). This capacity increases with the increasing age of mangroves (Panda et al. 2013). The present chapter examines the status of major estuarine mangrove complexes (Fig. 9.1) across the Indian coast with reference to occurrence of trace metals in the sediments.

9.1.1   Distribution of Major Indian Mangrove

According to the Forest Survey of India (FSI) report in 2015, the total mangrove cover in the country stands at 4628 km^2. The major Indian mangroves are described in brief as below.

Sundarbans (West Bengal) The Indian Sundarbans at the apex of the Bay of Bengal (between *21°40′ N* and *22°40′ N latitude* and *88°03′ E* and *89°07′ E longitude*) is located towards the northeast coast of India. It is a tide-dominated estuarine wetland at the lower deltaic plains of the Ganges-Brahmaputra Rivers. This wetland is a complex network of tidal creeks, surrounding hundreds of tidal islands exposed to different elevations at high and low semidiurnal tides (Sarkar et al. 2008; Jonathan et al. 2010; Banerjee et al. 2012; Kumar and Ramanathan 2015).

Bhitarkanika (Odisha) Bhitarkanika is located between *20°04′–20°08′ N latitudes* and *86°45′–87°50′ E longitude*s in the Kendrapara district of Odisha. It is the second largest mangrove ecosystem in India comprising mangrove forests, rivers, creeks, estuaries, backwater, accreted land and mud flats. Bhitarkanika mangroves, spread over an area of 672 km^2, were declared as a wildlife sanctuary in 1975. It is a tide-dominated mangrove with areas of high tidal range of semidiurnal nature with mean tide level of 1.5–3.4 m (Sarangi et al. 2002).

Fig. 9.1 Distribution of mangroves in India (Adopted from Kumar 2000)

Coringa and Gaderu (Andhra Pradesh) Coringa and Gaderu mangrove ecosystems are located to the north of Gautami-Godavari River (82° 15′ and 82° 22′ E *latitude*; 16° 43′ and 17° 00′ N *longitude*) with an area of 132 km². The Gautami-Godavari River opens into Kakinada bay via the main distributaries Gaderu (length 11 km) and Coringa (length 26 km). The area between Gautami-Godavari and Kakinada bay has dense vegetation of mangrove forests and mudflats belonging to Coringa wildlife sanctuary (Ray et al. 2006).

Pichavaram (Tamil Nadu) Pichavaram mangrove forest is located between Vellar and Coleroon estuaries at 11° 02′ N *latitude* and 79° 47′ E *longitude*. The area has 51 islets, separated by intricate waterways that connect the Vellar and Coleroon estuaries. The southern part close to the Coleroon estuary is mainly mangrove vegetation, while the northern part close to the Vellar estuary is dominated by mudflats. The Vellar estuary opens into the Bay of Bengal at Parangipettai and is connected with the Coleroon River, a distributary of the River Cauvery. The Pichavaram mangrove is influenced by mixing of three types of waters: (1) neritic water from the adjacent Bay of Bengal, (2) brackish water from the Vellar and Coleroon estuaries and (3) fresh water from an irrigation channel (Khan Sahib Canal) and also from the main channel of the Coleroon River. The mangrove covers an area of about 1100 ha, of which 50% is forest, 40% waterways and the remaining sandflats and mudflats (Ramanathan et al. 1999; Ranjan et al. 2013).

Kumarakom Mangrove (Kerala) Kumarakom mangrove is located between *latitude* 09°28′ and 10°10′ N and *longitude* 76°13′ E. Kumarakom mangrove and mangrove-associated forests are seen along the southeastern border of the Vembanad estuary. It was one of the best mangrove ecosystems of Kerala before commissioning of Thannirmukkam barrier constructed on Vembanad estuary to prevent saltwater intrusion during droughts. Now the mangrove ecosystem has severe regeneration problems owing to the drastic changes in the physico-chemical conditions caused by the Thannirmukkam barrier and the intensive shell mining taking place in the areas close to the Kumarakom mangroves (Badarudeen et al. 1996).

Goa Mangrove (Goa) Goa mangrove and associated swamps can be observed along most of the water bodies within the estuarine reaches. It is located on central western coast of India between *14°53′–15°48′ N latitude*s and *73°40′–74°20′ E longitudes*. The most prominent and extensive backwaters with mangroves are located along the east of the capital city Panaji. The total area covered by the estuaries in Goa including the major Mandovi-Zuari estuarine complex is approximately 120 km^2 (Attri and Kerkar 2011).

Mumbai (Maharashtra) The city of Mumbai lies between 18°55′ N and 19°20′ *N latitudes* and 72°45′ E and 73°00′ E *longitudes*. This city has at its northern end the Ulhas River, Thane Creek on the southeastern end and the Arabian Sea on the west. Extensive mudflats and mangroves are present along both estuarine banks. The creek is fringed with mangroves along both banks, along with heavy industrialization and urbanization (Fernandes et al. 2012).

Gulf of Kachchh (Gujarat) The Gulf of Kachchh (GoK) is situated in Saurashtra in the western state of Gujarat. The GoK, occupying an area of 7300 km^2, is biologically one of the most productive and diversified habitats along the western coast of India. The northern shore with numerous shoals and creeks also sustains large stretches of mangroves. The majority of the mangrove cover of Gujarat area is confined to the gulf. Of the 991 km^2 of mangrove cover in the state, those along the gulf

contribute 96% of the total. Due to high salinity, grazing and cutting pressure, Kachchh mangroves have stunted growth and are only 1–2 m tall, whereas at untouched patches mangroves gain a height up to 5 m (Ramaswamy et al. 2007; Chakraborty et al. 2014).

Andaman and Nicobar (Andaman and Nicobar Islands, ANI) Andaman and Nicobar archipelago, consisting of over 572 islands and islets, lie in the lap of Bay of Bengal (between *latitude* 6°45′–13°41′ N and *longitude* 92°12′–93°57′ E) to the eastern side of India. The islands, about 1200 km east from the mainland of India, have a total land area of about 8249 km^2 covered by luxuriant tropical rain forest. Fringing reef and barrier reef dominate the Andaman Islands forming a natural barrier to the wave energy from the Bay of Bengal (Ramesh et al. 2006). Coral reefs form the dominant ecosystem creating ground for sea grasses and mangroves in the lagoons and creeks protected by the reef (Nobi et al. 2010).

9.2 Analytical Methods

9.2.1 Contamination Factor (CF)

The CF is the ratio obtained by dividing the mean concentration of each metal in the soil (C_n) by the baseline or background value (concentration in unpolluted soil, Håkanson et al. 1980)

$$CF = C_n / B_n \tag{9.1}$$

C_n in the above formula is the concentration of the examined element '*n*' in the surface sediments, and *Bn* is the geochemical background concentration of the metal '*n*'. *Bn* usually refers to world's average shale or upper continental crust composition as a reference value. CF is categories into four categories, as follows: CF <1 as low level, CF between 1 and 3 as moderate level, CF 3–6 as considerable, and CF >6 as very high level of contamination.

9.2.2 Pollution Load Index (PLI)

The PLI is calculated as the nth root of the product of the contamination factor (CF) of all trace metals. The equation for PLI developed by Tomlinson et al. (1980) is given below:

$$PLI = \sqrt[n]{(CF1 \times CF2 \times CF3 \times \ldots \times CFn)} \tag{9.2}$$

In the above equation, CF denotes the contamination factors of different metals in the samples. The PLI >1 indicates pollution, whereas <1 indicates no pollution.

9.2.3   Enrichment Factor (EF)

The EF is a geochemical index based on the assumption that, under the natural sedimentation conditions, there is a linear relationship between a reference element and other elements. Elements that are most often used as reference are Al and Fe (Mucha et al. 2003; Esen et al. 2010; Kumar et al. 2016). The EF is defined as given below (Ergin et al. 1991):

$$EF = \left(M / Fe \right)_{sample} / \left(M / Fe \right)_{background} \tag{9.3}$$

where $(Me/Fe)_{sample}$ is the metal to Fe ratio in the sample of interest; $(Me/Fe)_{background}$ is the geochemical background value of metal to Fe ratio. The value of EF denotes the following category of enrichment of trace metals:

- EF < 2 – deficient to minimal enrichment
- EF = 2–5 – moderate enrichment
- EF = 5–20 – significant enrichment
- EF = 20–40 – very high enrichment
- EF >40 – extremely high enrichment

9.2.4   Geo-Accumulation Index (I-geo)

The index I-geo is widely used as a measure of sediment contamination. It denotes contamination by comparing current metal contents with preindustrial levels. The content accepted as background is multiplied by the constant 1.5 in order to take into account natural fluctuations of a given substance in the environment as well as very small anthropogenic influences. The I-geo as per Muller (1981) is described by the following equation:

$$\text{I-}geo = \log_2 \left(C_n / 1.5 B_n \right) \tag{9.4}$$

The interpretation of the results is as follows:

- I-geo ≤0 – practically uncontaminated
- 0< I-geo <1 – uncontaminated to moderately contaminated
- 1< I-geo < 2 – moderately contaminated
- 2< I-geo <3 – moderately to heavily contaminated
- 3< I-geo < 4 – heavily contaminated
- 4< I-geo <5 – heavily to very heavily contaminated
- I-geo ≥5 – very heavily contaminated

9.2.5 Potential Ecological Risk Index (Eif)

The Eif is used to express quantitatively the potential ecological risk of a given contaminant suggested by Håkanson (1980). It is calculated by the following equation:

$$Eif = CF \times Tif \tag{9.5}$$

where Tif is the toxic response factor for a given substance [toxic response index for different metals are Hg = 40, Cd = 30, As = 10, Cu = Pb = Ni = 5, Cr = 2 and Zn = 1 given by Håkanson (1980)], and CF is the contamination factor. The following terminologies are used to describe the risk factor:

- Eif <40 – low potential ecological risk
- 40≤ Eif < 80 – moderate potential ecological risk
- 80≤ Eif <160 – considerable potential ecological risk
- 160≤ Eif <320 – high potential ecological risk
- Eif ≥320 – very high ecological risk

9.2.6 Potential Toxicity Response Index (RI)

The RI was originally introduced by Håkanson (1980) to assess the degree of heavy metal pollution in soil, according to the toxicity of metals and the response of the environment. The calculation of RI is as given below:

$$RI = \Sigma \, Eif \tag{9.6}$$

There are four categories of RI: RI <150 low-grade, 150≤ RI <300 moderate, 300≤ RI <600 severe and 600≤ RI serious risk.

9.3 Scenario of Metal Pollution in Selected Indian Mangrove Ecosystem

Metal distributions are very uneven within mangrove forests; it varies with depth, distance from the coast, anthropogenic activities, types of vegetation and hydrology (Kehrig et al. 2003; Marchand et al. 2006; Chatterjee et al. 2009). The sources are usually difficult to identify as some have natural sources and others have anthropogenic, as point and non-point, sources. The concentration of Al, As, Cd, Cr, Cu, Co, Fe, Mn, Ni, Pb and Zn in mangrove sediments from different studies, published so far, for Indian mangrove is shown in Table 9.1.

The Sundarbans and Pichavaram have higher concentration of Al, As, Cd, Co, Cr, Fe and Mn (Table 9.1). In the tsunamigenic sediments in Pichavaram mangroves, Ranjan et al. (2008) reported higher concentration of almost all trace metals. Coringa-Gaderu, GoK and Manakudy estuary have higher concentration of Zn, Ni and Fe, whereas Coringa and Kumarakom have higher concentration of Cd.

Table 9.1 Trace metal concentration in different mangrove ecosystems of India

Location	Al (%)	As (ppm)	Cd (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Fe (%)	Mn (%)	Ni (ppm)	Pb (ppm)	Zn (ppm)	OC (%)	Sand (%)	Silt (%)	Clay (%)	References
Sundarbans (values in range)						36–82	3.9–5.3	0.424–0.770			55–83	0.601–0.932	2.46–7.62	64.14–73.92	19.60–31.22	Kumar and Ramanathan (2015)
Sundarbans (values in range)		4.12–11.46	0.02–4.4		21.2–60.9	11.6–102.47			19.10–52.6	7.09–183.88		0.47–0.91	0.51–37.40	18.20–66.64	23.18–77.80	Antizar-Ladislao et al. (2015)
Sundarbans		3.82	0.21	7.67	28.3	38.29	0.29	0.06	34.5	15.8	34.42	0.60–0.66	1.80–15.45	32.58–38.93	51.98–59.28	Chowdhury et al. (2015)
Sundarbans			1.88	23.48	44.13	38.47	3.75	0.0574	50.35	30.28	75.87	0.786				Banerjee et al. (2012)
Sundarbans		8.09	0.18		99.01	28.94			51.86	23.01		1.552	28.47			Jonathan et al. (2010)
Sundarbans	6.33	8.3	0.15	10.41	55.98	25.74	3.12	0.58	30.17	65.59	22.8	0.625	15.34	48.24	36.41	Chatterjee et al. (2009)
Sundarbans						90.765				38.175	303.75					Sarkar et al. (2008)
Sundarbans	2.46	3.5	0.1	12.46	36.44	35.47	3.08	0.14	33.46	17.2	74.18	0.457	21.684	56.54	21.76	Sarkar et al. (2004)
Bhitarkanika						3.786	0.003	0.0009			1.01					Sarangi et al. (2002)
Coringa-Gaderu			10.9	28.8	2.2	47.8	0.46	0.11	25.7	55.8						Ray et al. (2006)
Pichavaram			23		152	34	3.80	0.033	51	21	16					Ranjan et al. (2013)
Pichavaram			34.74		6200	132.3	2.50	0.08	252.1		106					Ranjan et al. (2008)
Pichavaram			6.6	35.3	141.2	43.4	3.25	0.09	62	11.2	93					Ramanathan et al. (1999)

Location	Al (%)	As (ppm)	Cd (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Fe (%)	Mn (%)	Ni (ppm)	Pb (ppm)	Zn (ppm)	OC (%)	Sand (%)	Silt (%)	Clay (%)	References
Muthupet			0.24	11	117.3	18.1	3.21	0.0225	53.2	21.6	115.2					Raman et al. (2007)
Muthupet										43.4	261.88		11.9			Natesan et al. (2014)
Vellar estuary mangrove	0.0542		9.15		9.44	16.28	1.00	0.0178	1.64	0.98	39.28					Palpandi and Kesavan (2012)
Kumarakom					9	13	1.83	0.003			84	2.3	45.31	50.75	4.07	Badarudeen et al. (1996)
Sharavati estuary mangrove, Karnataka	3.4			4	52	9	1.6	0.013	11		17	0.4	82	4	14	Fernandes and Nayak (2016)
Goa				114.35		64.99	8.72	0.25	118.565		277.9	1.89	55.27	20.88	24.07	Dias and Nayak (2016)
Goa						49.36	9.94	0.294	64.02	18.74		5.06	44.06	34.48	21.5	Chakraborty et al. (2015)
Goa				24.41	147.75	47.32	19.25	0.154		24.5	66.62		<20			Veerasingam et al. (2015)
Goa	8.38			22.85	271.18	36.26	14.53	0.512	47.15		104.34	2.13	5.82	48.55	45.64	Noronha-D'Mello and Nayak (2015)
Goa				34.36	17.32	45.34	12.18	0.16		22.51	72.853	2.63	26.74	20.69	52.28	Attri and Kerkar (2011)
Gulf of Kachchh			6.113		8.52	5.04	0.19	0.005	2.708	0.37	231					Chakraborty et al. (2014)
Gulf of Kachchh (values in range)			0.173–23.08	18–26	120–255	44–138	0.11–8.23	0.085–0.11	51–78	14–34	0.29–160	1.47–3.25	77.2–97.93	0.60–21.45	0.1–2.5	Kumar et al. (2015)

9.3.1 Contamination Factor (CF)

An overall synthesis of reported CF in sediments from various mangrove habitats in India is presented in Table 9.2. Almost all studies of Indian mangrove ecosystem show most of the trace metals contamination in the range from 'low' to 'moderate'. Few exceptions were 'Fe' in Sundarbans, Pichavaram, Muthupet, Sharavati and Goa and 'Cd' in Coringa-Gaderu, Pichavaram, Vellar and GoK. The CF for Co was high in Sharavati estuary and Goa (Feranandes and Nayak 2016; Dias and Nayak 2016).

9.3.2 Enrichment Factor (EF)

The scenario of trace metal enrichment in various mangrove ecosystems of India is presented in the Table 9.2. In Sundarbans mangrove ecosystem, trace metal enrichment level is deficient to minimal, except for Cd and Ni, in most of the studies (Chowdhury et al. 2015). Enrichment factors for most of the trace metals in the mangroves of Muthupet, Vellar, Sharavati, Kumarakom, Goa, Coringa and Gaderu, Gulf of Kachchh and Vellar were deficient to minimal. Pichavaram also seemed to have somewhat similar enrichment pattern of trace metals except Cd. The mangrove sediment in Vellar had high enrichment of Cd and that in Pichavaram (Tsunamigenic sediment, Ranjan et al. 2008), Coringa-Gaderu and Gulf of Kachchh showed extremely high enrichment of Cd. This extremely high enrichment of Cd is due to the geogenic origin and deposition of marine sediments during the tsunami episode of 2004. This can be attributed to the fact that marine sediments from deep oceans are rich in Cd, which might have been trapped in mangrove sediments after the tsunami.

Extremely high enrichment of Pb in Bhitarkanika mangrove ecosystem indicates that Pb is precipitated at around the redox boundaries (Lee and Cundy 2001); the downward flux of Pb is bound to biogenic particles (Lambert et al. 1991) which increase its concentration. Enrichment of Cd in this estuarine environment can be linked to both natural and non-point anthropogenic sources. The abnormally high enrichment in tsunamigenic sediment can be attributed to various factors (Purvaja and Ramesh 2000; Subramanian 2004), *viz.* anthropogenic wastes from nearby soils brought back by tsunami waves and discharge from nearby industries (aquaculture effluents, domestic sewage). Factors like enhanced organic matter content, flocculation due to varying salinity regimes and transportation of sea sediments to the coastal zone contribute significantly towards the enrichment of heavy metals in sediments.

9.3.3 Pollution Load Index (PLI)

The pollution load of Indian mangrove ecosystem is presented in Table 9.2. With only few exceptions, almost all the mangrove ecosystems seemed to be polluted.

Table 9.2 Contamination factor (*CF*), enrichment factor (*EF*), pollution load index (*PLI*), potential toxicity response index (*RI*) with respect to metals in major Indian mangrove ecosystems

Location	Contamination factor				Enrichment factor					PLI	RI	References
	Low	Moderate	Considerable	High	Deficient to minimal	Moderate	Significant	Very high	Extremely high			
Sundarbans	Al, As, Co, Cr, Fe, Pb, Zn	Cd, Cu, Mn, Ni			As, Co, Cu, Cr, Mn, Pb, Zn	Cd, Ni				Unpolluted	Low grade	Chowdhury et al. (2015)
Sundarbans	Mn	Co, Cr, Cu, Pb, Zn	Ni	Cd, Fe	Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn					Polluted	Serious	Banerjee et al. (2012)
Sundarbans	As, Zn	Cd, Cu, Pb	Cr, Ni							Polluted	Low grade	Jonathan et al. (2010)
Sundarbans	Al, As	Cd, Co, Cr, Cu, Ni	Pb	Fe, Mn	Al, As, Cd, Co, Cr, Cu, Mn, Pb, Zn					Polluted	Low grade	Chatterjee et al. (2009)
Sundarbans		Pb	Cu, Zn		Al, As, Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn					Polluted	Low grade	Sarkar et al. (2008)

(continued)

Table 9.2 (continued)

Location	Contamination factor				Enrichment factor					PLI	RI	References
	Low	Moderate	Considerable	High	Deficient to minimal	Moderate	Significant	Very high	Extremely high			
Sundarbans	Al, As, Pb	Cd, Co, Cr, Cu, Mn, Ni, Zn		Fe						Polluted	Low grade	Sarkar et al. (2004)
Bhitarkanika	Fe, Mn, Pb, Zn						Zn		Mn, Pb	Unpolluted	Low grade	Sarangi et al. (2002)
Coringa-Gaderu	Cr	Co, Cu, Fe, Mn, Ni, Pb		Cd	Cr, Cu, Mn, Ni	Co, Pb			Cd	Polluted	Serious	Ray et al. (2006)
Pichavaram	Mn, Zn	Cu, Ni, Pb	Cr	Cd, Fe	Cr, Cu, Mn, Ni, Pb, Zn			Cd		Polluted	Serious	Ranjan et al. (2013)
Pichavaram	Cr	Mn, Zn	Cu	Cd, Fe, Ni	Cr, Cu, Mn, Pb, Zn				Cd	Polluted	Serious	Ranjan et al. (2008)
Pichavaram	Pb	Cu, Zn	Co, Cr, Ni	Cd, Fe	Co, Cr, Cu, Mn, Ni, Pb, Zn		Cd			Polluted	Serious	Ramanathan et al. (1999)
Muthupet		Pb	Zn							Polluted	Low grade	Natesan et al. (2014)

Location	Contamination factor				Enrichment factor					PLI	RI	References
	Low	Moderate	Considerable	High	Deficient to minimal	Moderate	Significant	Very high	Extremely high			
Muthupet	Cu, Mn	Cd, Co, Ni, Pb, Zn	Cr	Fe	Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn					Polluted	Low grade	Raman et al. (2007)
Vellar estuary mangrove	Al, Cr, Cu, Mn, Ni, Pb, Zn	Fe		Cd	Al, Cr, Cu, Mn, Ni, Pb, Zn			Cd		Unpolluted	Serious	Palpandi and Kesavan (2012)
Kumarakom	Cr, Cu, Mn	Zn	Fe		Cr, Cu, Mn, Zn					Unpolluted	Low grade	Badarudeen et al. (1996)
Sharavati estuary mangrove, Karnataka		Zn	Mn, Pb	Co, Fe	Co, Cr, Cu, Mn, Ni, Pb, Zn					Polluted	Low grade	Fernandes and Nayak (2016)
Goa		Cu	Mn, Ni, Zn	Co, Fe	Co, Cu, Mn, Ni, Zn					Polluted	Low grade	Dias and Nayak (2016)
Goa	Zn,	Co, Cu, Mn, Pb	Cr	Fe	Co, Cr, Cu, Mn, Pb, Zn					Polluted	Low grade	Veerasingam et al. (2015)

(continued)

Table 9.2 (continued)

Location	Contamination factor					Enrichment factor						PLI	RI	References
	Low	Moderate	Considerable	High		Deficient to minimal	Moderate	Significant	High	Very high	Extremely high			
Goa		Al, Co, Cu, Ni, Zn				As, Co, Cu, Cr, Mn, Ni, Zn			Cr, Fe, Mn			Polluted	Low grade	Noronha-D'Mello and Nayak (2015)
Goa	Cr	Cu, Mn, Pb, Zn	Co			Co, Cr, Cu, Mn, Pb, Zn			Fe			Polluted	Low grade	Attri and Kerkar (2011)
Gulf of Kachchh	Cr, Cu, Fe, Mn, Ni, Pb		Zn			Cr, Cu, Mn, Ni, Pb		Zn	Cd		Cd	Unpolluted	Serious	Chakraborty et al. (2014)

Pollution of Pichavaram and Goa mangrove can be attributed to fishing, aquaculture, agricultural runoff, shipping, industries, tourism and boating. It was interesting to note that while most of the studies in Sundarbans showed the area to be highly polluted w.r.t. PLI, the recent findings by Chowdhury et al. (2015) were different.

9.3.4 Potential Toxicity Risk Index (RI)

Potential toxicity risk index (RI), presented in Table 9.2, reveals that the RI was in 'low-grade' category in all the studies done so far in Kumarakom, Muthupet, Goa and Bhitarkanika mangroves. Similar was the case with Sundarbans except for the study done by Banerjee et al. (2012). In Pichavaram, Coringa-Gaderu, Vellar and Gulf of Kachchh, the RI fell in 'serious' category.

9.3.5 Geo-Accumulation Index (I-geo)

Geo-accumulation index (I-geo) of various heavy metals in different mangrove ecosystems of India is presented in Table 9.3. Of all the mangroves in India, maximum investigations were undertaken in the Sundarbans. These investigations suggest different accumulation status of heavy metals in the mangrove sediments, ranging from 'practically uncontaminated' (Zn) to 'moderate to strong accumulation' (Fe and Mn). The category of geo-accumulation of metals in Pichavaram mangrove sediments differed from that reported in Sundarbans (practically uncontaminated includes Al, Mn, Pb and Zn; contaminated includes Cu; strongly accumulated includes Cd). However, tsunamigenic sediments showed different patterns of metal accumulation.

In the mangroves of Coringa-Gaderu (Table 9.3), the I-geo for Fe, Cr, and Ni were in 'practically uncontaminated' category, and Cu, Co, Mn and Pb in 'uncontaminated to moderate' category. In Kumarakom mangrove sediments, I-geo values for Cr, Cu, Mn and Zn were in 'practically uncontaminated' category, and Fe was found to be 'moderately accumulated in the sediments'. Most of the heavy metals examined in sediments of GoK and Bhitarkanika mangrove systems were found in "practically uncontaminated"' category. Similarly, Al, Cu and Zn were in 'practically uncontaminated' category in Muthupet and Goa mangroves.

9.3.6 Potential Ecological Risk Index (Eif)

An overall picture of potential ecological risk is presented in Table 9.3 for the Indian mangrove ecosystems. In all the Indian mangrove ecosystems examined, Al, As, Cr, Cd, Ni, Pb and Zn seemed to have 'low potential ecological risk', whereas Cd had 'high potential ecological risk' (in Pichavaram, Coringa-Gaderu, GoK and Vellar).

Table 9.3 Geo-accumulation index (I-geo) and potential ecological risk index (with respect to metals) in major Indian mangrove ecosystems

Location	I-geo							Eif					References
	Practically uncontaminated	Uncontaminated to moderate	Moderate	Moderate to strong	Strong	Strong to very strong	Very strong	Low	Moderate	Considerable	High	Very high	
Sundarbans	As, Co, Cr, Fe, Mn, Pb, Zn	Cd, Cu, Ni						As, Cr, Cu, Ni, Pb, Zn	Cd				Chowdhury et al. (2015)
Sundarbans	Cr, Zn	Co, Cu, Ni, Pb		Fe, Mn	Cd			Cr, Cu, Ni, Pb, Zn	Cd				Banerjee et al. (2012)
Sundarbans	As, Cu, Pb	Cd, Cr, Ni						As, Cr, Cu, Ni, Pb	Cd				Jonathan et al. (2010)
Sundarbans	Al, As, Co, Cu, Zn	Cd, Cr, Ni	Pb	Fe, Mn				As, Cr, Cu, Ni, Pb, Zn	Cd				Chatterjee et al. (2009)
Sundarbans		Pb	Cu, Zn					Cu, Pb, Zn					Sarkar et al. (2008)
Sundarbans	Al, As, Cd, Co, Cr, Cu, Zn	Mn, Ni		Fe				As, Cd, Cr, Cu, Ni, Pb, Zn					Sarkar et al. (2004)
Bhitarkanika	Fe, Mn, Pb, Zn							Pb, Zn					Sarangi et al. (2002)
Coringa-Gaderu	Cr, Fe, Ni	Co, Cu, Mn, Pb				Cd		Cr, Cu, Ni, Pb				Cd	Ray et al. (2006)

	I-geo							Eif					
Location	Practically uncontaminated	Uncontaminated to moderate	Moderate	Moderate to strong	Strong	Strong to very strong	Very strong	Low	Moderate	Considerable	High	Very high	References
Pichavaram	Cu, Mn, Pb, Zn	Ni	Cr				Cd	Cr, Cu, Ni, Pb, Zn				Cd	Ranjan et al. (2013)
Pichavaram	Cr, Mn, Zn		Cu		Pb		Cd	Cr, Cu, Zn	Pb			Cd	Ranjan et al. (2008)
Pichavaram	Pb, Zn	Cu, Mn	Co, Cr, Ni	Fe			Cd	Cr, Cu, Ni, Pb, Zn				Cd	Ramanathan et al. (1999)
Muthupet		Pb	Zn					Pb, Zn					Natesan et al. (2014)
Muthupet	Co, Cu, Pb, Mn	Cd, Ni, Zn	Cr					Cr, Cu, Ni, Pb, Zn	Cd				Raman et al. (2007)
Vellar estuary mangrove	Al, Cr, Cu, Mn, Ni, Pb, Zn	Fe					Cd	Cr, Cu, Ni, Pb, Zn				Cd	Palpandi and Kesavan (2012)
Kumarakom	Cr, Cu, Mn, Zn		Fe				Cd	Cr, Cu, Zn					Badarudeen et al. (1996)
Sharavati estuary mangrove, Karnataka		Zn	Cr, Cu, Mn, Pb	Co, Ni	Fe			Cr, Cu, Ni, Pb, Zn					Fernandes and Nayak (2016)

(continued)

Table 9.3 (continued)

Location	I-geo							Eif					References
	Practically uncontaminated	Uncontaminated to moderate	Moderate	Moderate to strong	Strong	Strong to very strong	Very strong	Low	Moderate	Considerable	High	Very high	
Goa	Co	Cu	Mn, Ni, Zn		Fe			Cu, Ni, Pb, Zn					Dias and Nayak (2016)
Goa	Pb, Zn	Co, Cu, Mn, Pb	Cr				Fe	Cr, Cu, Pb, Zn					Veerasingam et al. (2015)
Goa	Al, Cu, Zn	Co, Ni		Cr, Mn		Fe		Cr, Cu, Ni, Zn					Noronha-D'Mello and Nayak (2015)
Goa	Cr, Pb, Zn	Cu, Mn	Co			Fe		Cr, Cu, Pb, Zn					Attri and Kerkar (2011)
Gulf of Kachchh	Co, Cr, Cu, Fe, Mn, Ni	Pb						Cr, Cu, Ni, Pb, Zn				Cd	Chakraborty et al. (2014)

9.4   Processes Governing the Distribution of Trace Metals

Other than the inputs from the terrestrial runoff and marine inputs (Peters et al. 1997), processes like redox potential, organic matter content, texture of the sediment, flocculation-deflocculation, etc., control the distribution and availability of the trace metals in the mangrove ecosystems. The anaerobic sediments of mangrove with high sulphur content favour trace metal retention, especially Fe and Mn, by combining with sulphides (Silva et al. 1990). Further, the Fe-Mn complex encourages retention of other metals due to the geochemical affinity with other trace metals. Hence, it is also referred as sink of trace metals (Förstner and Wittman 1983). Changing redox potential (oxidation) also causes metal desorption from the sediment to the water column making it mobile and bioavailable (Silva et al. 1990; Marchand et al. 2006). Sediment organic matter acts as a metal carrier (Ray et al. 2006), changing salinity regimes encourages flocculation (Eckert and Slokowitz 1976) and fine particles enhance metal accumulation by precipitation of metals as hydroxide coating over them (Förstner and Wittman 1983; Salomons and Förstner 1984).

The high Cd concentration in surface sediments of Pichavaram mangrove was attributed to the combined effect of both non-point anthropogenic inputs (fertilizers brought in by Vellar, Uppanar and Coleroon river) as well as natural sources, along with inputs of Cd-rich sediment from deep ocean carried by the tsunami (Li et al. 2006; Seralathan et al. 2006). Enrichment of Pb in Pichavaram mangrove indicates that the metal is precipitated around the redox boundaries (Lee and Cundy 2001), and the downward flux of Pb is bound to biogenic particles (Lambert et al. 1991) which increases its concentration. Aquaculture effluents, agricultural runoff and domestic sewage also play a role in Pb enrichment in the area (Purvaja and Ramesh 2000; Subramanian 2004). A higher value of Pb at Manakudy estuary mangrove (161.254 μg/g) were due to the local redox condition that allowed Pb to coprecipitate with Mn during Mn-oxide formation in the superficial segment (Lee and Cundy 2001). Early diagenesis of organic matter in sediments may also cause trace metal redistribution (Prajith et al. 2016).

9.5   Concerns

Accumulations of trace metals have been already reported in many Asian mangroves and associated flora and fauna (Sandilyan and Kathiresan 2014). Trace metals' presence has been reported in more than 30 mangrove species and their various tissues (Lewis et al. 2011). Trace metals have been found in *Avicennia* and *Barringtonia* species of Kerala mangroves showing variable metal accumulation (Thomas and Fernandez 1997). Similarly, trace metals have been reported from stems and leaves of Bhitarkanika mangroves with stem showing higher accumulation (Panda et al. 2013). Bioaccumulation of trace metals in leaves of mangroves from Pichavaram revealed higher concentration of Pb than the normal range of contamination factor reported for plants (Agoramoorthy et al. 2008). Mangroves

support various species like fishes and crabs with 60% of commercial fishes in Fiji and India (Lewis et al. 2011). Thus, it may pose threat for many fishes and crustaceans as roots of mangroves have higher accumulation capacity (Sandilyan and Kathiresan 2014). Other bottom dwelling faunal species like crabs, shrimps and filter feeders also face the risk of metal accumulation (Kaviraj and Guhathakurta 2004). Trace metals from mangrove environment can make up their way to human beings directly or indirectly via herbal medicine, honey, seafood and dairy products (Sandilyan and Kathiresan 2014). Recently, Pb and Cr concentration in important edible species of bivalves in the Vellar estuary were reported to be higher than the permitted WHO/EPA limits (Ponnusamy et al. 2014).

Mangrove ecosystems act as a trap for contaminants transported to the coastal ecosystems (Sandilyan and Kathiresan 2014), adversely affecting various species surviving there and ultimately affecting the food chain. Metal stress can weaken the mangrove vivacity (vigour) making it prone to pathological attacks (Awal 2014) and also affecting the general biodiversity in those habitats.

9.6   Summary and Conclusion

The increase of trace metals in the mangrove sediment may be attributed to many factors like the abundance of fine particles having a greater surface area, which increases precipitation of metals as hydroxide coating (mainly Fe and Mn) over them. Factors like high organic matter content, flocculation due to varying salinity and transportation of deep shore sediments to the coastal zone also contribute significantly towards enrichment of heavy metals in sediments. The high values of metals like Fe and Mn in the mangrove sediment could be attributed to the precipitation of the respective metal sulphide compounds in anaerobic sediments. Fe-Mn also shows very close distribution pattern of enrichment in surface/subsurface layers of sediment cores which might be due to the early diagenetic processes as well as the strong association to the geochemical matrix between the two elements. The precipitated Fe in the form of oxyhydroxides has the affinity to scavenge other metals such as Cu and Pb, as they pass through the water en route to the sediment. Many trace metals like Cd, Cu, Pb and Zn have a wide range of sources, mainly anthropogenic, like untreated waste discharge from industries, agricultural runoff, sewage effluent and other surface runoffs. Tsunamigenic sediments show higher contamination factor, enrichment factor and potential ecological risk index than other mangrove sediments, which might be due to higher waste discharge at that time along with tsunami-driven sediments derived from the deep ocean. Thus, it shows that mangrove ecosystem act as the sink for trace metals; many mangrove species also act as a bioaccumulator of trace metals that after dying and degeneration enhances the trace metal concentration in mangrove ecosystem thus increasing its vulnerability.

References

Agoramoorthy G, Hsu MJ (2005) China's battle against escalating environmental pollution. Curr Sci 89:1073–1074

Agoramoorthy G, Chen FA, Hsu MJ et al (2008) Threat of heavy metal pollution in halophytic and mangrove plants of Tamil Nadu, India. Environ Pollut 155(2):320–326

Antizar-Ladislao B, Mondal P, Mitra S, Sarkar SK (2015) Assessment of trace metal contamination level and toxicity in sediments from coastal regions of West Bengal, eastern part of India. Mar Pollut Bull 101(2):886–894

Attri K, Kerkar S (2011) Seasonal assessment of heavy metal pollution in tropical mangrove sediments (Goa, India). J Ecobiotechnol 3(8):09–15

Awal MA (2014) Analysis of possible environmental factors causing top-dying in mangrove forest trees in the Sundarbanss in Bangladesh. Am J Biosci 2(4):135–146

Badarudeen A, Damodaran KT, Sajan K, Padmalal D (1996) Texture and geochemistry of the sediments of a tropical mangrove ecosystem, southwest coast of India. Environ Geo 27(3):164–169

Banerjee K, Senthilkumar B, Purvaja R, Ramesh R (2012) Sedimentation and trace metal distribution in selected locations of Sundarbans mangroves and Hooghly estuary, Northeast coast of India. Environ Geochem Health 34:27–42

Borges AV, Djenidi S, Lacroix G, Theate J, Delille B, Frankignoule M (2003) Atmospheric CO_2 fluxes from mangrove surrounding waters. Geophys Res Lett 30(11):12–14

Chakraborty R, Zaman S, Mukhopadhyay N, Banerjee K, Mitra A (2009) Seasonal variation of Zn, Cu and Pb in the estuarine stretch of west Bengal. Indian J Mar Sci 38(1):104–109

Chakraborty S, Bhattacharya T, Singh G, Maity JP (2014) Benthic macroalgae as biological indicators of heavy metal pollution in the marine environments: a biomonitoring approach for pollution assessment. Ecotoxicol Environ Saf 100:61–68

Chakraborty P, Ramteke D, Chakraborty S (2015) Geochemical partitioning of Cu and Ni in mangrove sediments: relationships with their bioavailability. Mar Pollut Bull 93(1):194–201

Chatterjee M, Massolo S, Sarkar SK, Bhattacharya AK, Bhattacharya BD, Satpathy KK, Saha S et al (2009) An assessment of trace element contamination in intertidal sediment cores of Sundarbans mangrove wetland, India for evaluating sediment quality guidelines. Environ Monit Assess 150:307–322

Chowdhury R, Favas PJC, Pratas J, Jonathan MP, Ganesh PS, Sarkar SK (2015) Accumulation of trace metals by mangrove plants in Indian Sundarban Wetland: prospects for phytoremediation. Int J Phytoremediat 17:885–894

Dias HQ, Nayak GN (2016) Geochemistry and bioavailability of mudflats and mangrove sediments and their effect on bioaccumulation in selected organisms within a tropical (Zuari) estuary, Goa, India. Mar Pollut Bull 105(1):227–236

Eckert JM, Sholkovitz ER (1976) The flocculation of Fe, Al and humates from river water by electrolytes. Geochim Cosmochim Acta 40(7):847–856

Ergin M, Saydam C, Baştürk Ö, Erdem E, Yörük R (1991) Heavy metal concentrations in surface sediments from the two coastal inlets (Golden Horn Estuary and Izmit Bay) of the northeastern sea of Marmara. Chem Geol 91(3):269–285

Esen E, Kucuksezgin F, El U (2010) Assessment of trace metal pollution in surface sediments of Nemrut Bay, Aegean Sea. Environ Monit Assess 160(1–4):257–266

Fernandes MC, Nayak GN (2016) Role of sediment size in the distribution and abundance of metals in a tropical (Sharavati) estuary, west coast of India. Arab J Geosci 9(1):1–3

Fernandes L, Nayak GN, Ilangovan D (2012) Geochemical assessment of metal concentrations in mangrove sediments along Mumbai Coast, India. World Acad Sci Eng Technol 6:1–26

Förstner U, Wittman GTW (1983) Metal pollution in the aquatic environment. Springer Science & Business Media, Berlin

FSI (2015) India state of forest report 2015: mangrove cover, forest survey of India (Ministry of Environment, Forests and Climate Change). Government of India, Dehradun, pp 62–67

Håkanson L (1980) An ecological risk index for aquatic pollution control, a sedimentological approach. Water Res 14:975–1001

Jonathan MP, Sarkar SK, Roy PD, Alam MA, Chatterjee M, Bhattacharya BD, Bhattacharya A, Satpathy KK (2010) Acid leachable trace metals in sediment cores from Sundarbans mangrove Wetland, India: an approach towards regular monitoring. Ecotoxicology 19:405–418

Kathiresan K, Bingham BL (2001) Biology of mangroves and mangrove ecosystems. Adv Mar Biol 40:81–251

Kaviraj A, Guhathakurta H (2004) Heavy metal deposition in some Brackish water ponds of Sundarbans (India) during off-season of shrimp culture. Asian Fish Sci 17:29–38

Kehrig HA, Pinto FN, Moreira I, Malm O et al (2003) Heavy metals and methyl mercury in a tropical coastal estuary and a mangrove in Brazil. Org Geochem 34(5):661–669

Kumar R (2000) Conservation and management of mangroves in India, with special reference to the state of Goa and the Middle Andaman Islands. Unasylva 203(51):41–46

Kumar A, Ramanathan AL (2015) Speciation of selected trace metals (Fe, Mn, Cu and Zn) with depth in the sediments of Sundarbans mangroves: India and Bangladesh. J Soils Sediments 15(12):2476–2486

Kumar G, Kumar M, Ramanathan AL (2015) Assessment of heavy metal contamination in the surface sediments in the mangrove ecosystem of Gulf of Kachchh, West Coast of India. Environ Earth Sci 74:545–556

Kumar A, Ramanathan AL, Prasad MBK, Datta D, Kumar M, Sappal SM (2016) Distribution, enrichment, and potential toxicity of trace metals in the surface sediments of Sundarbans mangrove ecosystem, Bangladesh: a baseline study before Sundarbans oil spill of December, 2014. Environ Sci Pollut Res 23:8985–8999

Lambert C, Veron A, Buatmenard P et al (1991) The role of large biogenic particles in the transport of atmospheric pollutant Pb down to north-Atlantic sediments. Oceanol Acta 14(1):67–76

Lee SV, Cundy AB (2001) Heavy metal contamination and mixing processes in sediments from the Humber Estuary, eastern England. Estuar Coast Shelf Sci 53:619–636

Leivouri M (1998) Heavy metal contaminants in surface sediments in the gulf of Finland and comparison with the gulf of Bothnia. Chemosphere 36:43–59

Lewis M, Pryor R, Wilkin L et al (2011) Fate and effects of anthropogenic chemicals in mangrove ecosystems: a review. Environ Pollut 159:2328–2346

Li XD, Wai OWH, Li YS, Seralathan P, Srinivasalu S, Ramanathan AL (2006) Post tsunami sediments characteristics of Tamilnadu coast. In: Rajamanickam GV (ed) 26th December 2004 tsunami causes, effects remedial measures, pre and post tsunami disaster management, a geoscientific perspective. New Academic Publisher, New Delhi, pp 190–215

Macfarlane GR, Koller CE, Blomberg SP (2007) Accumulation and partitioning of heavy metals in mangroves: a synthesis of field-based studies. Chemosphere 69:1454–1464

Marchand C, Lallier-verges E, Baltzer F, Albéric P, Cossa D, Baillif P (2006) Heavy metals distribution in mangrove sediments along the mobile coastline of French Guiana. Mar Chem 98:1–17

Mucha AP, Vasconcelos MTS, Bordalo AA (2003) Macrobenthic community in the Douro estuary: relations with trace metals and natural sediment characteristics. Environ Pollut 121(2):169–180

Muller G (1981) Die Schwermetallbelastung der Sedimenten des Neckars und Seiner Nebenflusse. Chemiker-Zeitung 6:157–164

Natesan U, Kumar M, Deepthi K (2014) Anthropogenic effects on sediment quality of Muthupet mangroves assessing the sediment core geochemical record. Indian J Mar Sci 43(6):1045–1054

Nobi EP, Dilipan E, Thangaradjou T, Sivakumar K, Kannan L (2010) Geochemical and geostatistical assessment of heavy metal concentration in the sediments of different coastal ecosystems of Andaman Islands, India. Estuar Coast Shelf Sci 87:253–264

Noronha-D'Mello CA, Nayak GN et al (2015) Geochemical characterization of mangrove sediments of the Zuari estuarine system, West coast of India. Estuar Coast Shelf Sci 167:313–325

Palpandi C, Kesavan K (2012) Heavy metal monitoring using *Nerita crepidularia* – mangrove mollusc from the Vellar estuary, Southeast coast of India. Asian Pac J Trop Biomed 2(1):S358–S367

Panda S, Chaturvedi N, Dhal N, Rout N (2013) An assessment of heavy metal accumulation in mangrove species of Bhitarkanika, Odisha, India. Res Plant Biol 3:1–5

Peters EC, Gassman NJ, Firman JC, Richmond RH, Power EA (1997) Ecotoxicology of tropical marine ecosystems. Environ Toxicol Chem 16:12–40

Ponnusamy K, Sivaperumal P, Suresh M, Arularasan S, Munilkumar S, Pal AK (2014) Heavy metal concentration from biologically important edible species of bivalves (*Perna viridis* and *Modiolus metcalfei*) from Vellar estuary, south east coast of India. J Aquacult Res Dev 5(5):1–5

Prajith A, Rao VP, Chakraborty P (2016) Distribution, provenance and early diagenesis of major and trace metals in sediment cores from the Mandovi estuary, western India. Estuar Coast Shelf Sci 170:173–185

Purvaja R, Ramesh R (2000) Human impacts on methane emission from mangrove ecosystems in India. Reg Environ Chang 1:86–97

Raman DJ, Jonathan MP, Srinivasalu S, Armstrong AJS, Mohan SP, Rammohan V (2007) Trace metal enrichments in core sediments in Muthupet mangroves, SE coast of India: application of acid leachable technique. Environ Pollut 145:245–257

Ramanathan AL, Subramanian V, Ramesh R, Chidambaram S, James A et al (1999) Environmental geochemistry of the Pichavaram mangrove ecosystem (tropical), southeast coast of India. Environ Geol 37(3):223–233

Ramaswamy V, Nath BN, Vethamony P, Illangovan D (2007) Source and dispersal of suspended sediment in the macro-tidal gulf of Kachchh. Mar Pollut Bull 54(6):708–719

Ramesh R, Kumar RA, Inamdar AB, Mohan PM, Pritiviraj M, Ramachandran S, Purvaja R, Chinkeri MK, Dolendro TH, Venkataraman G, Khire MV, Gedam SS, Rao YS, Adinarayana J, Nagarajan R (2006) Tsunami characterization and mapping in Andaman and Nicobar islands. In: Rajamanickam GV (ed) 26th December 2004 tsunami causes, effects remedial measures, pre and post tsunami disaster management, a geoscientific perspective. New Academic Publisher, New Delhi, pp 150–174

Ranjan RK, Ramanathan AL, Singh G, Chidambaram S (2008) Assessment of metal enrichments in tsunamigenic sediments of Pichavaram mangroves, southeast coast of India. Environ Monit Assess 147:389–411

Ranjan RK, Singh G, Routh J, Ramanathan AL (2013) Trace metal fractionation in the Pichavaram mangrove–estuarine sediments in southeast India after the tsunami of 2004. Environ Monit Assess 185:8197–8213

Ray AK, Tripathy SC, Patra S, Sarma VV (2006) Assessment of Godavari estuarine mangrove ecosystem through trace metal studies. Environ Int 32:219–222

Salomons W, Förstner U (1984) Sediments and the transport of metals. In: Metals in the hydrocycle. Springer, Berlin, p 63–98

Sandilyan S, Kathiresan K (2014) Decline of mangroves–a threat of heavy metal poisoning in Asia. Ocean Coast Manag 102:161–168

Sarangi RK, Kathiresan K, Subramanian AN (2002) Metal concentrations in five mangrove species of the Bhitarkanika, Orissa, east coast of India. Indian J Mar Sci 31(3):251–253

Sarkar SK, Bilinski SF, Bhattacharya AK, Saha M, Bilinski H (2004) Levels of elements in the surficial estuarine sediments of the Hugli River, northeast India and their environmental implications. Environ Int 30:1089–1098

Sarkar SK, Cabral H, Chatterjee M, Cardoso I, Bhattacharya AK, Satpathy KK, Aftab AMA (2008) Biomonitoring of heavy metals using the bivalve molluscs in Sundarbans mangrove wetland, Northeast coast of bay of Bengal (India): possible risks to human health. CLEAN – Soil Air Water 36(2):187–194

Seralathan P, Srinivasalu S, Ramanathan AL, Rajamanickam GV, Nagendra R, Singarasubramanian SR (2006) Post tsunami sediments characteristics of Tamilnadu Coast. In: Rajamanickam GV (ed) 26th December 2004 tsunami causes, effects remedial measures, pre and post tsunami disaster management, a geoscientific perspective. New Academic Publisher, New Delhi, pp 124–149

Silva CAR, Lacerda LD, Rezende CE (1990) Metals reservoir in a red mangrove forest. Biotropica 22(4):339–345

Subramanian AN (2004) Status of Indian mangroves: pollution status of the Pichavaram mangrove area, southeast coast of India. In: Vannucci M (ed) Mangrove management and conservation. United Nations University Press, Tokyo, pp 59–75

Thomas G, Fernandez TV (1997) Incidence of heavy metals in the mangrove flora and sediments in Kerala, India. In: Asia-Pacific Conference on Science and Management of Coastal Environment, Springer, p 77–87

Tomlinson DL, Wilson JG, Harris CR, Jeffrey DW (1980) Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. Helgoländer Meeresun 33(1–4):566–575

Veerasingam S, Vethamony P, Mani Murali R, Fernandes B (2015) Depositional record of trace metals and degree of contamination in core sediments from the Mandovi estuarine mangrove ecosystem, west coast of India. Mar Pollut Bull 91:362–367