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RESEARCH ARTICLE

10.1029/2026GH002170

Key Points:

- A global comparison revealed large differences in metal pollution among major estuaries in India, China, and the United States
- Combining Pollution Load Index and the new Population Normalized Pollution Load helped assess pollution and population pressure
- Long-term monitoring and environmental policies were found to be effective in reducing estuarine metal pollution

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Chatterjee, S., Chakraborty, P., Das, A., Roy, G., Mohanta, S., & Chakraborty, S. (2026). Tracking temporal changes in metal pollution in estuarine sediments: Population pressure, pollution trends, and policy responses in India, China, and the USA. *GeoHealth*, *10*, e2026GH002170. https://doi.org/10.1029/2026GH002170

Received 23 AUG 2026
Accepted 13 OCT 2026

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Tracking Temporal Changes in Metal Pollution in Estuarine Sediments: Population Pressure, Pollution Trends, and Policy Responses in India, China, and the USA

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Abstract This study introduces the Population Normalized Pollution Load (PNPL) as a complementary approach to the Pollution Load Index (PLI) to evaluate sediment metal contamination in relation to population pressure. A global comparative assessment of sediment metal contamination was conducted across major estuarine systems from India, China, and the United States using published data sets. The PLI ranked the investigated estuaries from least to most polluted as: Galveston Bay < Yellow River Estuary < Hudson Estuary < Hooghly (Ganga) Estuary < Mahanadi Estuary < Yangtze Estuary < Chesapeake Bay < Pearl River Estuary < Cochin Estuary < Ulhas Estuary. Temporal PLI trends revealed contrasting contamination trajectories, which reflected differences in historical pollution intensity, population pressure, and pollution control practices. The combined PLI–PNPL assessment indicated declining population-normalized contamination intensity in estuaries such as Mahanadi, Hooghly, Hudson River, and Galveston Bay, while Ulhas and Cochin continued to exhibit elevated contamination burdens. This study also assessed historical and ongoing environmental monitoring and pollution-control programs and their potential influence on sediment metal pollution, highlighting the need for sustained monitoring, effective wastewater management, and consistent policy implementation. The combined use of PLI and PNPL provided a more comprehensive assessment of estuarine contamination by considering both the overall sediment pollution burden and the associated population pressure. This approach could be adopted in future studies to provide a broader understanding of estuarine contamination patterns.

Plain Language Summary Globally, estuaries receive pollutants from adjacent urban areas, industries, agricultural activities, and other land-based sources. As populations grow, the pressure on these environments is expected to increase. This study examines how metal pollution in estuarine sediments has changed over time in major estuaries of India, China, and the United States. Pollution levels from different time periods were compared using the Pollution Load Index (PLI) and a new Population Normalized Pollution Load (PNPL) index. While PLI shows the overall level of metal contamination, PNPL helps determine whether changes in pollution are related to population growth and increasing human pressure. The results show that estuaries in the three countries have followed different pollution trajectories. In some systems, pollution relative to population pressure has declined, suggesting possible improvements in pollution status, whereas other estuaries continue to experience substantial metal contamination. By comparing these changes with environmental monitoring and pollution-control programs, the study provides insights into the possible role of environmental policies in improving sediment quality. Overall, this study highlights the importance of considering population pressure, pollution trends, and policy responses together when evaluating long-term changes in estuarine metal pollution. The findings may support future monitoring, pollution-control strategies, and sustainable estuarine management.

1. Introduction

Rapid industrialization and economic growth have resulted in increasing inputs of potentially toxic elements into estuarine systems through multiple anthropogenic pathways (Chakraborty et al., 2010). Once introduced into estuaries, a substantial proportion of these contaminants is scavenged and accumulated in bottom sediments (Chapman & Wang, 2001, 2). As a result, sediment metal contamination has emerged as a major environmental concern worldwide (Burton Jr & Scott, 1992; Caccia et al., 2003; Zhang et al., 2007). However, contamination

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levels vary considerably among estuaries owing to differences in anthropogenic pressures and the effectiveness of different policies and pollution-control measures. Despite this variability, comparative evaluations of temporal contamination trends across estuaries with contrasting development trajectories remain scarce. To address this knowledge gap, the present study compiled published sediment metal concentration data spanning several decades and used these data to compare contamination trajectories among estuaries from India, China, and the United States.

These three countries were selected because they represent three of the world's largest economies with contrasting stages of industrialization, urbanization, and environmental governance. Such differences provide a unique opportunity to evaluate how varying development pathways and environmental policies shape the history of sediment metal pollution. The Pollution Load Index (PLI) was, therefore, used to compare sediment metal contamination trajectories across these estuaries.

The study considered 10 representative and extensively studied estuarine systems: Hooghly Estuary (eastern India, Bay of Bengal), Mahanadi Estuary (eastern India, Bay of Bengal), Cochin Estuary (southwestern India, Arabian Sea), Ulhas Estuary (western India, Arabian Sea), Chesapeake Bay (Mid-Atlantic USA, Atlantic Ocean), Galveston Bay (Texas, Gulf of Mexico), Hudson River Estuary (northeastern USA, Atlantic Ocean), Yangtze Estuary (eastern China, East China Sea), Yellow River Estuary (northern China, Bohai Sea), and Pearl River Estuary (southern China, South China Sea). These estuaries were selected based on their geographical representation, population density and extent of urbanization within and adjacent to the estuarine systems, anthropogenic pressures, environmental and socio-economic importance, environmental management and pollution-control policies, and availability of published data on metal contamination and environmental quality.

Based on these contrasting settings, it is hypothesized that sediment metal contamination is governed not only by the intensity of anthropogenic activities but also by the effectiveness of pollution-control and environmental management programs. Accordingly, the objectives of this study were to: (a) evaluate temporal changes in sediment metal contamination using the PLI; and (b) examine the influence of pollution-control measures and environmental management programs on sediment quality. The findings are expected to improve our understanding of how anthropogenic activities and the implementation of environmental policies influence long-term sediment metal contamination trends.

2. Study Areas

The locations of the 10 selected estuaries are shown in Figure 1. The 10 estuaries selected for this study (Hooghly, Mahanadi, Cochin, and Ulhas in India; Chesapeake Bay, Hudson River, and Galveston Bay in the United States; and Yangtze, Pearl River, and Yellow River in China) represent diverse climatic, hydrological, socioeconomic, and industrial settings. Together, they provide an appropriate basis for evaluating long-term sediment metal contamination under contrasting anthropogenic pressures and environmental management regimes.

In India, the Hooghly Estuary is impacted by municipal wastewater, industrial effluents, agricultural runoff, and port-related discharges from the Kolkata metropolitan region (>15 million inhabitants) and numerous upstream cities (Sadhuram et al., 2005). The Ulhas Estuary is affected by large volumes of municipal wastewater and industrial effluents from the Mumbai Metropolitan Region (>20 million inhabitants), one of India's largest industrial corridors (Fernandes & Nayak, 2012; Thomas et al., 2019). The Cochin Estuary is affected by anthropogenic inputs from Kochi, a major port city with petrochemical, fertilizer, shipbuilding, seafood processing, and chemical industries (Sarkar et al., 2016; Shyleshchandran et al., 2018; Verma et al., 2002). The Mahanadi Estuary receives inputs from the industrial belt extending across Cuttack, Paradip, and Talcher, which includes steel, aluminum, thermal power, fertilizer, and mining industries (Sundaray et al., 2014; Swain et al., 2021).

In the United States, the Chesapeake Bay is influenced by the Baltimore-Washington metropolitan corridor and receives large volumes of effluents from urban development, agriculture, and wastewater treatment facilities (Boesch & Goldman, 2009). The Hudson River Estuary is affected by substantial urban runoff, industrial discharges, and legacy contamination from the New York metropolitan area (Harmon et al., 2003; Rodenburg et al., 2011). Galveston Bay is adjacent to Houston, one of the world's largest petrochemical and energy hubs, and is affected by petroleum refining, chemical manufacturing, shipping, and municipal discharges (Harmon et al., 2003; Santschi et al., 2001).

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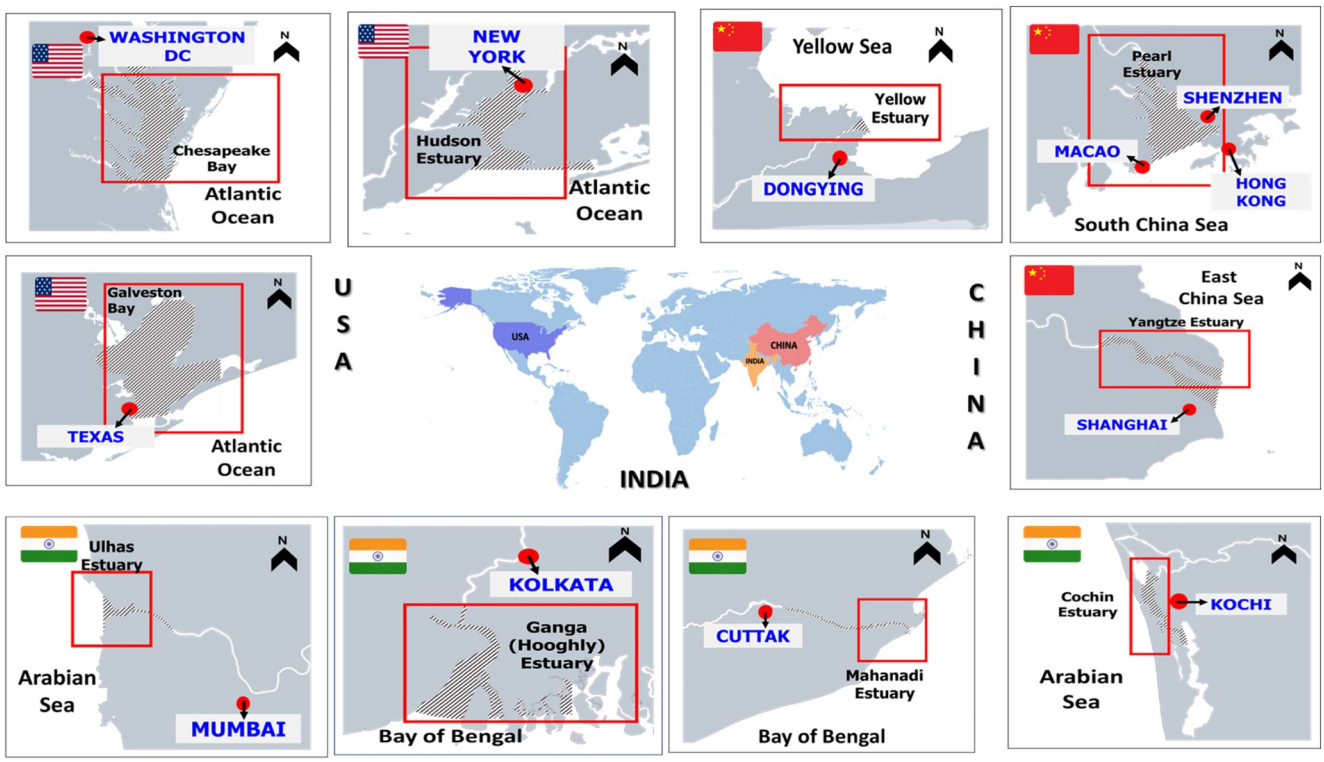


Figure 1. Study area maps showing the geographic locations of the estuarine systems investigated in this study across India, the USA, and China. The Indian systems include the Ulhas, Vembanad Lake (Cochin), Hooghly (Ganga), and Mahanadi estuaries; the US systems include the Hudson, Galveston Bay, and Chesapeake Bay estuaries; and the Chinese systems include the Yangtze, Yellow, and Pearl River estuaries.

In China, the Yangtze Estuary is influenced by Shanghai and the Yangtze River Delta, a global center for manufacturing, electronics, petrochemicals, and shipping (Adeleye et al., 2016; Chen et al., 2001). The Pearl River Estuary receives contaminants from industrial discharges and urban runoff from Guangzhou, Shenzhen, and Hong Kong (Ma et al., 2024; Ye et al., 2012). The Yellow River Estuary is impacted by oil extraction, petrochemical industries, agriculture, and rapid urban expansion in northern China (Qin et al., 2024; Tang et al., 2010).

3. Materials and Methods

3.1. Bibliometric Analysis

A bibliometric analysis was performed to evaluate temporal trends in research on metal contamination in estuarine sediments. Publications were retrieved from the Scopus and Web of Science databases using predefined search keywords (Table S1 in Supporting Information S1) (Chatterjee et al., 2026). The literature search covered publications up to December 2025. After screening for relevance and removing duplicates, a total of 1,323 publications were identified. Of these, approximately 150 publications contained sufficient quantitative data on sediment metal concentrations and were therefore considered for the comparative pollution assessment. A standardized data-screening procedure was followed. Surface sediment data from clearly identified estuarine sampling locations were selected, and information on sampling year, analytical method, and metals analyzed was recorded. Studies lacking sufficient information on sampling characteristics, analytical procedures, or metal concentrations were excluded.

3.2. Assessment of Sediment Metal Contamination

Published sediment metal concentration data were compiled from the literature to calculate the contamination factor (CF) and Pollution Load Index (PLI) for assessing sediment metal contamination in the selected estuaries. The CF was calculated as follows:

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$$CF = \frac{\text{Metal content in the sediment}}{\text{Background value of metal}}$$

Upper Continental Crust metal concentrations (Rudnick & Gao, 2003) were used as background values. All the data are presented in Table S1 in Supporting Information S1 (Chatterjee et al., 2026).

The PLI was calculated using the following formula proposed by Tomlinson et al. (1980):

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

Where, CF_1–CF_n represent the contamination factors of individual metals, and n is the total number of metals included in the calculation. Pollution levels were interpreted using the PLI classification proposed in the literature (Suwanmanon & Kim et al., 2021) (Table S2 in Supporting Information S1) (Chatterjee et al., 2026), where PLI values of 0–1 indicate unpolluted conditions, 1–2 unpolluted to moderately polluted conditions, 2–3 moderately polluted conditions, 3–4 moderately to highly polluted conditions, 4–5 highly polluted conditions, and >5 very highly polluted conditions.

3.3. Assessment of Temporal Changes in Sediment Quality Using the PLI

To evaluate temporal changes in sediment metal contamination, published sediment metal concentration data were compiled for two distinct periods representing historical and recent conditions. Owing to differences in the availability of published data among estuaries, a uniform historical time period could not be adopted. Therefore, for each estuary, the earliest available data set, which was approximately 25–30 years older than the most recent data set for the same estuary, was used to calculate the historical PLI, whereas data from studies published within the last five years were used to calculate the recent PLI. Average PLI values were calculated separately for the historical and recent data sets for each estuary. When multiple PLI values were available for an estuary in the same sampling year, their arithmetic mean was calculated and used as the representative PLI for that year. The percentage change in PLI between the two periods was calculated using the following equation:

$$\%\Delta PLI = \frac{PLI_{historical} - PLI_{recent}}{PLI_{historical}} \times 100$$

Where $PLI_{historical}$ and PLI_{recent} represent the average PLI values the historical and recent periods, respectively. Positive percentage changes indicate a decrease in PLI and, therefore, an improvement in sediment quality, whereas negative percentage changes indicate an increase in PLI, reflecting deterioration in sediment quality over time.

It is important to note that the PLI-based assessment has inherent limitations, including differences in the temporal availability of published data, spatial heterogeneity in sampling locations, variations in analytical methodologies, and the use of UCC values as a common geochemical background. Therefore, in this study, the results are interpreted as indicators of broad temporal patterns in sediment metal contamination rather than as direct measures of ecological risk or ecosystem health.

3.4. Methodology for Estimating Temporal Variation of Population Normalized Pollution Load (PNPL)

Population and area data were compiled for the districts adjacent to the selected Indian estuaries. Decennial population data for 1901–2011 were obtained from the Census of India (2011) (Tables A–01 and A–02; https://censusindia.gov.in/census.website/data/census-tables). For the U.S. estuaries, decennial population data for 1790–2020 were obtained from the National Historical Geographic Information System (Schroeder et al., 2026), while the corresponding county area data were obtained from the U.S. Census Bureau (2026) (https://www.census.gov/geographies.html). Population data were obtained from successive decennial census records. Population values for years between census years were estimated by interpolation, while values for years beyond the most recent census were projected using fitted mathematical models. Detailed descriptions are provided in Supporting Information S1 (Chatterjee et al., 2026). The Population Normalized Pollution Load (PNPL) was then calculated

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to normalize the pollution load according to the population size of the respective estuarine regions using the following expression:

$$\text{PNPL} = \text{PLI} \times \frac{\text{Total Area}}{\text{Total Population}}$$

Temporal variation of PNPL was established using PNPL and year data in MS Excel 2019 and coefficient of determination (R^2) was determined.

3.5. Compilation of Pollution-Control and Environmental Management Information

Information on pollution-control policies, environmental regulations, wastewater management programmes, and estuarine restoration initiatives was compiled from government reports, official policy documents, peer-reviewed publications, and reports issued by national and regional environmental agencies. For each estuary, emphasis was placed on identifying the major management interventions implemented during the study period, including their timing and scope. The compiled information was subsequently used to interpret temporal changes in the Pollution Load Index (PLI) and to examine whether changes in sediment metal contamination corresponded with the implementation of pollution-control measures and environmental management programmes.

4. Results and Discussion

Total metal concentrations in sediments from the different estuaries across different parts of the world are presented in Tables S3 (India), S4 (USA), and S5 (China) in Supporting Information S1, and the corresponding contamination factors are provided in Tables S6 (India), S7 (the USA), and S8 (China) in Supporting Information S1 (Chatterjee et al., 2026). Variations in PLI from different estuaries are presented in Figure 2 (Table S9 in Supporting Information S1) (Chatterjee et al., 2026).

4.1. Temporal Changes in Sediment Metal Contamination in Indian Estuaries

The Indian estuaries exhibited contrasting temporal trends in sediment metal contamination, reflecting differences in anthropogenic pressures, pollution sources, and the effectiveness of pollution-control measures over time. The Ulhas and Cochin estuaries showed persistent and highly variable contamination patterns, respectively, whereas the Hooghly and Mahanadi estuaries displayed an overall declining trend in contamination levels in the most recent assessment period.

The Ulhas Estuary exhibited one of the most severe and persistent contamination patterns among the Indian estuaries assessed. PLI values remained consistently high throughout the study period (Figure 2a), ranging from 3.27 to 4.66. Values exceeded 3 from the mid-1980s to 2023, indicating sustained high levels of sediment metal contamination. Although temporal fluctuations were observed, no clear declining trend was evident over the assessment period. The consistently elevated PLI values suggest that ongoing inputs from urban, industrial, and port-related activities within the Mumbai metropolitan region have maintained metal enrichment in sediments, pointing to potential limitations in current pollution-control measures in fully mitigating contaminant inputs.

In contrast to the Ulhas Estuary, the Cochin Estuary exhibited substantial temporal variability in PLI values, ranging from 0.97 to 6.60 (Figure 2b). A pronounced increase in contamination was observed during the mid-2010 s, when PLI values exceeded 6, indicating severe metal enrichment in sediments. Conversely, the lowest PLI value (0.97) was recorded in 2021 (Narayana et al., 2021), which coincides temporally with reduced anthropogenic activities during the COVID-19 pandemic (Kulk et al., 2021; Yunus et al., 2020); however, variations in sampling conditions and sediment dynamics cannot be ruled out. Subsequent observations indicate a renewed increase in PLI values, suggesting that the decline observed in 2021 was temporary rather than indicative of sustained improvement in sediment quality. The marked temporal variability observed in the Cochin Estuary highlights the association between changing anthropogenic pressures, particularly those arising from industrial, port-related, and urban activities, and sediment metal contamination dynamics.

However, the Hooghly Estuary (also known as the Ganga Estuary) exhibited a gradual decline in sediment metal contamination over the recent assessment period. PLI values ranged from 0.61 to 2.66 (Figure 2c), with the

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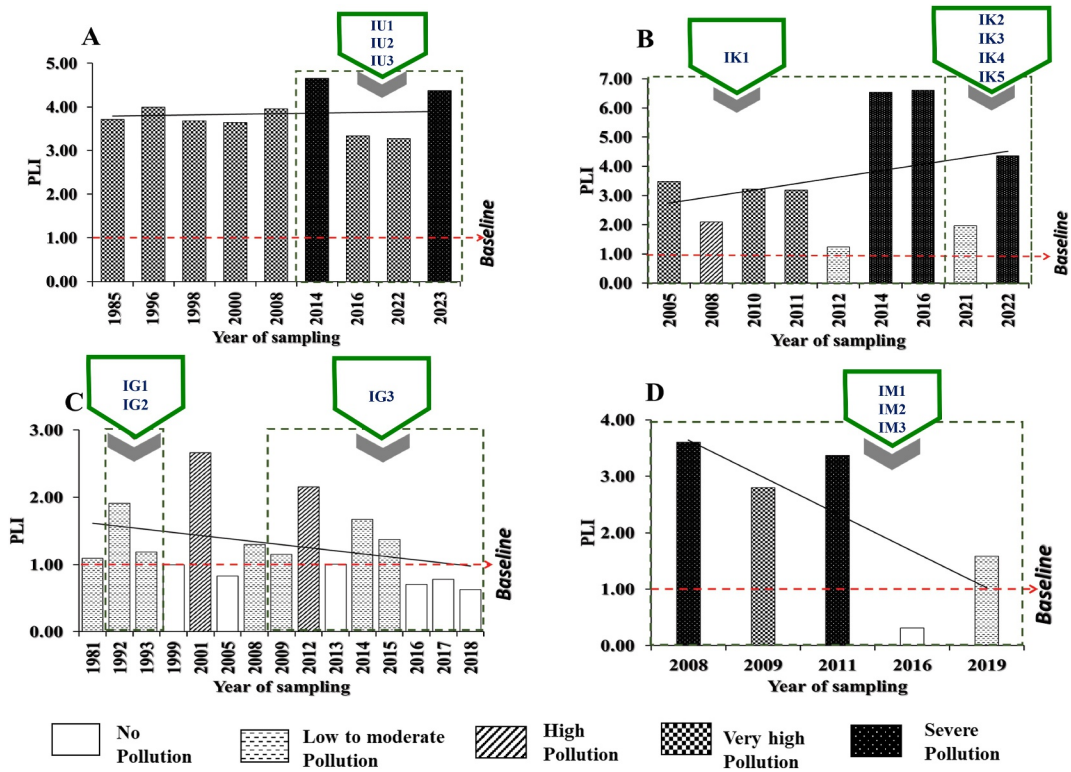


Figure 2. Changes in bed-sediment pollution load index over time in Indian estuaries (Policies and programs organized by the governments of different countries to reduce pollution presented in Brackets): (a) Ulhas River [IU1: Ulhas River Conservation Project; IU2: Ulhas Action Plan; IU3: NGT order (OA 637/2018)]; (b) Vembanad Lake [IK1: Vembanad Wetland Conservation Program, IK2: Integrated Management Plan; IK3: Eco-Restoration Strategy—Kochi Sector Program; IK4: Kerala Cleanup Project; IK5: Vembanad Lake Rejuvenation Project]; (c) Ganga River [IG1: Swachha Ganga Abhiyan; IG2: Ganga Action Plan-Phase; IG3: Namami Gange Program]; and (d) Mahanadi River [IM1: National River conservation plan—Mahanadi Stretches; IM2: Green Mahanadi Mission; IM3: Mahanadi Riverfront Development Project].

highest contamination recorded in 2001 (Samanta et al., 2007). Elevated PLI values persisted until 2012, followed by a gradual decrease, reaching a minimum value of 0.61 after 2015 (Sarkar et al., 2017).

A similar declining trend was observed in the Mahanadi Estuary, although sediment contamination exhibited considerable spatial and temporal variability. PLI values ranged from 0.31 to 5.00 (Figure 2d), with elevated values during 2008–2011 indicating moderate to high levels of metal contamination. The broad range of PLI values recorded in 2011 (1.55–5.00) reflects pronounced spatial heterogeneity, likely arising from differences in sediment characteristics, sampling locations, and proximity to contaminant sources (Khadanga et al., 2022; Sundaray et al., 2011, 2014). A substantial decline in PLI was observed in subsequent years, reaching a minimum value of 0.31 in 2019 (Swain et al., 2021). However, recent increases in PLI values indicate the continued influence of localized pollution sources affecting sediment quality. These findings suggest that, although overall sediment quality has improved, localized contamination hotspots may persist due to site-specific pollutant inputs and ongoing anthropogenic pressures.

Collectively, the Indian estuaries demonstrate that long-term sediment metal contamination is controlled by the magnitude, persistence, and spatial distribution of anthropogenic inputs. The elevated PLI values observed during earlier decades, particularly between the 1970s and 1990s, correspond temporally with periods of rapid industrialization, urban expansion, and increased wastewater discharge. In contrast, declining contamination trends observed in some estuaries in recent decades indicate periods of overall improvement in sediment quality metrics. However, the persistence of localized enrichment highlights the continued influence of site-specific pollution sources and emphasizes the need for sustained monitoring and effective management strategies.

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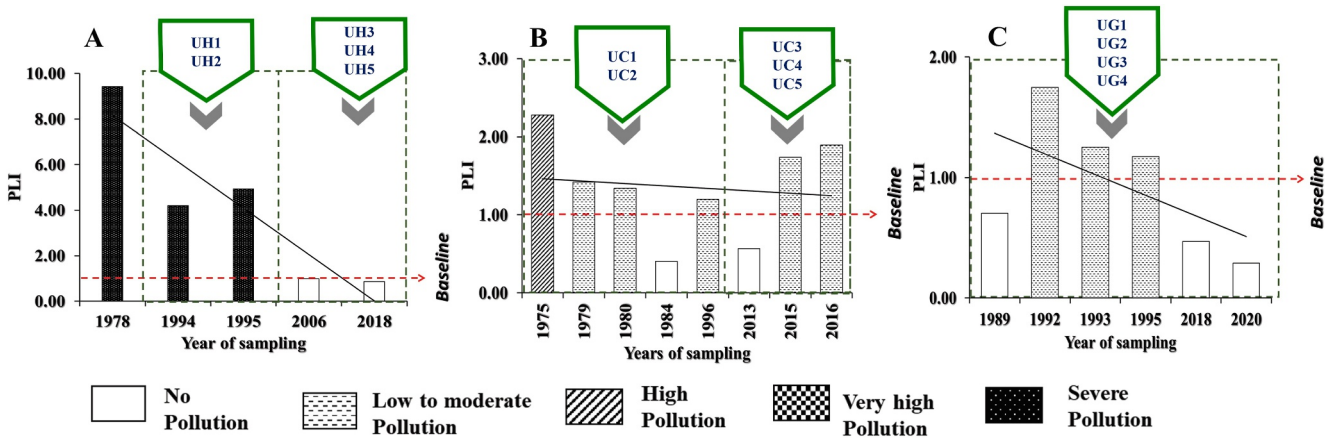


Figure 3. Temporal changes in the pollution load index of bed sediments in selected estuaries of the USA (Policies and programs organized by the governments of different countries to reduce pollution presented in Brackets)—(a) Hudson River [UH1:– Hudson River Estuary Management Program; UH2: New York-New Jersey Harbor and Estuary program; UH3: Hudson River Estuary Management Program (Phase-1-2009 Target); UH4: Hudson River PCBs Superfund Cleanup; UH5: Hudson River Estuary Management Program (Phase-2 Habitat/Resilience)] (b) Chesapeake Bay [UC1: Chesapeake Bay Program; UC2: Chesapeake Bay Agreement (40%-Nutrients); UC3: Chesapeake 2000; UC4: Chesapeake Bay total maximum daily load; UC5: Watershed Program] and (c) Galveston Bay [UG1: Adopt a beach program; UG2: Galveston Bay Estuary Program; UG3: The Galveston Bay Plan (CCMP); UG4: Trash Bash].

4.2. Temporal Changes in Sediment Metal Contamination in Major U.S. Estuaries

Changes in sediment PLI across the three major U.S. estuaries are presented in Figure 3 and data are presented in Table S9 in Supporting Information S1 (Chatterjee et al., 2026).

The three major U.S. estuaries exhibited contrasting temporal trends in sediment metal contamination, reflecting differences in historical anthropogenic pressures, pollution sources, and environmental management practices. The Galveston Bay and Hudson River estuaries showed a clear long-term decline in sediment contamination, whereas the Chesapeake Bay Estuary exhibited persistent temporal fluctuations without a sustained declining trend.

The Galveston Bay Estuary exhibited considerable temporal variability in sediment metal contamination (Figure 3a), with PLI values ranging from 0.29 to 1.75. Relatively low contamination during the early 1990s (PLI = 0.70; Morse et al., 1993) was followed by a sharp increase during the mid-1990s (PLI = 1.75; Carr et al., 1996), after which PLI remained moderately elevated for nearly a decade (PLI = 1.17–1.25; Park & Presley, 1997; Santschi et al., 2001). Thereafter, contamination declined progressively, reaching low PLI values during the most recent assessment period (PLI = 0.29 in 2020; Yakubu & Atobiloye, 2024; PLI = 0.47; Lopez et al., 2022). Overall, the temporal trend indicates a substantial improvement in sediment quality over the past two decades.

The Hudson Estuary exhibited the highest historical sediment contamination among the three U.S. estuaries (Figure 3b), with PLI values ranging from 0.86 to 9.43. Exceptionally high contamination recorded during the late 1970s (PLI = 9.43; Williams et al., 1978) declined progressively over subsequent decades, although sediments remained highly contaminated through the 1990s (PLI = 4.93–3.48; Feng et al., 1998, 2002). A marked reduction in PLI was observed thereafter (PLI = 0.99; Gilchrist et al., 2009), with values falling below unity during the most recent assessment (PLI = 0.86; Urbaniak et al., 2020). Overall, the Hudson Estuary exhibited the greatest long-term improvement in sediment quality, reflecting a substantial reduction in sediment metal contamination over the past four decades.

In contrast, the Chesapeake Bay Estuary exhibited pronounced temporal variability in sediment metal contamination without a consistent long-term declining trend (Figure 3c). PLI values ranged from 0.40 to 2.28, with the highest contamination reported during the 1970s (PLI = 2.28; Goldberg et al., 1978). Although contamination declined during the late 1980s (PLI = 0.40; Helz et al., 1985), PLI values fluctuated around the turn of the century before declining around 2012 (PLI = 0.57, Krahforst et al., 2022). However, PLI increased again during the most recent assessment (PLI = 1.74–1.90; Russ et al., 2020). Overall, the Chesapeake Bay Estuary exhibited repeated phases of improvement and deterioration, indicating persistent temporal variability in sediment contamination.

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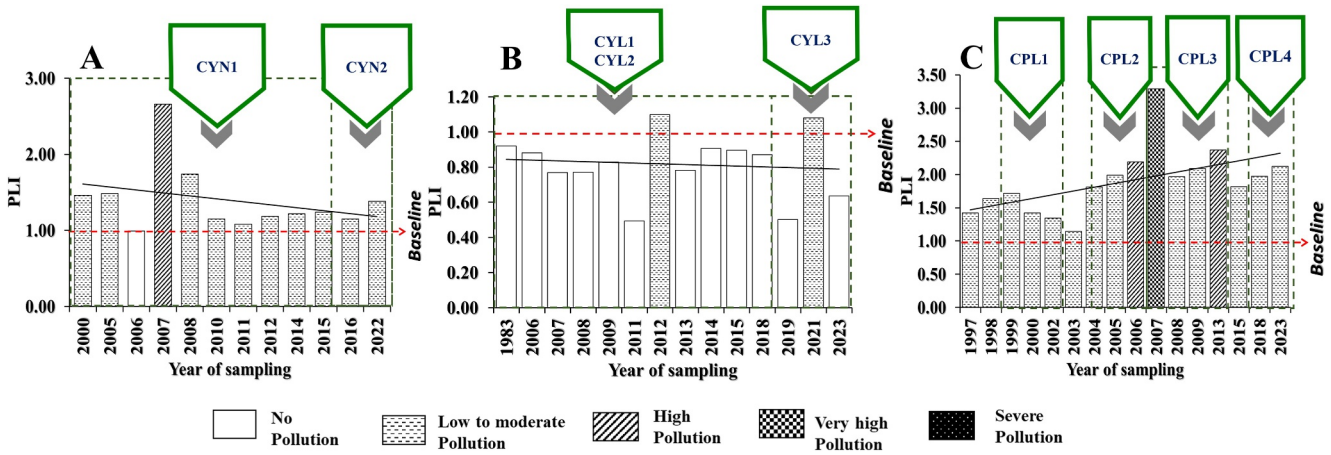


Figure 4. Temporal variation in the pollution load index of bed sediments across major estuarine systems of China (Policies and programs organized by the governments of different countries to reduce pollution presented in Brackets), (a) Yangtze River [CYN1: Yangtze Estuary Wetland Restoration Projects; CYN2: Action Plan for the Protection and Restoration of the Yangtze River; CYN3: Redline Policy-Yangtze River Economic Belt (YREB) Ecological Redline Policy; CYN4 Yangtze River Protection and Ecological Restoration Program (P171644)], (b) Yellow River [CYL1: Yellow River Delta National Nature Reserve; CYL2: water-sediment reglation scheme; CYL3: Yellow River ecological corridor Program; CYL4: Yellow River Basin Ecological Protection and Environmental Pollution Control Program (P172806)], and (c) Pearl River [CPL1: Pearl River estuary pollution project; CPL2: Guangdong Pearl River Delta Urban Environment Project; CPL3: Second Guangdong Pearl River Delta Urban Environment Project; CPL4: Guangdong Provincial Water Pollution Control Plan].

Overall, the exceptionally high PLI values reported during the 1970s may reflect the combined influence of intensive industrialization, urban discharges, and comparatively limited environmental regulation during that period. However, these values should also be interpreted in the context of substantial changes in sampling strategies and analytical methodologies over the past three decades. Earlier studies may have been subject to greater uncertainties associated with sample collection and preparation, contamination control, detection limits, and instrumental sensitivity, potentially contributing to greater variability and, in some cases, elevated reported contaminant concentrations. In contrast, the declining contamination observed in the Galveston Bay and Hudson River estuaries in recent decades suggests that strengthened environmental regulations, improved wastewater treatment, and reduced industrial emissions have contributed to the recovery of sediment quality. However, the fluctuating contamination pattern in the Chesapeake Bay Estuary indicates that localized pollution sources and variable contaminant inputs continue to influence sediment metal contamination despite broader improvements in environmental management.

4.3. Temporal Changes in Sediment Metal Contamination in Major Chinese Estuaries

Figure 4 and Table S9 in Supporting Information S1 (Chatterjee et al., 2026) present the temporal changes in sediment PLI across the three major Chinese estuaries. The three major Chinese estuaries exhibited contrasting temporal trends in sediment metal contamination, reflecting differences in anthropogenic pressures, industrial development, and watershed characteristics. The Yangtze and Pearl River estuaries displayed pronounced temporal variability with recurrent episodes of elevated metal enrichment, whereas the Yellow River Estuary generally maintained relatively low contamination levels despite occasional fluctuations.

The Yangtze Estuary displayed marked temporal fluctuations in sediment PLI (Figure 4a), with values ranging from 0.82 to 2.66. Moderate contamination was evident around 2000 (PLI = 1.46; Yang et al., 2004), followed by considerable variability, with periods of relatively low PLI values (0.88–1.07; An et al., 2009; H. Liu et al., 2015) and subsequent deterioration, reaching the highest recorded value (2.66; H. Liu et al., 2016; R. Liu et al., 2016). Thereafter, PLI declined to comparatively lower levels during 2014–2016 (0.94–1.15; Han et al., 2017; Zhuang & Zhou, 2021), before increasing again in the most recent assessment (1.38; Zhang et al., 2025). Overall, the Yangtze Estuary exhibited substantial temporal variability, characterized by alternating periods of improvement and deterioration rather than a consistent long-term trend.

The Yellow River Estuary exhibited the lowest sediment metal enrichment among the three Chinese estuaries (Figure 4b), with PLI values ranging from 0.44 to 1.28. Sediment quality remained relatively stable from the early 1980s through the early 2000s (PLI = 0.88–0.96; Li et al., 1985; Zhang et al., 1988), followed by a moderate

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increase in 2012 (PLI = 1.28; H. Liu et al., 2015). Subsequently, PLI declined progressively, reaching its lowest value in 2019 (0.44; Wang et al., 2022). Although a temporary increase was observed in 2021 (1.08; Hu et al., 2024), recent assessments indicate comparatively low values (0.59–0.80; Li et al., 2024; S. S. Liu et al., 2025). Overall, the Yellow River Estuary exhibited relatively low sediment metal contamination, with only occasional increases in PLI values during the assessment period.

In contrast, the Pearl River Estuary showed the highest contamination intensity and greatest temporal variability among the three Chinese estuaries (Figure 4c), with PLI values ranging from 1.00 to 3.29. Moderate enrichment during the late 1990s (PLI = 1.42–1.72; Li et al., 2000; Zhang & Wang, 2001; Zhou et al., 2004) intensified markedly during the mid-2000s, when PLI increased to 3.03 (Li et al., 2007) and reached the highest recorded value (3.29; Yang et al., 2014). Although subsequent periods showed partial recovery, with PLI declining to 1.68–1.86 during 2008 and further to 1.06 in 2015 (Zhao et al., 2019), recent assessments indicate renewed deterioration (2.12; Sun et al., 2024). Overall, the Pearl River Estuary experienced persistent metal enrichment with alternating phases of deterioration and recovery, reflecting sustained anthropogenic pressures within one of China's most industrialized and densely populated watersheds.

Overall, sediment PLI trends across the major Chinese estuaries reveal pronounced spatial and temporal variability in metal contamination. The Yellow River Estuary consistently exhibited the lowest contamination levels, whereas the Yangtze and Pearl River estuaries experienced recurrent episodes of elevated PLI associated with changing anthropogenic pressures. These contrasting patterns likely reflect differences in industrialization, urbanization intensity, population density, riverine contaminant inputs, and regional environmental management practices.

4.4. Assessment of Current Estuarine Pollution Status Using Recent PLI Values

The present contamination status of the selected estuaries was evaluated using recent PLI values calculated as the average of the latest data reported in the literature during the past 4 years (Table 1). Among the Indian estuaries, the Hooghly (Ganga) Estuary exhibited the lowest recent PLI value (0.90), closely followed by the Mahanadi Estuary (0.93), indicating relatively low levels of sediment metal contamination. In contrast, the Cochin Estuary showed substantially higher contamination (PLI = 3.05), while the Ulhas Estuary exhibited the highest recent PLI (3.86) among all estuaries assessed in this study.

Among the U.S. estuaries, Galveston Bay exhibited the lowest recent PLI (0.37), followed by the Hudson Estuary (0.85), whereas Chesapeake Bay showed comparatively higher contamination (PLI = 1.40). Among the Chinese estuaries, the Yellow River Estuary exhibited the lowest recent PLI (0.76), followed by the Yangtze Estuary (1.23), while the Pearl River Estuary recorded the highest recent PLI (2.02).

Overall, the estuaries were ranked in ascending order of recent sediment metal contamination as follows: Galveston Bay < Yellow River Estuary < Hudson Estuary < Hooghly (Ganga) Estuary < Mahanadi Estuary < Yangtze Estuary < Chesapeake Bay < Pearl River Estuary < Cochin Estuary < Ulhas Estuary.

These contrasting patterns likely reflect differences in industrialization, urbanization, watershed characteristics, contaminant inputs, and the effectiveness of pollution-control measures. However, the present contamination status alone does not fully capture the extent of environmental recovery or deterioration over time. Therefore, long-term changes in PLI were evaluated to provide additional insights into the temporal trajectories of sediment contamination and possible associations with pollution-control measures across estuarine systems.

4.5. Ranking of Estuaries Based on Long-Term PLI Improvement

To evaluate long-term changes in sediment quality, the percentage change in PLI between historical and recent assessments was calculated for each estuary. Among the Indian estuaries, the Mahanadi (70.46%) and Hooghly (37.76%) estuaries exhibited substantial reductions in PLI, indicating considerable improvements in sediment quality over time, whereas the Ulhas Estuary (−1.41%) showed only marginal change despite remaining highly contaminated, and the Cochin Estuary (−7.95%) exhibited a slight increase in PLI, indicating deterioration in sediment quality. Among the U.S. estuaries, the Hudson Estuary (80.68%) showed the greatest improvement among all estuaries assessed, followed by Galveston Bay (68.96%), whereas the Chesapeake Bay (−2.89%) exhibited a slight increase in PLI. Among the Chinese estuaries, the Yellow River (16.03%) and Yangtze

Table 1
Overview of Estuary Clean-Up Policies and Programmes Undertaken by Governmental and Non-Governmental Organizations in India, the USA, and China

Estuary (Country)	Name of the program	Duration	Leading organisation
Ulhas (India)	• Ulhas River Conservation Project	2010–Present	Vanashakti NGO, Vanashakti, 2025
	• Ulhas action plan	2019–Present	Maharashtra Pollution Control Board (MPCB), 2019
	• River Rejuvenation Action Plan (NGT OA 673/2018)	2018–Present	Based on order of National Green Tribunal-*OA 673/2018*, Press Information Bureau, 2025
Ganges (India)	• Swachh Ganga Abhiyan	1982–Present	Sankat Mochan Foundation. Sankat Mochan Foundation, 2025
	• Ganga Action Plan	1986–1996	Government of India, Press Information Bureau, 1985
	• Namami Gange program	2014–Present	Government of India, National Mission for Clean Ganga 2014; Ministry of Environment, Forest and Climate Change, 2025
Vembanad lake/Cochin estuary (India)	• Vembanad Wetland Conservation Program (VWCP)	2005–Present	Ashoka Trust for Research in Ecology and the Environment (ATREE)
	• Integrated Management Plan	2018–2023	Kerala Center for Integrated Coastal Zone Management (KCICM)
	• Eco-Restoration Strategy—Kochi Sector Program	2021–Present	Earth5R, 2025
	• Kerala Cleanup Project	2023–Present	RiverRecycle Oy (Finland-based NGO specializing in river plastic interception). RiverRecycle, 2025; State Wetland Authority Kerala, 2026
	• Vembanad Lake Rejuvenation Project	2025–Present	Alappuzha District Administration, 2025
Mahanadi (India)	• National River Conservation Plan (NRCP)—Mahanadi Stretches	2000–Present	National River Conservation Directorate (NRCD) under the Ministry of Jal Shakti,
	• Green Mahanadi Mission, Forest, Environment & Climate Change Department, Government of Odisha, 2018	2018–2023	State Government of Odisha, India
	• Mahanadi Riverfront Development Project, 2026	2025–2028	Water Resources Development Department, Government of Odisha
Galveston Bay (USA)	• Adopt-A-Beach Program	1986–Present	Texas General Land Office (GLO), 2025
	• Galveston Bay Estuary Program (GBEP), 1989	1989–Present	Texas Commission on Environmental Quality (TCEQ)
	• The Galveston Bay Plan (CCMP)	1990–1995	Texas Commission on Environmental Quality (TCEQ) in Collaboration with the US-EPA, Galveston Bay Estuary Program, 1995
	• Trash Bash	1994–Present	Galveston Bay Foundation, Galveston Bay Estuary Program, 2025
Hudson (USA)	• Hudson River Estuary Management Program	1987–Present	New York State Department of Environmental Conservation (NYSDEC), 2025a, 2025b
	• Hudson River Estuary Management Program (Phase-1-2009 Target)	2005–2009	New York State Department of Environmental Conservation (NYSDEC), 2009
	• Hudson River Estuary Management Program (Phase-2 Habitat/Resilience)	2015–2020	New York State Department of Environmental Conservation (NYSDEC), 2025a, 2025b
	• New York-New Jersey Harbor and Estuary Program (HEP)	1988–Present	Hudson River Foundation, 2025
	• Hudson River PCBs Superfund Cleanup	2011–Present	U.S. Environmental Protection Agency (EPA), 2025
Chesapeake Bay (USA)	• Chesapeake Bay Program (CBP), 2025a	1983–Present	U.S. Environmental Protection Agency (EPA)
	• Chesapeake Bay Agreement (40%- Nutrients), Chesapeake Bay Program (CBP), 1987	1987–Present	U.S. Environmental Protection Agency (EPA)
	• Chesapeake 2000 agreement	2000–2010	U.S. Environmental Protection Agency (EPA), 2010
	• Chesapeake Bay Total Maximum Daily Load (TMDL)	2010–Present	U.S. Environmental Protection Agency (EPA)
	• Chesapeake Watershed agreement, Chesapeake Bay Program, 2025b	2014–Present	U.S. Environmental Protection Agency (EPA), Chesapeake Executive Council

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Table 1
Continued

Estuary (Country)	Name of the program	Duration	Leading organisation
Yangtze (China)	• Yangtze Estuary Wetland Restoration Projects, World Bank, 2021a	2000–Present	Shanghai Forestry Bureau and the Office of the Leading Group for the Development of the Yangtze River Economic Belt under the NDRC, Chinese academy of sciences
	• Action Plan for the Protection and Restoration of the Yangtze River	2016–2020	Ministry of Ecology and Environment (MEE) and the National Development and Reform Commission (NDRC). State Council of the People's Republic of China, 2022
	• Yangtze River Economic Belt (YREB) Ecological Redline Policy	2018–Present	National Development and Reform Commission (NDRC), Ministry of Ecology and Environment, Government of China, International Department of the Central Committee of the Communist Party of China, 2023
	• Yangtze River Protection and Ecological Restoration Program (P171644), World Bank, 2021b	2021–2028	Ministry of Ecology and Environment (MEE), National Development and Reform Commission, Ministry of Water Resources; Government of China
Yellow (China)	• Yellow River Delta National Nature Reserve	1992–Present	Shandong Yellow River Delta National Nature Reserve Administrative Bureau, Ramsar Convention Secretariat, 2010
	• Water-Sediment Regulation Scheme (WSRS), Yellow River Conservancy Commission of the Ministry of Water Resources, 2026	2002–Present	Yellow River Conservancy Commission (YRCC) under China's Ministry of Water Resources
	• Yellow River Ecological Corridor (YREC) Program	2020–2030	Asian Development Bank (ADB) in association with Yellow River Conservancy Commission. United Nations, 2026
	• Yellow River Basin Ecological Protection and Environmental Pollution Control Program (P172806)	2024–2029	Yellow River Conservancy Commission (YRCC), Henan Provincial Finance Bureau, and Shaanxi Provincial Financial Bureau, World Bank, 2024
Pearl (China)	• Pearl River Estuary Pollution Project (PREPP)	1999–2002	Hong Kong University of Science and Technology (HKUST), 2025
	• Guangdong Pearl River Delta Urban Environment Project, World Bank, 2016a	2004–2007	World Bank and the Guangdong Provincial Government
	• Second Guangdong Pearl River Delta Urban Environment Project, World Bank, 2016b	2007–2013	Guangdong Provincial Government and local municipal governments, World Bank, PR Water Resources Commission of the Ministry of Water Resources (MWR), Ministry for Environmental Protection (MEP)
	• Guangdong Provincial Water Pollution Control Plan	2023–Present	Guangdong Provincial Environmental Protection Bureau (GDEPB), Hong Kong Trade Development Council, 2025

(14.68%) estuaries exhibited moderate improvements, whereas the Pearl River Estuary (−35.62%) showed the greatest deterioration in sediment quality.

Based on the magnitude of long-term improvement, the estuaries were ranked as follows: Hudson (80.68%) > Mahanadi (70.46%) > Galveston Bay (68.96%) > Hooghly (37.76%) > Yellow River (16.03%) > Yangtze (14.68%). Conversely, the Pearl River (−35.62%), Cochin (−7.95%), and Chesapeake Bay (−2.89%) exhibited increasing PLI values, indicating deterioration in sediment quality over time, whereas the Ulhas Estuary showed only marginal temporal change (−1.41%).

However, improvement in PLI should not be interpreted as an indication of good environmental status, as several estuaries continue to exhibit elevated contamination levels. Notably, the Ulhas Estuary remains the most contaminated system based on recent PLI values despite showing little temporal change, whereas the Pearl River and Cochin estuaries represent systems where sediment contamination has intensified over time. Therefore, both

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the current contamination status and long-term temporal trends should be considered together to provide a comprehensive assessment of estuarine sediment quality. The contrasting patterns of recovery and deterioration observed among the studied estuaries highlight the importance of examining the role of environmental management in shaping long-term sediment quality trends.

4.6. Relating Sediment PLI Trends to Environmental Management Strategies

Governmental policies, regulatory frameworks, and NGO-led initiatives have contributed to changes in pollutant inputs and sediment quality in estuarine systems. However, the magnitude and persistence of these improvements vary among estuaries depending on implementation effectiveness, catchment characteristics, pollution sources, and legacy contamination. Therefore, evaluating the temporal association between major management interventions and changes in sediment PLI provides valuable insights into the long-term response of estuarine systems (Table 1). The influence of these interventions on PLI trajectories across individual estuaries is discussed below.

4.6.1. Association Between PLI Trends and Policy Interventions in Indian Estuaries

Temporal variations in sediment PLI across major Indian estuaries reflect the combined influence of management interventions, regulatory actions, changing anthropogenic pressures, and watershed-scale pollution dynamics.

The Ulhas Estuary remains the most contaminated among the studied Indian estuaries. Scientific assessments and advocacy efforts, including those led by Vanashakti (Ulhas River Conservation Project-2013), contributed to the formulation of the Ulhas action plan by the Maharashtra Pollution Control Board in 2019. However, recent PLI values show no measurable improvement in sediment quality following these interventions. The PLI increased from approximately 3.85 (historical assessment period) to 3.91 (recent assessment), representing a marginal increase of ∼1.4% over the monitoring period. This trend suggests that ongoing industrial activities, urbanization, and diffuse anthropogenic inputs continue to exert strong pressure on sediment quality, indicating that current interventions have not yet resulted in measurable recovery of sediment quality.

The Hooghly (Ganga) Estuary experienced a prolonged period of limited improvement following early pollution control initiatives, including the Ganga Action Plan (1986). The findings of this study suggest that, following the implementation of the Namami Gange Programme in 2014, the PLI decreased from approximately 1.40 to 0.87, representing a reduction of approximately 37% over the past decade (2014–present). The observed improvement in PLI coincided with the implementation of the Namami Gange Program and its associated wastewater treatment, pollution-control, and river-restoration measures, highlighting the potential contribution of sustained government-led river rejuvenation and pollution-control efforts to improving estuarine sediment quality.

The Cochin Estuary shows a contrasting pattern, with temporary improvements that were not sustained. Following the Vembanad Wetland Conservation Programme (2005), PLI initially declined; however, subsequent assessments indicated renewed contamination. The PLI increased from approximately 2.93 to 3.16, representing a deterioration of ∼8% over the recent assessment period. A temporary decline reported during the COVID-19 period may have reflected reduced anthropogenic activity (Kulk et al., 2021; Yunus et al., 2020); however, variations in hydrodynamic conditions, sediment characteristics, and sampling periods may also have contributed to the observed changes. Continued urban expansion, industrial activities, and land-use changes remain important factors affecting sediment quality despite ongoing restoration initiatives.

The Mahanadi Estuary exhibited a substantial decline in PLI, from approximately 3.20 to 0.95, representing an improvement of about 70% over the last two decades. This decline coincided with broader river management and pollution-control initiatives, including National River Conservation Plan interventions in the early 2000s, followed by subsequent river-basin assessment and management initiatives. More recently, the establishment of the Center for Mahanadi River Basin Management Studies (cMahanadi) in 2024 and the Mahanadi Riverfront Development Project approved in 2025 have further strengthened the focus on river restoration, monitoring, environmental management, and riverfront improvement. Although a slight recent increase in PLI was observed, the overall trend indicates a substantial reduction in sediment contamination compared with levels reported in earlier periods.

Overall, the temporal association between policy interventions and PLI trajectories suggests that sustained, integrated, and catchment-scale management approaches may contribute to long-term reductions in estuarine metal

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contamination. The substantial improvements observed in systems such as Mahanadi and Hooghly contrast with limited recovery in Ulhas and Cochin, where persistent industrial, urban, and watershed-derived pressures continue to influence sediment quality. These findings emphasize the importance of long-term monitoring, regulatory enforcement, source-specific pollution control, and adaptive management strategies for sustainable estuarine restoration.

4.6.2. Policy Interventions and PLI Trends in Major U.S. Estuaries

In the United States, long-term regulatory frameworks, institutional enforcement, and sustained stakeholder participation have contributed substantially to reductions in contaminant inputs to estuarine systems. The influence of these measures is reflected in the declining PLI trends observed in several major U.S. estuaries, although the magnitude of improvement varies depending on historical contamination, pollution sources, and remediation effectiveness.

The Galveston Bay Estuary represents a successful example of long-term environmental management. Early initiatives such as the Adopt-A-Beach Program (1986) by the Texas General Land Office and the Galveston Bay Estuary Program (1989) led by the Texas Commission on Environmental Quality, together with continued involvement of organizations such as the Galveston Bay Foundation and community programmes including Trash Bash (since 1994), were associated with sustained pollution reduction efforts. During this period, sediment PLI declined from historical values of 1.75 during the mid-1990s to 0.29 in the most recent assessment, representing a substantial reduction in contamination over time. The recent PLI value reflects substantial improvement in sediment quality relative to historical conditions.

The Hudson River Estuary demonstrates the influence of large-scale remediation programmes on sediment quality improvement. The Hudson River Estuary Management Program initiated in 1987 by the New York State Department of Environmental Conservation, followed by the Hudson River PCBs Superfund Cleanup implemented by the U.S. Environmental Protection Agency in 2011 and Hudson River Estuary Management Program (Phase-2 Habitat/Resilience) in 2015, together with broader estuarine monitoring and restoration initiatives, were associated with long-term restoration efforts and improved sediment quality. These interventions coincided with a decline in PLI from 9.43 during the late 1970s to 0.86 in 2020, representing one of the largest reductions in contamination among the evaluated estuaries. This decline indicates substantial improvement in sediment quality (with respect to metal concentrations) relative to historical conditions, although the contribution of individual remediation measures to the overall PLI reduction cannot be isolated from the available temporal comparisons.

In contrast, the Chesapeake Bay Estuary exhibits a more complex response to management interventions. The establishment of the Chesapeake Bay Program in 1983, through a partnership coordinated by the U.S. Environmental Protection Agency and involving multiple states, marked a major step towards watershed-scale restoration. Subsequent initiatives, including the Chesapeake Bay Total Maximum Daily Load, established in 2010, and the Chesapeake Bay Watershed Agreement, signed in 2014, further strengthened pollution-control and restoration efforts. However, recent PLI values (1.74–1.90 during 2015–2016) indicate persistent moderate metal contamination, suggesting continued influence of watershed-derived inputs, localized pollution sources, and the complexity of managing diffuse contaminants across a large watershed despite long-term restoration efforts. It should be noted that, based on the literature search conducted for the present study, no more recent studies reporting sedimentary metal concentrations were identified for this estuary. Accordingly, the PLI values discussed here are based on the most recent sediment metal concentration data available in the published literature and may not necessarily reflect the current sediment quality of this estuary.

Overall, the contrasting responses among U.S. estuaries demonstrate that sustained regulatory frameworks, effective enforcement, and long-term stakeholder engagement can support improvements in estuarine sediment quality. However, restoration outcomes depend strongly on pollution source characteristics, contaminant persistence, and watershed-scale management challenges. These findings highlight the importance of continuous monitoring, adaptive management, and effective control of ongoing pollutant sources to prevent renewed deterioration of estuarine sediment quality.

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4.6.3. Policy Interventions and PLI Trends in Major Chinese Estuaries

China has implemented multiple large-scale policy interventions to mitigate estuarine pollution through strengthened regulatory frameworks, scientific research initiatives, and increasing public awareness. However, PLI trajectories indicate contrasting outcomes among major estuarine systems, reflecting differences in industrial development, urbanization intensity, watershed characteristics, legacy contamination, and management effectiveness.

The Yangtze River Estuary has experienced persistent contamination pressures associated with rapid industrialization, urban expansion, and intensive watershed development. Early restoration efforts, including the Yangtze Estuary Wetland Restoration Projects initiated during the early 2000s by the Shanghai Municipal Government and the Chinese Academy of Sciences, were followed by broader regulatory measures such as the Yangtze River Economic Belt Ecological Redline Policy (2018) implemented by the National Development and Reform Commission. In 2021, the Yangtze River Protection and Ecological Restoration Program (P171644) was launched by the Ministry of Ecology and Environment (MEE), in collaboration with relevant national agencies and with World Bank support. Despite these initiatives, PLI values have shown considerable fluctuations, increasing to 2.66 during the mid-2000s before declining to approximately 1.38 in recent assessments (2022). This pattern indicates partial improvement in sediment quality; however, continued industrial activity, urban development, and watershed-derived inputs may contribute to persistent contamination.

The Yellow River Estuary has maintained comparatively low sediment metal contamination throughout the assessment period. Long-term ecosystem investigations by the Chinese Academy of Sciences since the 1980s provided a scientific foundation for subsequent conservation and restoration measures. The establishment of the Yellow River Delta National Nature Reserve in 1992, followed by wetland restoration, biodiversity conservation, and climate adaptation initiatives, strengthened ecosystem protection. More recently, the Yellow River Basin Ecological Protection and Environmental Pollution Control Program (P172806) (2024), led by the MEE with support from the World Bank, promoted basin-scale pollution management. These long-term conservation and basin-scale management efforts coincided with relatively low sediment contamination, although the contribution of individual interventions to observed PLI trends cannot be separated. PLI values declined from historical levels of 0.88–0.92 during the 1980s to approximately 0.63 in the most recent assessment (2023), indicating improved sediment quality compared with historical conditions.

In contrast, the Pearl River Estuary continues to exhibit comparatively high sediment metal contamination despite multiple pollution control initiatives. Scientific programmes such as the Pearl River Estuary Pollution Project (1999–2002), led by the Hong Kong University of Science and Technology, improved understanding of estuarine pollution processes and supported early management efforts. Subsequent interventions, including the Guangdong Pearl River Delta Urban Environment Project (2004–2007) and Second Guangdong Pearl River Delta Urban Environment Project (2007–2013) supported by the World Bank and the Guangdong Provincial Water Pollution Control Plan (2011; revised in 2021), aimed to reduce pollutant inputs. However, rapid urbanization, industrial expansion, and intensive land-use pressures may have constrained long-term recovery. PLI values increased from approximately 1.42–1.72 during the late 1990s to a maximum of 3.29 during the mid-2000s, and although partial improvement occurred thereafter, recent assessments still indicate elevated contamination (PLI = 2.12 in 2023). This trend suggests that existing management measures have not yet fully offset the influence of continued anthropogenic pressures.

Overall, PLI-based assessments demonstrate that policy outcomes in Chinese estuaries are highly system-specific. The Yellow River Estuary has maintained comparatively low contamination levels, coinciding with long-term conservation and basin-scale management efforts, whereas the Yangtze Estuary shows partial recovery but persistent moderate contamination. The Pearl River Estuary remains a highly impacted system, where rapid socioeconomic development has challenged pollution control efforts. Importantly, reductions in PLI should be interpreted as relative improvement rather than complete restoration, as legacy contaminants and ongoing anthropogenic inputs may continue to influence sediment quality. These findings highlight the importance of sustained regulatory enforcement, source-specific pollution control, and integrated catchment-to-coast management for achieving long-term improvements in estuarine environments.

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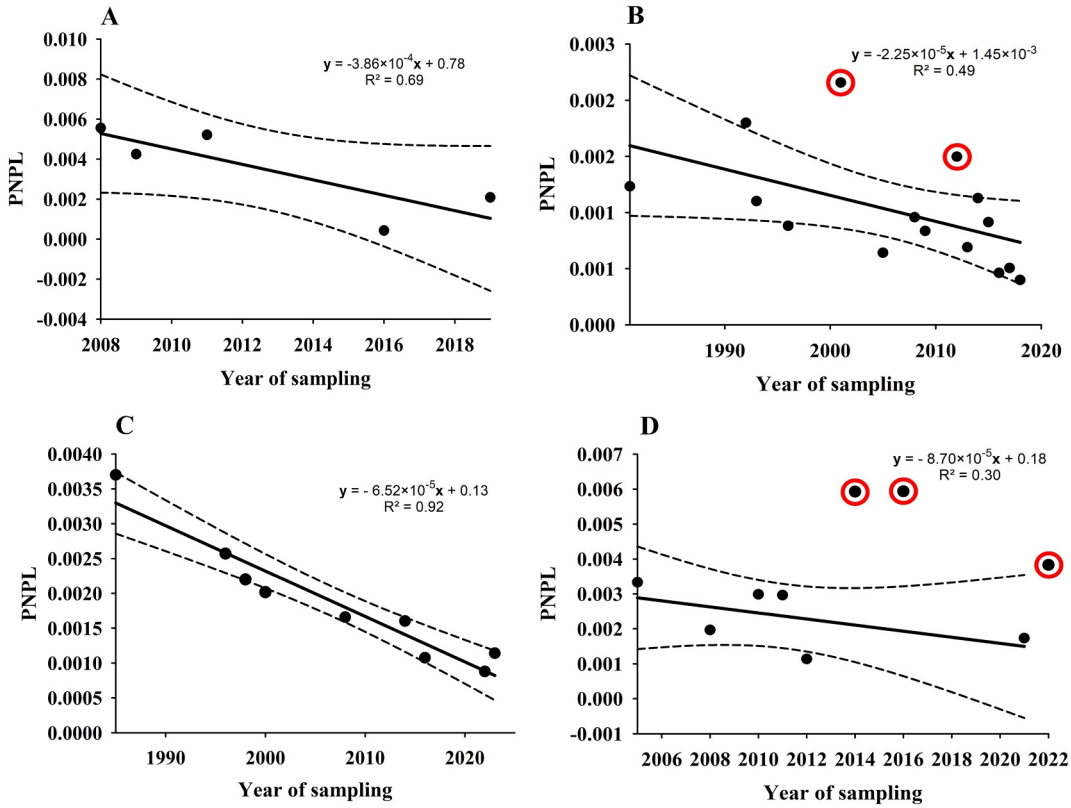


Figure 5. Temporal variation of population normalized pollution load in India (outliers are marked in red circles) (a) Mahanadi, (b) Ganga, (c) Ulhas, and (d) Vembanad lake.

4.7. Factors Influencing Changes in Estuarine Sediment Metal Contamination Over Time

The temporal variations in sediment PLI observed across the investigated estuaries are likely influenced by multiple interacting factors, including industrialization, urbanization, wastewater discharge, pollution control measures, and natural estuarine processes. However, direct attribution of these temporal trends to specific drivers was beyond the scope of the present study, as comparable long-term datasets on industrial activities, industrial and municipal effluent discharge, sewage and effluent treatment infrastructure (STPs and ETPs), land-use change, port activities, dredging operations, and watershed-scale management interventions were not consistently available across the investigated estuaries. Consequently, the relative contributions of these factors to long-term variations in sediment contamination could not be quantitatively assessed.

Among the various indicators of anthropogenic pressure, long-term population data were the most consistently available across the investigated regions, allowing temporal comparisons for estuaries where comparable demographic information could be obtained. Although catchment-scale population data sets were not available for all estuarine systems, available population records provide a useful proxy for cumulative anthropogenic pressure because population growth is closely associated with urbanization, industrial development, wastewater generation, and resource consumption. Therefore, population was considered as an indicator of broader anthropogenic influence rather than a direct measure of metal pollution sources.

4.8. Population Normalized Pollution Load (PNPL) and Temporal Trends

The PNPL trends provided an additional perspective by evaluating changes in sediment contamination intensity in relation to population pressure within each estuarine system. While PLI reflects the overall contamination status of estuarine sediments, PNPL enables comparison of contamination intensity among estuaries with different demographic conditions. Therefore, in this study, PNPL trends were interpreted alongside recent PLI values to distinguish changes in population-normalized contamination intensity from changes in the overall sediment contamination status (Table S10 in Supporting Information S1) (Chatterjee et al., 2026).

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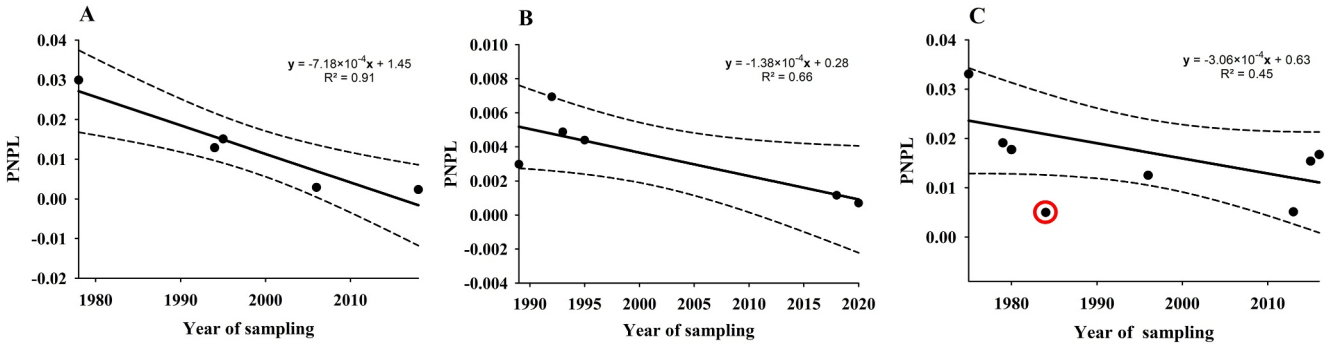


Figure 6. Temporal variation of population normalized pollution load in the USA (outliers are marked in red circles) (a) Hudson, (b) Galveston Bay and, (c) Chesapeake Bay.

Among the Indian estuaries, the Mahanadi Estuary showed a pronounced decline in PNPL (Figure 5a, slope = – (3.86 ± 1.49) × 10^{-4}, R^2 = 0.69) and had a low recent PLI value of 0.95. The declining PNPL trend suggested a reduction in sediment contamination intensity relative to population pressure, whereas the recent PLI value of 0.95 indicated a relatively low level of sediment metal contamination in the Mahanadi Estuary (Satapathy et al., 2019; Swain et al., 2021). However, this trend should be interpreted cautiously, as changes in population, pollutant inputs, sediment transport processes, and environmental management practices (Table 1; Table S10 in Supporting Information S1) may all have contributed to the observed pattern (Chatterjee et al., 2026).

The Hooghly (Ganga) Estuary also showed a declining PNPL trend (Figure 5b, slope = –(2.25 ± 0.70) × 10^{-5}, R^2 = 0.49) and had a low recent PLI value of 0.87 among the Indian estuaries (Arienzo et al., 2023; Bonnail et al., 2019; Sarkar et al., 2017). The concurrent decline in PNPL and relatively low recent PLI suggested a reduction in population-normalized contamination intensity accompanied by relatively low recent sediment metal contamination. This pattern may be associated with the combined effects of long-term pollution control measures (Table 1), regulatory interventions, and changes in anthropogenic loading over recent decades.

In contrast, the Ulhas Estuary showed a pronounced declining PNPL trend (Figure 5c, slope = –(6.52 ± 0.74) × 10^{-5}, R^2 = 0.92). However, this decline should be interpreted with caution because the estuary had the highest recent PLI value (3.91) among all the investigated estuarine systems (Botle et al., 2024; Fernandes & Nayak, 2014; Fernandes & Nayak, 2016; Thorat et al., 2023). Thus, although sediment contamination intensity relative to population pressure declined over time, the high recent PLI indicated that sediment metal contamination remained substantial. This contrast demonstrates that a declining PNPL does not necessarily correspond to a low level of sediment contamination and may reflect the continued influence of industrial and urban pressures despite pollution-management efforts.

Similarly, the Cochin Estuary showed a relatively weak declining PNPL trend (Figure 5d, slope = –(8.70 ± 6.71) × 10^{-5}, R^2 = 0.30) and had a high recent PLI value (3.16) (Narayana et al., 2021; This study). The weak weak declining PNPL trend, together with the high recent PLI, suggested that sediment contamination intensity relative to population pressure had changed only modestly, while sediment metal contamination remained high. The observed pattern may be associated with continuing urban, industrial, and watershed pressures and highlights the need for sustained pollution-control measures and integrated watershed-scale management.

The Hudson River Estuary showed a pronounced declining PNPL trend (Figure 6a, slope = −(7.18 ± 1.34) × 10^{-4}, R^2 = 0.91) and had a low recent PLI value of 0.86 (Urbaniak et al., 2020). The declining PNPL trend indicated a reduction in sediment contamination intensity relative to population pressure, while the low recent PLI value indicated relatively low current sediment metal contamination. Together, these results suggested an overall improvement in sediment contamination status over the study period. This pattern may be associated with the long-term regulatory measures, remediation activities, and watershed management practices.

Galveston Bay also showed a declining PNPL trend (Figure 6b, slope = −(1.38 ± 0.50) × 10^{-4}, R^2 = 0.66) and had the lowest recent PLI value (0.38) among all investigated estuaries (Lopez et al., 2022; Yakubu & Atobi-loye, 2024). The combination of a declining PNPL trend and the lowest recent PLI value indicated a

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comparatively favorable contamination status, which may be associated with sustained pollution-control and environmental management efforts.

In comparison, the Chesapeake Bay showed a modest declining PNPL trend (Figure 6c, slope = $-(3.06 \pm 1.53) \times 10^{-4}$, $R^2 = 0.45$) and had a comparatively higher recent PLI value of 1.40 (Krahforst et al., 2022; Russ et al., 2020). The declining PNPL trend indicated a possible reduction in contamination intensity relative to population pressure; however, the recent PLI value indicated that sediment metal contamination remained a concern. Continued pollution-control and watershed management efforts may therefore be needed to further reduce sediment contamination.

A similar pattern was observed in the Ulhas and Cochin estuaries, where declining PNPL trends (Figure 5c, slope = $-(6.52 \pm 0.74) \times 10^{-5}$, and Figure 5d, slope = $-(8.70 \pm 6.71) \times 10^{-5}$) occurred despite relatively high recent PLI values. These results demonstrate that a decline in PNPL does not necessarily indicate a low level of recent sediment metal contamination or an overall improvement in sediment quality. The persistence of relatively high PLI values in some estuaries also highlights the need to strengthen existing pollution-control measures and consider adopt management strategies and strengthen policy implementation according to local pollution sources and environmental conditions.

Comparable long-term and spatially consistent population data for areas surrounding the major Chinese estuaries, including the Yangtze, Pearl River, and Yellow River, were not available. Therefore, reliable temporal PNPL trends could not be assessed for these systems, and the PNPL analysis was restricted to the Indian and U.S. estuaries.

5. Conclusions

This study provides a global comparative assessment of long-term sediment metal contamination across major estuarine systems from South Asia, East Asia, and North America. The PLI values for the recent period showed differences in contamination levels among the estuaries. Galveston Bay, Hudson River, Hooghly River (Ganga), Yellow River, and Mahanadi exhibited relatively lower contamination, whereas Ulhas, Cochin, Pearl River, and Yangtze displayed higher or fluctuating contamination levels.

Temporal PLI trends revealed contrasting trajectories among the estuaries, with declining contamination trends observed in several systems, including Hudson River, Galveston Bay, Hooghly (Ganga), Yellow River, and Mahanadi. These changes reflect differences in historical pollution intensity, population pressure represented by available catchment data sets, and pollution control practices. In contrast, persistent contamination in some estuaries highlights the challenge of managing legacy metal accumulation and continued pollutant inputs.

A key contribution of this study is the introduction of PNPL as a complementary indicator to PLI. While PLI represents the absolute contamination status of sediments, PNPL evaluates contamination intensity relative to population pressure. The combined PLI–PNPL assessment indicated that Mahanadi, Hooghly (Ganga), Hudson River, and Galveston Bay exhibited declining population-normalized contamination intensity along with relatively low contamination levels in the recent period. It also highlighted that a decline in PNPL alone does not necessarily indicate improvement when absolute contamination levels remain high.

The contrasting pollution trajectories among estuaries highlight the need for sustained policy implementation, including regulation of industrial activities, effective wastewater and effluent management, pollution source control, sediment quality monitoring, and long-term restoration strategies. Future research should complement PLI- and PNPL-based assessments with chemical speciation studies and long-term monitoring. These approaches will help determine how changes in metal concentrations influence metal mobility, persistence, and potential environmental risks. This approach could help strengthen environmental management and improve strategies for controlling future metal contamination.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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Availability Statement

The data used in this study were obtained from previously published studies and publicly available sources. Baseline metal concentration data were obtained from Rudnick and Gao (2003). Population data for India were obtained from the Census of India (https://censusindia.gov.in/census.website/data/census-tables), while population data for the USA were obtained from Schroeder et al. (2026). Total area data were obtained from the U.S. Census Bureau (https://www.census.gov/geographies.html). The compiled and processed data set used in the analyses is archived on Zenodo (Chatterjee et al., 2026; DOI: https://doi.org/10.5281/zenodo.23261383).

Acknowledgments
The authors are grateful to the Ministry of Earth Sciences (MoES) for providing financial support (Project 503, Code: F/No.: MoES/36/OOIS/Extra/76/2020 (E-6931). SC acknowledges financial support from the Department of Science and Technology (DST), Government of India, through the INSPIRE Fellowship. The authors gratefully acknowledge the Indian Institute of Technology Kharagpur for providing institutional support, research infrastructure, and financial assistance to carry out this study.

References

Adeleye, A. O., Jin, H., Di, Y., Li, D., Chen, J., & Ye, Y. (2016). Distribution and ecological risk of organic pollutants in the sediments and seafood of Yangtze Estuary and Hangzhou Bay, East China Sea. *Science of the Total Environment*, *541*, 1540–1548. https://doi.org/10.1016/j.scitotenv.2015.09.124

An, Q., Wu, Y., Wang, J., & Li, Z. (2009). Heavy metals and polychlorinated biphenyls in sediments of the Yangtze river Estuary, China. *Environmental Earth Sciences*, *59*(2), 363–370. https://doi.org/10.1007/s12665-009-0034-4

Arienzo, M., Trifuoggi, M., Ferrara, L., Donadio, C., Mondal, P., Ponniah, J. M., et al. (2023). Influence of monsoon season on heavy metal composition of Hooghly River Estuary sediments, West Bengal, India. *Journal of Geochemical Exploration*, *248*, 107181. https://doi.org/10.1016/j.gexplo.2023.107181

Boesch, D. F., & Goldman, E. B. (2009). Chesapeake Bay, USA. *Ecosystem-based management for the oceans*, 268–293.

Bonnail, E., Antón-Martín, R., Riba, I., & DelValls, T. Á. (2019). Metal distribution and short-time variability in recent sediments from the Ganges River towards the Bay of Bengal (India). *Geosciences*, *9*(6), 260. https://doi.org/10.3390/geosciences9060260

Botle, A., Salgaonkar, S., Tiwari, R., & Barabde, G. (2024). Unveiling heavy metal pollution dynamics in sediments of river ulhas, Maharashtra, India: A comprehensive analysis of anthropogenic influence, pollution indices, and health risk assessment. *Environmental Geochemistry and Health*, *46*(10), 419. https://doi.org/10.1007/s10653-024-02208-8

Burton, G. A.Jr., & Scott, K. J. (1992). Sediment toxicity evaluations. *Environmental Science and Technology*, *26*(11), 2068–2075. https://doi.org/10.1021/es00035a002

Caccia, V. G., Millero, F. J., & Palanques, A. (2003). The distribution of trace metals in Florida Bay sediments. *Marine Pollution Bulletin*, *46*(11), 1420–1433. https://doi.org/10.1016/S0025-326X(03)00288-1

Carr, R. S., Chapman, D. C., Howard, C. L., & Biedenbach, J. M. (1996). Sediment quality triad assessment survey of the Galveston Bay, Texas system. *Ecotoxicology*, *5*(6), 341–364. https://doi.org/10.1007/BF00351951

Census of India. (2011). Census tables: A-01 and A-02. *Office of the Registrar General & Census Commissioner, India*. Retrieved from https://censusindia.gov.in/census.website/data/census-tables

Chakraborty, P., Babu, P. R., Acharyya, T., & Bandyopadhyay, D. (2010). Stress and toxicity of biologically important transition metals (Co, Ni, Cu and Zn) on phytoplankton in a tropical freshwater system: An investigation with pigment analysis by HPLC. *Chemosphere*, *80*(5), 548–553. https://doi.org/10.1016/j.chemosphere.2010.04.039

Chapman, P. M., & Wang, F. (2001). Assessing sediment contamination in estuaries. *Environmental Toxicology and Chemistry*, *20*(1), 3–22. https://doi.org/10.1002/etc.5620200102

Chatterjee, S., Chakraborty, P., Das, A., Roy, G., Mohanta, S., & Chakraborty, S. (2026). Supporting data for temporal changes in metal pollution in estuarine sediments: Population pressure, pollution trends, and policy responses in India, China, and the USA. *Zenodo*. [Dataset]. https://doi.org/10.5281/zenodo.23261383

Chen, Z., Li, J., Shen, H., & Zhanghua, W. (2001). Yangtze river of China: Historical analysis of discharge variability and sediment flux. *Geomorphology*, *41*(2–3), 77–91. https://doi.org/10.1016/S0169-555X(01)00106-4

Chesapeake Bay Program. (2025a). Chesapeake bay program (CBP). *Chesapeake Bay Program*. Retrieved from https://www.chesapeakebay.net/

Chesapeake Bay Program. (1987). Chesapeake Bay agreement. *Chesapeake Bay Program*. Retrieved from https://www.chesapeakebay.net/what/what-guides-us/watershed-agreement#1987-accordion

Chesapeake Bay Program. (2000). Chesapeake 2000 agreement. *Chesapeake Bay Program*. Retrieved from https://www.chesapeakebay.net/what/publications/chesapeake-2000-agreement

Chesapeake Bay Program. (2025b). Chesapeake watershed agreement. *Chesapeake Bay Program*. Retrieved from https://www.chesapeakebay.net/files/documents/CBWA-2025-IV-Final-Facing.pdf

District Administration, Alappuzha. (2025). *Vembanad Lake rejuvenation project*. Government of Kerala. Retrieved from https://alappuzha.nic.in/en/gallery/april-2025/dsc_3399a-2/

Earth5R. (2025). *Eco-restoration strategy – Kochi sector program*. Earth5R. Retrieved from https://earth5r.org/

Feng, H., Cochran, J. K., & Hirschberg, D. J. (2002). Transport and sources of metal contaminants over the course of tidal cycle in the turbidity maximum zone of the Hudson River Estuary. *Water Research*, *36*(3), 733–743. https://doi.org/10.1016/S0043-1354(01)00268-8

Feng, H., Cochran, J. K., Hirschberg, D. J., & Wilson, R. E. (1998). Small-scale spatial variations of natural radionuclide and trace metal distributions in sediments from the Hudson River estuary. *Estuaries*, *21*(2), 263–280. https://doi.org/10.2307/1352474

Fernandes, L. L., & Nayak, G. N. (2012). Heavy metals contamination in mudflat and mangrove sediments (Mumbai, India). *Chemistry and Ecology*, *28*(5), 435–455. https://doi.org/10.1080/02757540.2012.666527

Fernandes, L. L., & Nayak, G. N. (2014). Characterizing metal levels and their speciation in intertidal sediments along Mumbai Coast, India. *Marine Pollution Bulletin*, *79*(1–2), 371–378. https://doi.org/10.1016/j.marpolbul.2013.11.013

Fernandes, L. L., & Nayak, G. N. (2016). Geochemical assessment and fractionation of trace metals in estuarine sedimentary sub-environments, in Mumbai, India. *Environmental Nanotechnology, Monitoring and Management*, *6*, 14–23. https://doi.org/10.1016/j.enmm.2016.06.003

Forest, Environment and Climate Change Department, Government of Odisha. (2018). *Green mahanadi mission*. Government of Odisha. Retrieved from https://forest.odisha.gov.in/sites/default/files/2022-03/FE%20Dept_AAR%20Book2017-18_English.pdf

Galveston Bay Estuary Program. (1995). The Galveston Bay plan: Comprehensive conservation and management plan (CCMP). Galveston Bay Estuary program. Retrieved from https://oaktrust.library.tamu.edu/items/71096b27-21fe-458a-bf62-983e4351e8a1

Galveston Bay Estuary Program. (2025). Galveston bay estuary program (GBEP). *Galveston Bay Estuary Program*. Retrieved from https://gbep.texas.gov/

24711403, 2026, 11, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GH002170, Wiley Online Library on [19/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Galveston Bay Foundation. (1989). *Trash bash 2025*. Galveston Bay Foundation. Retrieved from https://galvbay.org/event/trash-bash-2025/

Gilchrist, S., Gates, A., Szabo, Z., & Lamothe, P. J. (2009). Impact of AMD on water quality in critical watershed in the Hudson River drainage basin: Phillips mine, Hudson Highlands, New York. *Environmental Geology*, *57*(2), 397–409. https://doi.org/10.1007/s00254-008-1310-4

Goldberg, E. D., Hodge, V., Koide, M., Griffin, J., Gamble, E., Bricker, O. P., et al. (1978). A pollution history of Chesapeake Bay. *Geochimica et Cosmochimica Acta*, *42*(9), 1413–1425. https://doi.org/10.1016/0016-7037(78)90047-9

Han, D., Cheng, J., Hu, X., Jiang, Z., Mo, L., Xu, H., et al. (2017). Spatial distribution, risk assessment, and source identification of heavy metals in sediments of the Yangtze river Estuary, China. *Marine Pollution Bulletin*, *115*(1–2), 141–148. https://doi.org/10.1016/j.marpolbul.2016.11.062

Harmon, M., Pait, A. S., & Hameedi, M. J. (2003). Sediment contamination, toxicity, and macroinvertebrate infaunal community in Galveston Bay. *NOAA Technical Memorandum NOS NCCOS CCMA 122. Silver Spring, MD: NOAA, NOS, Center for Coastal Monitoring and Assessment*, 66. Retrieved from https://repository.library.noaa.gov/view/noaa/2413/noaa_2413_DS1.pdf

Helz, G. R., Sinex, S. A., Ferri, K. L., & Nichols, M. (1985). Processes controlling Fe, Mn and Zn in sediments of northern Chesapeake Bay. *Estuarine, Coastal and Shelf Science*, *21*(1), 1–16. https://doi.org/10.1016/0272-7714(85)90002-2

Hong Kong Trade Development Council. (2025). Guangdong provincial water pollution control plan. *Hong Kong Trade Development Council*. Retrieved from https://research.hktdc.com/en/

Hong Kong University of Science and Technology. (2025). *Pearl river estuary pollution project (PREPP)*. Hong Kong University of Science and Technology. Retrieved from https://envf-ienv.hkust.edu.hk/pearl-river-estuary-pollutionproject

Hu, C., Liu, M., Li, Y., Li, J., Che, X., & Wang, H. (2024). Sedimentation and transformation of heavy metals during the transport from the yellow river Estuary to the sea: Evidence from surface sediments of the yellow river subaqueous Delta. *Marine Pollution Bulletin*, *207*, 116862. https://doi.org/10.1016/j.marpolbul.2024.116862

Hudson River Foundation. (2025). *New york-new Jersey harbor and Estuary program (HEP)*. Hudson River Foundation. Retrieved from https://hudsonriver.org/estuary-program/

International Department of the Central Committee of the Communist Party of China. (2023). *Yangtze River Economic belt (YREB) ecological redline policy*. International Department of the Central Committee of the Communist Party of China. Retrieved from https://www.idcpc.org.cn/english2023/ttxw_5749/202310/t20231016_162520.html

Khadanga, M. K., Mishra, R. K., & Sahu, B. K. (2022). Assessment of pollution and ecological risk index of heavy metals in the surface sediment of Estuary and the coastal environment of Bay of Bengal. *Journal of Environmental Informatics*, *39*(1). https://doi.org/10.3808/jei.202100469

Krahforst, C., Sherman, L. A., & Kehm, K. (2022). Trace metal enrichment in a tidally influenced, rural tributary of the upper Chesapeake Bay. *Marine Pollution Bulletin*, *175*, 113377. https://doi.org/10.1016/j.marpolbul.2022.113377

Kulk, G., George, G., Abdulaziz, A., Menon, N., Theenathayalan, V., Jayaram, C., et al. (2021). Effect of reduced anthropogenic activities on water quality in Lake vembanad, India. *Remote Sensing*, *13*(9), 1631. https://doi.org/10.3390/rs13091631

Li, J., Chen, S., Liu, M., Yang, S., Huang, W., & Zhang, J. (1985). Distribution and seasonal variation of heavy metal in the sediments from huanghe river Estuary and adjacent areas. *Journal of Shandong College of Oceanology*, *15*(2), 105–111.

Li, J., Wang, W., Li, X., Liu, S., Xu, X., & Ren, S. (2024). Heavy metals in the continuous river– estuary– sea system of the yellow river Delta, China: Spatial patterns, potential sources, and influencing factors. *Marine Pollution Bulletin*, *209*, 117247. https://doi.org/10.1016/j.marpolbul.2024.117247

Li, Q., Wu, Z., Chu, B., Zhang, N., Cai, S., & Fang, J. (2007). Heavy metals in coastal wetland sediments of the pearl river Estuary, China. *Environmental Pollution*, *149*(2), 158–164. https://doi.org/10.1016/j.envpol.2007.01.006

Li, X., Wai, O. W., Li, Y. S., Coles, B. J., Ramsey, M. H., & Thornton, I. (2000). Heavy metal distribution in sediment profiles of the pearl river Estuary, south China. *Applied Geochemistry*, *15*(5), 567–581. https://doi.org/10.1016/S0883-2927(99)00072-4

Liu, H., Liu, G., Da, C., Yuan, Z., & Wang, J. (2015). Concentration and fractionation of heavy metals in the old yellow river Estuary, China. *Journal of Environmental Quality*, *44*(1), 174–182. https://doi.org/10.2134/jeq2014.04.0180

Liu, H., Liu, G., Wang, J., Yuan, Z., & Da, C. (2016). Fractional distribution and risk assessment of heavy metals in sediments collected from the yellow river, China. *Environmental Science and Pollution Research*, *23*(11), 11076–11084. https://doi.org/10.1007/s11356-016-6291-3

Liu, R., Men, C., Liu, Y., Yu, W., Xu, F., & Shen, Z. (2016). Spatial distribution and pollution evaluation of heavy metals in yangtze Estuary sediment. *Marine Pollution Bulletin*, *110*(1), 564–571. https://doi.org/10.1016/j.marpolbul.2016.05.060

Liu, S. S., Song, J. M., Li, X. G., Yuan, H. M., Duan, L. Q., Ma, J., et al. (2025). Performance of heavy metals in the intertidal zone surface sediments of the yellow river Estuary under water-sediment regulation scheme. *Marine Pollution Bulletin*, *221*, 118592. https://doi.org/10.1016/j.marpolbul.2025.118592

Lopez, A. M., Fitzsimmons, J. N., Adams, H. M., Dellapenna, T. M., & Brandon, A. D. (2022). A time-series of heavy metal geochemistry in sediments of Galveston Bay Estuary, Texas, 2017-2019. *Science of the Total Environment*, *806*, 150446. https://doi.org/10.1016/j.scitotenv.2021.150446

Ma, Y., Ma, Y., Zhang, W., Zhang, H., Li, T., Kong, D., et al. (2024). The spatiotemporal variation and historical evolution of heavy metal pollution in sediments from the pearl river Estuary. *China. Water*, *16*(4), 531. https://doi.org/10.3390/w16040531

Mahanadi Riverfront Development Project. (2026). Mahanadi riverfront development project. Retrieved from https://timesofindia.indiatimes.com/city/bhubaneswar/odisha-government-approves-rs-240-crore-mahanadi-riverfront-development-project-for-tourism-and-ecological-enhancement/articleshow/123837574.cms

Maharashtra Pollution Control Board. (2019). Action plan for restoration of water quality of polluted river stretches: Ulhas river. *Maharashtra Pollution Control Board*. Retrieved from https://www.mpcb.gov.in/sites/default/files/river-polluted/action-planpriority/Action_plans_priority_V_ULHAS_2019_03072019.pdf

Ministry of Environment, Forest and Climate Change. (2025). *National River Conservation plan (NRCP) – Mahanadi stretches*. Government of India. Retrieved from https://nrcd.nic.in/

Morse, J. W., Presley, B. J., Taylor, R. J., Benoit, G., & Santschi, P. (1993). Trace metal chemistry of Galveston Bay: Water, sediments and biota. *Marine Environmental Research*, *36*(1), 1–37. https://doi.org/10.1016/0141-1136(93)90087-G

Narayana, A. C., Ismaiel, M., & Priju, C. P. (2021). An environmental magnetic record of heavy metal pollution in vembanad lagoon, southwest Coast of India. *Marine Pollution Bulletin*, *167*, 112344. https://doi.org/10.1016/j.marpolbul.2021.112344

National Mission for Clean Ganga. (2014). Namami gange programme. *National Mission for Clean Ganga, Ministry of Jal Shakti, Government of India*. Retrieved from https://nmcg.nic.in/NamamiGanga.aspx

New York State Department of Environmental Conservation. (2025a). Hudson river Estuary management program. *New York State Department of Environmental Conservation*. Retrieved from https://dec.ny.gov/nature/waterbodies/oceansestuaries/hudson-river-estuary-program

New York State Department of Environmental Conservation. (2009). Hudson river Estuary management program (phase 1–2009 Target). *New York State Department of Environmental Conservation*. Retrieved from https://dec.ny.gov/nature/waterbodies/oceans-estuaries/hudson-river-estuary-program

24711403, 2026, 11, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GH002170, Wiley Online Library on [19/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

New York State Department of Environmental Conservation. (2025b). Hudson River Estuary management program (phase 2—Habitat/Resilience). *New York State Department of Environmental Conservation*. Retrieved from https://dec.ny.gov/nature/waterbodies/oceans-estuaries/hudson-river-estuary-program

Park, J., & Presley, B. J. (1997). Trace metal contamination of sediments and organisms from the Swan Lake area of Galveston Bay. *Environmental Pollution*, *98*(2), 209–221. https://doi.org/10.1016/S0269-7491(97)00137-1

Press Information Bureau. (1985). Ganga action plan (Phase-I). *Government of India*. Retrieved from https://www.pib.gov.in/newsite/erelcontent.aspx?relid=18777&reg=3&lang=2

Press Information Bureau. (2025). River rejuvenation action plan (NGT OA 673/2018). *Government of India*. Retrieved from https://www.pib.gov.in/PressReleseDetailm.aspx?PRID=2197181&reg=3&lang=2

Qin, J., Yang, J., Zhang, J., Liu, X., Yu, J., Wang, Z., et al. (2024). Effects of tidal hydrology on soil phosphorus forms in the yellow river Estuary wetland: A field study of soil core translocation. *Science of the Total Environment*, *922*, 171360. https://doi.org/10.1016/j.scitotenv.2024.171360

Ramsar Convention Secretariat. (2010). *Yellow river Delta national nature reserve*. Ramsar Convention Secretariat. Retrieved from https://www.ramsar.org/sites/default/files/documents/pdf/lib/hbk4-07cs05.pdf

RiverRecycle. (2025). *Kerala cleanup project*. RiverRecycle. Retrieved from https://www.riverrecycle.com/projects/kerala-kochi-cleanup/

Rodenburg, L. A., Du, S., Xiao, B., & Fennell, D. E. (2011). Source apportionment of polychlorinated biphenyls in the New York/new Jersey harbor. *Chemosphere*, *83*(6), 792–798. https://doi.org/10.1016/j.chemosphere.2011.02.058

Rudnick, R. L., & Gao, S. (2003). Composition of the Continental crust. In R. L. Rudnick (Ed.), *Treatise on geochemistry* (Vol. 3, pp. 1–64). Elsevier. https://doi.org/10.1016/B0-08-043751-6/03016-4

Russ, E., Palinkas, C., & Cornwell, J. (2020). Evaluating estuarine sediment provenance from geochemical patterns in upper Chesapeake Bay. *Chemical Geology*, *533*, 119404. https://doi.org/10.1016/j.chemgeo.2019.119404

Sadhuram, Y., Sarma, V. V., Murthy, T. R., & Rao, B. P. (2005). Seasonal variability of physico-chemical characteristics of the haldia channel of Hooghly Estuary, India. *Journal of Earth System Science*, *114*(1), 37–49. https://doi.org/10.1007/BF02702007

Samanta, S., Chandra, K., Manna, S. K., & Saha, K. (2007). Sediment status of the Hooghly and haldi estuaries at Haldia industrial area with special reference to trace metals. *Journal of the Indian Society of Soil Science*, *55*(3), 349–359. https://doi.org/10.5555/20113013209

Sankat Mochan Foundation. (2025). *Swachh Ganga abhiyan*. Sankat Mochan Foundation. Retrieved from https://sankatmochanfoundationonline.org/

Santschi, P. H., Presley, B. J., Wade, T. L., Garcia-Romero, B., & Baskaran, M. (2001). Historical contamination of PAHs, PCBs, DDTs, and heavy metals in Mississippi River Delta, Galveston Bay and Tampa Bay sediment cores. *Marine Environmental Research*, *52*(1), 51–79. https://doi.org/10.1016/S0141-1136(00)00260-9

Sarkar, A., Chakraborty, P., & Nath, B. N. (2016). Distribution and nature of sedimentary organic matter in a tropical Estuary: An indicator of human intervention on environment. *Marine Pollution Bulletin*, *102*(1), 176–186. https://doi.org/10.1016/j.marpolbul.2015.11.013.Verma.2002

Sarkar, S. K., Mondal, P., Biswas, J. K., Kwon, E. E., Ok, Y. S., & Rinklebe, J. (2017). Trace elements in surface sediments of the Hooghly (Ganges) Estuary: Distribution and contamination risk assessment. *Environmental Geochemistry and Health*, *39*(6), 1245–1258. https://doi.org/10.1007/s10653-017-9952-3

Satapathy, S., Panda, C. R., & Jena, B. S. (2019). Risk-based prediction of metal toxicity in sediment and impact on human health due to consumption of seafood (Saccostrea cucullata) found in two highly industrialised coastal estuarine regions of eastern India: A food safety issue. *Environmental Geochemistry and Health*, *41*(5), 1967–1985. https://doi.org/10.1007/s10653-019-00251-4

Schroeder, J., Van Riper, D., Manson, S., Cooper, G., Krause, Z., Kugler, T., et al. (2026). IPUMS national historical geographic information system: Version 21.0. *IPUMS*. https://doi.org/10.18128/D050.V21.0

Shyleshchandran, M. N., Mohan, M., & Ramasamy, E. V. (2018). Risk assessment of heavy metals in vembanad Lake sediments (south-west Coast of India), based on acid-volatile sulfide (AVS)-Simultaneously extracted metal (SEM) approach. *Environmental science and pollution research*, *25*(8), 7333–7345. https://doi.org/10.1007/s11356-017-0997-8

State Council of the People's Republic of China. (2022). *In-depth action plan for protection and restoration of the Yangtze River*. Government of the People's Republic of China. Retrieved from https://english.www.gov.cn/policies/policywatch/202209/22/content_WS632bd28bc6d0a757729e0574.html

State Wetland Authority Kerala. (2026). Integrated management plan (phase I). State wetland authority Kerala. Retrieved from https://www.swak.kerala.gov.in/images/downloads/IMP-of-VembanadKol.pdf

Sun, Y., Liu, B., Zheng, H., Zou, Y., Yang, J., & Li, Q. (2024). Trace element geochemistry of sediments in the pearl river Estuary and its implication for provenance. *Regional Studies in Marine Science*, *70*, 103388. https://doi.org/10.1016/j.rsma.2024.103388

Sundaray, S. K., Nayak, B. B., Lee, B. G., & Bhatta, D. (2014). Spatio-temporal dynamics of heavy metals in sediments of the river estuarine system: Mahanadi basin (India). *Environmental Earth Sciences*, *71*(4), 1893–1909. https://doi.org/10.1007/s12665-013-2594-6

Sundaray, S. K., Nayak, B. B., Lin, S., & Bhatta, D. (2011). Geochemical speciation and risk assessment of heavy metals in the river estuarine sediments—a case study: Mahanadi basin, India. *Journal of hazardous materials*, *186*(2–3), 1837–1846. https://doi.org/10.1016/j.jhazmat.2010.12.081

Suwanmanon, S., & Kim, K. I. (2021). Pollution load index for heavy metals of agricultural soils adjacent to industrial complexes in the jeon-buk regions of Korea. *Korean Journal of Soil Science and Fertilizer*, *54*(3), 311–321. https://doi.org/10.7745/KJSSF.2021.54.3.311

Swain, S., Pattanayak, A. A., Sahu, B. K., Satapathy, D. R., & Panda, C. R. (2021). Time-series monitoring and ecological risk assessment of heavy metal pollution in Mahanadi Estuary, east Coast of India. *Regional Studies in Marine Science*, *47*, 101923. https://doi.org/10.1016/j.rsma.2021.101923

Tang, A., Liu, R., Ling, M., Xu, L., & Wang, J. (2010). Distribution characteristics and controlling factors of soluble heavy metals in the yellow river Estuary and adjacent sea. *Procedia Environmental Sciences*, *2*, 1193–1198. https://doi.org/10.1016/j.proenv.2010.10.129

Texas General Land Office. (2025). Adopt-A-Beach program. Texas general land office. Retrieved from https://www.glo.texas.gov/coastal/adopt-beach

Thomas, J., Velamala, S. N., & Prasad, K. V. S. R. (2019). Numerical simulation of tidal constituents in thane creek and the ulhas Estuary, west coast of India. *Journal of Coastal Research*, *35*(2), 376–388. https://doi.org/10.2112/JCOASTRES-D-17-00189.1

Thorat, B. R., Prasad, P., & Ram, A. (2023). Heavy metal accumulation in a moderately polluted ulhas Estuary, Western India. *Regional Studies in Marine Science*, *60*, 102818. https://doi.org/10.1016/j.rsma.2023.102818

Tomlinson, D. L., Wilson, J. G., Harris, C. R., & Jeffrey, D. W. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgolaender Meeresuntersuchungen*, *33*(1–4), 566–575. https://doi.org/10.1007/BF02414780

24711403, 2026, 11, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GH002170, Wiley Online Library on [19/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

United Nations. (2026). *Yellow river ecological corridor (YREC) program*. United Nations. Retrieved from https://sdgs.un.org/partnerships/yellow-river-ecologicalcorridor-program

Urbaniak, M., Baran, A., Szara, M., Mierzejewska, E., Lee, S., Takazawa, M., & Kannan, K. (2020). Evaluation of ecotoxicological and chemical properties of soil amended with Hudson River (New York, USA) sediment. *Environmental Science and Pollution Research*, *27*(7), 7388–7397. https://doi.org/10.1007/s11356-019-07354-6

U.S. Census Bureau. (2026). *Geographies*. U.S. Census Bureau. Retrieved from https://www.census.gov/geographies.html

U.S. Environmental Protection Agency. (2010). *Chesapeake Bay total maximum daily load (TMDL)*. U.S. Environmental Protection Agency. Retrieved from https://www.epa.gov/chesapeake-bay-tmdl

U.S. Environmental Protection Agency. (2025). *Hudson river PCBs superfund cleanup*. U.S. Environmental Protection Agency. Retrieved from https://www.epa.gov/hudsonriverpcbs/hudson-river-cleanup

Vanashakti. (2025). *Ulhas river conservation Project*. Vanashakti. Retrieved from https://vanashakti.org/success-stories/revival-of-ulhas-river

Vembanad Wetland Conservation Programme. (2005). *Vembanad Wetland Conservation Programme (VWCP)*. Vembanad Wetland Conservation Programme. Retrieved from https://www.vembanad.org/

Verma, A., Subramanian, V., & Ramesh, R. (2002). Methane emissions from a coastal lagoon: Vembanad Lake, West Coast, India. *Chemosphere*, *47*(8), 883–889. https://doi.org/10.1016/S0045-6535(01)00288-0

Wang, Z., Lin, K., & Liu, X. (2022). Distribution and pollution risk assessment of heavy metals in the surface sediment of the intertidal zones of the Yellow River Estuary, China. *Marine Pollution Bulletin*, *174*, 113286. https://doi.org/10.1016/j.marpolbul.2021.113286

Williams, S. C., Simpson, H. J., Olsen, C. R., & Bopp, R. F. (1978). Sources of heavy metals in sediments of the Hudson River Estuary. *Marine Chemistry*, *6*(3), 195–213. https://doi.org/10.1016/0304-4203(78)90030-0

World Bank. (2016a). *Guangdong pearl river Delta urban environment project*. World Bank. Retrieved from https://www.worldbank.org/en/results/2016/05/26/cleaning-up-china-polluted-pearl-river

World Bank. (2016b). *Second Guangdong pearl river Delta urban environment project*. World Bank. Retrieved from https://www.worldbank.org/en/results/2016/05/26/cleaning-up-china-polluted-pearl-river

World Bank. (2021a). *Yangtze Estuary wetland restoration projects*. World Bank. Retrieved from https://documents1.worldbank.org/curated/en/099749311242117207/pdf/Final0Technica0n0Program000P171644.pdf

World Bank. (2021b). *Yangtze river protection and ecological restoration program (P171644)*. World Bank. Retrieved from https://documents1.worldbank.org/curated/en/639221641932904526/pdf/China-Yangtze-River-Protection-andEcological-Restoration-Program.pdf

World Bank. (2024). *Yellow river basin ecological protection and Environmental Pollution control program (P172806)*. World Bank. Retrieved from https://documents1.worldbank.org/curated/en/099112824012021864/pdf/P172806-0a0ee412-675d-4246-a816-0b61370b62b4.pdf

Yakubu, M. A., & Atobiloye, S. O. (2024). Detection of heavy metals in surface water and sediment from Galveston Bay and Estuary: Health risk assessment. Available at SSRN 4869882. https://doi.org/10.2139/ssrn.4869882

Yang, M., Kostaschuk, R., & Chen, Z. (2004). Historical changes in heavy metals in the Yangtze Estuary, China. *Environmental Geology*, *46*(6), 857–864. https://doi.org/10.1007/s00254-004-1072-6

Yang, Y., Liu, Z., Chen, F., Wu, S., Zhang, L., Kang, M., & Li, J. (2014). Assessment of trace element contamination in sediment cores from the pearl River and estuary, south China: Geochemical and multivariate analysis approaches. *Environmental Monitoring and Assessment*, *186*(12), 8089–8107. https://doi.org/10.1007/s10661-014-3989-x

Ye, F., Huang, X., Zhang, D., Tian, L., & Zeng, Y. (2012). Distribution of heavy metals in sediments of the pearl river Estuary, southern China: Implications for sources and historical changes. *Journal of Environmental Sciences*, *24*(4), 579–588. https://doi.org/10.1016/S1001-0742(11)60783-3

Yellow River Conservancy Commission of the Ministry of Water Resources. (2026). Water-sediment regulation scheme (WSRS). *Yellow River Conservancy Commission of the Ministry of Water Resources*. Retrieved from http://www.yrcc.gov.cn/

Yunus, A. P., Masago, Y., & Hijioka, Y. (2020). COVID-19 and surface water quality: Improved Lake water quality during the lockdown. *Science of the Total Environment*, *731*, 139012. https://doi.org/10.1016/j.scitotenv.2020.139012

Zhang, C., & Wang, L. (2001). Multi-element geochemistry of sediments from the pearl river system, China. *Applied Geochemistry*, *16*(9–10), 1251–1259. https://doi.org/10.1016/S0883-2927(01)00007-5

Zhang, J., Huang, W. W., & Martin, J. M. (1988). Trace metals distribution in huanghe (Yellow River) estuarine sediments. *Estuarine, Coastal and Shelf Science*, *26*(5), 499–516. https://doi.org/10.1016/0272-7714(88)90003-0

Zhang, W., Yu, L., Lu, M., Hutchinson, S. M., & Feng, H. (2007). Magnetic approach to normalizing heavy metal concentrations for particle size effects in intertidal sediments in the Yangtze Estuary, China. *Environmental Pollution*, *147*(1), 238–244. https://doi.org/10.1016/j.envpol.2006.08.003

Zhang, Z., Lou, S., Liu, S., Yang, Z., Chen, S., Zou, Y., & Fedorova, I. V. (2025). Vegetation morphology and phytobiology intervene in heavy metal contamination of surface sediments in Yangtze River Estuary. *Marine Pollution Bulletin*, *214*, 117795. https://doi.org/10.1016/j.marpolbul.2025.117795

Zhao, M., Wang, E., Xia, P., Feng, A., Chi, Y., & Sun, Y. (2019). Distribution and pollution assessment of heavy metals in the intertidal zone environments of typical sea areas in China. *Marine Pollution Bulletin*, *138*, 397–406. https://doi.org/10.1016/j.marpolbul.2018.11.050

Zhou, H. Y., Peng, X. T., & Pan, J. M. (2004). Distribution, source, and enrichment of some chemical elements in sediments of the Pearl River Estuary, China. *Continental Shelf Research*, *24*(16), 1857–1875. https://doi.org/10.1016/j.csr.2004.06.012

Zhuang, W., & Zhou, F. (2021). Distribution, source, and pollution assessment of heavy metals in the surface sediments of the Yangtze River Estuary and its adjacent East China Sea. *Marine Pollution Bulletin*, *164*, 112002. https://doi.org/10.1016/j.marpolbul.2021.112002

References From the Supporting Information

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. *Environmental Geochemistry and Health*, *34*(1), 27–42. https://doi.org/10.1007/s10653-011-9388-0

Bi, S., Yang, Y., Xu, C., Zhang, Y., Zhang, X., & Zhang, X. (2017). Distribution of heavy metals and environmental assessment of surface sediment of typical estuaries in eastern China. *Marine Pollution Bulletin*, *121*(1–2), 357–366. https://doi.org/10.1016/j.marpolbul.2017.06.013

Chakraborty, P., Chakraborty, S., Vudamala, K., Sarkar, A., & Nath, B. N. (2016). Partitioning of metals in different binding phases of tropical estuarine sediments: Importance of metal chemistry. *Environmental Science and Pollution Research*, *23*(4), 3450–3462. https://doi.org/10.1007/s11356-015-5475-6

24711403, 2026, 11, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GH002170, Wiley Online Library on [19/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Chatterjee, M. V. S. F. E., Silva Filho, E. V., Sarkar, S. K., Sella, S. M., Bhattacharya, A., Satpathy, K. K., et al. (2007). Distribution and possible source of trace elements in the sediment cores of a tropical macrotidal Estuary and their ecotoxicological significance. *Environment International*, *33*(3), 346–356. https://doi.org/10.1016/j.envint.2006.11.013

Chatterjee, M., Massolo, S., Sarkar, S. K., Bhattacharya, A. K., Bhattacharya, B. D., Satpathy, K. K., & Saha, S. (2009). An assessment of trace element contamination in intertidal sediment cores of Sunderban mangrove wetland, India for evaluating sediment quality guidelines. *Environmental Monitoring and Assessment*, *150*(1), 307–322. https://doi.org/10.1007/s10661-008-0232-7

Chen, B., Liu, J., Qiu, J., Zhang, X., Wang, S., & Liu, J. (2017). Spatio-temporal distribution and environmental risk of sedimentary heavy metals in the Yangtze River Estuary and its adjacent areas. *Marine Pollution Bulletin*, *116*(1–2), 469–478. https://doi.org/10.1016/j.marpolbul.2016.11.055

Chen, F., Yang, Y., Zhang, D., & Zhang, L. (2006). Heavy metals associated with reduced sulfur in sediments from different deposition environments in the Pearl River Estuary, China. *Environmental Geochemistry and Health*, *28*(3), 265–272. https://doi.org/10.1007/s10653-006-9042-4

Chen, Y., Liu, M., Zhang, X., Bu, X., Chen, J., & Wu, X. (2021). Metals in Yellow river Estuary sediments during the 2018 water-sediment regulation scheme period. *Marine Pollution Bulletin*, *166*, 112177. https://doi.org/10.1016/j.marpolbul.2021.112177

Cheng, Q., Lou, G., Huang, W., & Li, X. (2017). Assessment and potential sources of metals in the surface sediments of the Yellow River Delta, Eastern China. *Environmental Science and Pollution Research*, *24*(21), 17446–17454. https://doi.org/10.1007/s11356-017-9059-5

Cheng, Q., Zhou, W., Zhang, J., Shi, L., Xie, Y., & Li, X. (2019). Spatial variations of arsenic and heavy metal pollutants before and after the water-sediment regulation in the wetland sediments of the Yellow River Estuary, China. *Marine Pollution Bulletin*, *145*, 138–147. https://doi.org/10.1016/j.marpolbul.2019.05.032

Di Giulio, R. T., & Scanlon, P. F. (1985). Heavy metals in aquatic plants, clams, and sediments from the Chesapeake Bay, USA implications for waterfowl. *Science of the total environment*, *41*(3), 259–274. https://doi.org/10.1016/0048-9697(85)90145-7

Fan, H., Chen, S., Li, Z., Liu, P., Xu, C., & Yang, X. (2020). Assessment of heavy metals in water, sediment, and shellfish organisms in typical areas of the Yangtze River Estuary, China. *Marine Pollution Bulletin*, *151*, 110864. https://doi.org/10.1016/j.marpolbul.2019.110864

Fan, J., Fan, D., & Wu, Y. (2023). Spatiotemporal variations of heavy metal historical accumulation records and their influencing mechanisms in the Yangtze River Estuary. *Science of the Total Environment*, *854*, 158733. https://doi.org/10.1016/j.scitotenv.2022.158733

George, R., Martin, G. D., Nair, S. M., Thomas, S. P., & Jacob, S. (2016). Geochemical assessment of trace metal pollution in sediments of the Cochin backwaters. *Environmental Forensics*, *17*(2), 156–171. https://doi.org/10.1080/15275922.2016.1163623

Ip, C. C., Li, X. D., Zhang, G., Wai, O. W., & Li, Y. S. (2007). Trace metal distribution in sediments of the Pearl River Estuary and the surrounding coastal area, South China. *Environmental Pollution*, *147*(2), 311–323. https://doi.org/10.1016/j.envpol.2006.06.028

Knight, M. A., & Pasternack, G. B. (2000). Sources, input pathways, and distributions of Fe, Cu, and Zn in a Chesapeake Bay tidal freshwater marsh. *Environmental Geology*, *39*(12), 1359–1371. https://doi.org/10.1007/s002540000108

Li, F., Mao, L., Jia, Y., Gu, Z., Shi, W., Chen, L., & Ye, H. (2018). Distribution and risk assessment of trace metals in sediments from Yangtze River Estuary and Hangzhou Bay, China. *Environmental Science and Pollution Research*, *25*(1), 855–866. https://doi.org/10.1007/s11356-017-0425-0

Li, X., Wang, Y., Li, B., Feng, C., Chen, Y., & Shen, Z. (2013). Distribution and speciation of heavy metals in surface sediments from the Yangtze Estuary and coastal areas. *Environmental Earth Sciences*, *69*(5), 1537–1547. https://doi.org/10.1007/s12665-012-1988-1

Li, L., Jiang, M., Liu, Y., & Shen, X. (2019). Heavy metals inter-annual variability and distribution in the Yangtze River Estuary sediment, China. *Marine Pollution Bulletin*, *141*, 514–520. https://doi.org/10.1016/j.marpolbul.2019.03.008

Li, L., Wang, X., Zhu, A., Yang, G., & Liu, J. (2014). Assessing metal toxicity in sediments of Yellow River wetland and its surrounding coastal areas, China. Estuarine. *Coastal and Shelf Science*, *151*, 302–309. https://doi.org/10.1016/j.ecss.2014.07.010

Liang, H., Wang, G., Guo, H., Niu, L., & Yang, Q. (2025). Evaluation of heavy metal accumulation and sources in surface sediments of the Pearl River Estuary (China). *Marine Environmental Research*, *204*, 106948. https://doi.org/10.1016/j.marenvres.2025.106948

Liang, R. Z., Gu, Y. G., Li, H. S., Han, Y. J., Niu, J., Su, H., et al. (2023). Multi-index assessment of heavy metal contamination in surface sediments of the Pearl River Estuary intertidal zone. *Marine Pollution Bulletin*, *186*, 114445. https://doi.org/10.1016/j.marpolbul.2022.114445

Liu, W. X., Li, X. D., Shen, Z. G., Wang, D. C., Wai, O. W. H., & Li, Y. S. (2003). Multivariate statistical study of heavy metal enrichment in sediments of the Pearl River Estuary. *Environmental Pollution*, *121*(3), 377–388. https://doi.org/10.1016/S0269-7491(02)00234-8

Liu, R., Guo, L., Men, C., Wang, Q., Miao, Y., & Shen, Z. (2019). Spatial-temporal variation of heavy metals' sources in the surface sediments of the Yangtze River Estuary. *Marine Pollution Bulletin*, *138*, 526–533. https://doi.org/10.1016/j.marpolbul.2018.12.010

Lin, H., Sun, T., Adams, M. P., Zhou, Y., Zhang, X., Xu, S., & Gu, R. (2018). Seasonal dynamics of trace elements in sediment and seagrass tissues in the largest Zostera japonica habitat, the Yellow River Estuary, northern China. *Marine Pollution Bulletin*, *134*, 5–13. https://doi.org/10.1016/j.marpolbul.2018.02.043

Liu, B., Hu, K., Jiang, Z., Yang, J., Luo, X., & Liu, A. (2011). Distribution and enrichment of heavy metals in a sediment core from the Pearl River Estuary. *Environmental Earth Sciences*, *62*(2), 265–275. https://doi.org/10.1007/s12665-010-0520-8

Martin, G. D., George, R., Shaiju, P., Muraleedharan, K. R., Nair, S. M., & Chandramohanakumar, N. (2012). Toxic metals enrichment in the surficial sediments of a eutrophic tropical Estuary (cochin backwaters, Southwest Coast of India). *The Scientific World Journal*, *2012*(1), 972839–17. https://doi.org/10.1100/2012/972839

Massolo, S., Bignasca, A., Sarkar, S. K., Chatterjee, M., Bhattacharya, B. D., & Alam, A. (2012). Geochemical fractionation of trace elements in sediments of Hugli River (Ganges) and Sundarban wetland (West Bengal, India). *Environmental Monitoring and Assessment*, *184*(12), 7561–7577. https://doi.org/10.1007/s10661-012-2519-y

Mondal, P., Lofrano, G., Carotenuto, M., Guida, M., Trifuoggi, M., Libralato, G., & Sarkar, S. K. (2021). Health risk and geochemical assessment of trace elements in surface sediment along the Hooghly (Ganges) River Estuary (India). *Water*, *13*(2), 110. https://doi.org/10.3390/w13020110

Mondal, P., Reichelt-Brushett, A. J., Jonathan, M. P., Sujitha, S. B., & Sarkar, S. K. (2018). Pollution evaluation of total and acid-leachable trace elements in surface sediments of Hooghly River Estuary and Sundarban Mangrove Wetland (India). *Environmental Science and Pollution Research*, *25*(6), 5681–5699. https://doi.org/10.1007/s11356-017-0915-0

Mukherjee, D. P., & Kumar, B. (2012). Evaluation of metal contamination in freshly deposited sediment of Hugli Estuary, India. *Archives of Applied Science Research*, *4*(2), 1155–1168. http://scholarsresearchlibrary.com/aasr-vol4-iss2/AASR-2012-4-2-1155-1168.pdf

Niu, L., Li, J., Luo, X., Fu, T., Chen, O., & Yang, Q. (2021). Identification of heavy metal pollution in estuarine sediments under long-term reclamation: Ecological toxicity, sources and implications for estuary management. *Environmental Pollution*, *290*, 118126. https://doi.org/10.1016/j.envpol.2021.118126

Qi, S., Leipe, T., Rueckert, P., Di, Z., & Harff, J. (2010). Geochemical sources, deposition and enrichment of heavy metals in short sediment cores from the Pearl River Estuary, Southern China. *Journal of Marine Systems*, *82*, S28–S42. https://doi.org/10.1016/j.jmarsys.2010.02.003

24711403, 2026, 11, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GH002170, Wiley Online Library on [19/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Raj, S., Jee, P. K., & Panda, C. R. (2013). Textural and heavy metal distribution in sediments of Mahanadi Estuary, East Coast of India. *Indian Journal of Geo-Marine Sciences*, *42*(3), 370–374. https://www.researchgate.net/profile/Sudarshan-Raj-2/publication/248400050_Textural_and_heavy_metal_distribution_in_sediments_of_Mahanadi_estuary_East_coast_of_India/links/02e7e51dfdfaf46c8a000000/Textural-and-heavy-metal-distribution-in-sediments-of-Mahanadi-estuary-East-coast-of-India.pdf

Ramesh, R., Ramanathan, A. L., James, R. A., Subramanian, V., Jacobsen, S. B., & Holland, H. D. (1999). Rare Earth elements and heavy metal distribution in estuarine sediments of the east Coast of India. *Hydrobiologia*, *397*, 89–99. https://doi.org/10.1023/A:1003646631589

Rokade, M. A. (2009). Heavy metal burden in coastal marine sediments of North West Coast of India in relation to pollution. *Doctoral dissertation, National Institute of Oceanography, Goa, India*. http://drs.nio.org/drs/handle/2264/3826

Rule, J. H. (1986). Assessment of trace element geochemistry of Hampton roads harbor and lower Chesapeake Bay area sediments. *Environmental Geology and Water Sciences*, *8*(4), 209–219. https://doi.org/10.1007/BF02524948

Sahu, K. C., & Bhosale, U. (1991). Heavy metal pollution around the island city of Bombay, India. Part I: Quantification of heavy metal pollution of aquatic sediments and recognition of environmental discriminants. *Chemical Geology*, *90*(3–4), 263–283. https://doi.org/10.1016/0009-2541(91)90104-Y

Samanta, S., Amrutha, K., Dalai, T. K., & Kumar, S. (2017). Heavy metals in the Ganga (Hooghly) River Estuary sediment column: Evaluation of association, geochemical cycling and anthropogenic enrichment. *Environmental Earth Sciences*, *76*(4), 1–14. https://doi.org/10.1007/s12665-017-6451-x

Selvam, A. P., Priya, S. L., Banerjee, K., Hariharan, G., Purvaja, R., & Ramesh, R. (2012). Heavy metal assessment using geochemical and statistical tools in the surface sediments of Vembanad Lake, Southwest Coast of India. *Environmental Monitoring and Assessment*, *184*(10), 5899–5915. https://doi.org/10.1007/s10661-011-2389-8

Shen, J. J., Fan, D. J., Yang, D. F., Qi, H. Y., & Xu, L. (2008). Distribution patterns of heavy metals in surface sediments of the Yangtze Estuary and its adjacent areas and environmental quality assessment. *Chinese Journal of Environmental Science*, *29*, 2405–2412.

ShyleshChandran, M. S., Ramasamy, E. V., Mohan, M., Jayasooryan, K. K., Augustine, T., & Mohan, K. (2019). Distribution and risk assessment of trace metals in multifarious matrices of Vembanad Lake system, peninsular India. *Marine Pollution Bulletin*, *145*, 490–498. https://doi.org/10.1016/j.marpolbul.2019.06.034

Song, M., Yin, P., Zhao, L., Jiao, Z., Duan, S., & Lu, G. (2016). Distribution and risk assessment of heavy metals in sediments of the Pearl River Estuary, Southern China. *Soil and Sediment Contamination: International Journal*, *25*(2), 101–116. https://doi.org/10.1080/15320383.2014.916251

Sruthi, S. N., Shyleshchandran, M. S., Mohan, M., & Ramasamy, E. V. (2018). Distribution of priority pollutants in the sediment of Vembanad Estuary, Peninsular India. *Marine Pollution Bulletin*, *133*, 294–303. https://doi.org/10.1016/j.marpolbul.2018.05.033

Subramanian, V. (1993). Phosphorus, silicon, and some trace contaminants in the Ganges Estuary. *Estuaries*, *16*(3), 453–458. https://doi.org/10.2307/1352593

Subramanian, V., Jha, P. K., & Van Grieken, R. (1988). Heavy metals in the Ganges estuary. *Marine Pollution Bulletin*, *19*(6), 290–293. https://doi.org/10.1016/0025-326X(88)90602-9

Sun, Z., Mou, X., Tong, C., Wang, C., Xie, Z., Song, H., et al. (2015). Spatial variations and bioaccumulation of heavy metals in intertidal zone of the Yellow River Estuary, China. *Catena*, *126*, 43–52. https://doi.org/10.1016/j.catena.2014.10.037

Trifuoggi, M., Ferrara, L., Toscanesi, M., Mondal, P., Ponniah, J. M., Sarkar, S. K., & Arienzo, M. (2022). Spatial distribution of trace elements in surface sediments of Hooghly (Ganges) river Estuary in West Bengal, India. *Environmental Science and Pollution Research*, *29*(5), 6929–6942. https://doi.org/10.1007/s11356-021-15918-8

Wang, S., Cao, Z., Lan, D., Zheng, Z., & Li, G. (2008). Concentration distribution and assessment of several heavy metals in sediments of west-four Pearl River Estuary. *Environmental Geology*, *55*(5), 963–975. https://doi.org/10.1007/s00254-007-1046-6

Wang, Y., Ling, M., Liu, R. H., Yu, P., Tang, A. K., Luo, X. X., & Ma, Q. (2017). Distribution and source identification of trace metals in the sediment of Yellow River Estuary and the adjacent Laizhou Bay. *Physics and Chemistry of the Earth, Parts A/B/C*, *97*, 62–70. https://doi.org/10.1016/j.pce.2017.02.002

Wu, B., Song, J. M., & Li, X. G. (2013). Environmental characteristics of heavy metals in surface sediments from the Huanghe Estuary. *Huan Jing ke Xue= Huanjing Kexue*, *34*(4), 1324–1332.

Wu, Q., Li, R., Chen, J., Yang, Z., Li, S., Yang, Z., et al. (2024). Historical construction, quantitative source identification and risk assessment of heavy metals contamination in sediments from the Pearl river Estuary, South China. *Journal of Environmental Management*, *359*, 120943. https://doi.org/10.1016/j.jenvman.2024.120943

Wu, X. Y., Liu, R. H., Qin, J., Sun, P. Y., Gao, Z. H., & Jia, Y. G. (2007). Study on the variance character of heavy metals contents in sediments in Yellow River Estuary. *Transactions of Oceanology and Limnology*, *1*, 69–74.

Yang, Y., Chen, F., Zhang, L., Liu, J., Wu, S., & Kang, M. (2012). Comprehensive assessment of heavy metal contamination in sediment of the Pearl River Estuary and adjacent shelf. *Marine Pollution Bulletin*, *64*(9), 1947–1955. https://doi.org/10.1016/j.marpolbul.2012.04.024

Yu, X., Yan, Y., & Wang, W. X. (2010). The distribution and speciation of trace metals in surface sediments from the Pearl River Estuary and the Daya Bay, Southern China. *Marine Pollution Bulletin*, *60*(8), 1364–1371. https://doi.org/10.1016/j.marpolbul.2010.05.012b

Zhang, W., Feng, H., Chang, J., Qu, J., Xie, H., & Yu, L. (2009). Heavy metal contamination in surface sediments of Yangtze River intertidal zone: An assessment from different indexes. *Environmental pollution (Barking, Essex : 1987)*, *157*(5), 1533–1543. https://doi.org/10.1016/j.envpol.2009.01.007

Zhang, D., Zhang, X., Tian, L., Ye, F., Huang, X., Zeng, Y., & Fan, M. (2013). Seasonal and spatial dynamics of trace elements in water and sediment from Pearl River Estuary, South China. *Environmental Earth Sciences*, *68*(4), 1053–1063. https://doi.org/10.1007/s12665-012-1807-8

Zhao, G., Ye, S., Yuan, H., Ding, X., & Wang, J. (2017). Surface sediment properties and heavy metal pollution assessment in the Pearl River Estuary, China. *Environmental Science and Pollution Research*, *24*(3), 2966–2979. https://doi.org/10.1007/s11356-016-8003-4

Zhuang, H., Gao, M., Yan, C., Cao, Y., & Zhang, J. (2020). Vertical profiles and contamination assessments of heavy metals in sediment cores from typical intertidal zones in northern China. *Marine Pollution Bulletin*, *159*, 111442. https://doi.org/10.1016/j.marpolbul.2020.111442

Zhang, Y. N. (2013). Estuarine processes and sediment pollution risk assessment of heavy metals in the yellow River Estuary, Yangtze River Estuary, Pearl River Estuary, and adjacent sea areas. *Third Institute of Oceanography, State Oceanic Administration, Xiamen, China*. http://refhub.elsevier.com/S0025-326X(25)01068-9/rf0370

24711403, 2026, 11, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GH002170, Wiley Online Library on [19/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License