Vietnam Journal of Marine Science and Technology 2024, 24(1) 17–32

Vietnam Academy of Science and Technology

Vietnam Journal of Marine Science and Technology

journal homepage: vjs.ac.vn/index.php/jmst

Heavy metals assessment for sustainable management in estuaries of Ba Ria-Vung Tau Province

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Received: 21 September 2023; Accepted: 26 October 2023

ABSTRACT

Heavy metal concentration in the aquatic environment of estuaries is a significant environmental concern with potential consequences for ecosystems and human health. Heavy metals are naturally occurring elements that can enter aquatic environments through both natural processes and human activities. The interplay between natural processes and human activities, particularly urbanization and industrialization, often exacerbates heavy metal pollution in aquatic ecosystems. Some of the most common heavy metals of concern in estuarine pollution include arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb), zinc (Zn), and iron (Fe). Based on the results of two surveys in rainy and dry seasons, the paper aims to assess the concentrations of heavy metals in the estuarine environment of Ba Ria-Vung Tau Province, Vietnam, to understand the extent of contamination and its potential impacts on the ecosystem and human health. The average concentrations As, Cd, Hg, Pb, Zn, and Fe were 2.01, 0.024, 0.028, 1.63, 4.71, and 492.9 µg/L in water, and 6.70, 0.175, 0.060, 11.78, 41.94, and 3,108.9 mg/kg in sediment, respectively. Heavy metal concentrations in water have an increased trend during the rainy season. In contrast, values in sediment exhibit an opposite pattern, which can be explained by various environmental factors and processes. For water and sediment quality, individual metals, and overall metal contamination levels (the contamination factor - C_f, contamination degree - C_d, and metal pollution index - *MPI*) may appear to be low, whereas the assessment of the combined effects of multiple metals (Metal quality index - $MI > 1$) indicates that there is a potential risk to aquatic life in the estuaries. This assessment may underscore the importance of considering not only individual metal concentrations but also their cumulative effects when evaluating water and sediment quality and making decisions regarding protecting aquatic ecosystems. Further investigations and measures may be needed to mitigate potential harm to aquatic organisms and for sustainable management in estuaries.

Keywords: Heavy metal, water quality, sediment quality, estuaries, Ba Ria-Vung Tau.

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https://doi.org/10.15625/1859-3097/18976

ISSN 1859-3097; e-ISSN 2815-5904/

INTRODUCTION

Balancing economic development with the environmental protection of estuarine ecosystems is essential to ensure their long-term sustainability. Estuaries play a crucial role in economic development, offering various benefits and supporting various industries and activities. These unique coastal ecosystems provide a valuable interface between freshwater rivers and marine environments, making them highly productive and necessary for both local economies and the broader regional economy. However, it is essential to acknowledge that many economic activities and industries mentioned can also have adverse environmental impacts, mainly when waste discharges are not adequately managed. These discharges can contain dissolved compounds and suspended matter, harming water quality and, subsequently, ecosystems and human health. Heavy metals can enter the aquatic environment through a combination of natural processes (geological weathering, precipitation, erosion, and bioturbation) and human activities (industrialization, urbanization, agriculture) [1–6]. Human activities are the primary sources of heavy metal emissions into aquatic environments. Various anthropogenic activities, including the generation of domestic waste, industrial emissions, and the indiscriminate use of pesticides and fertilizers, can result in the accumulation of heavy metals in aquatic environments [7, 8]. Heavy metals contamination in the aquatic environment can have significant negative impacts on both the ecosystem and various environmental parameters, such as pH and salinity [9]. Moreover, heavy metal pollution exerts significant pressure on the environment due to several key characteristics, including toxicity, bioaccumulation, biomagnification, and non-degradability, which make them significant threats to living organisms and aquatic ecosystems through the food chain [10–14], so they can also lead to diseases and health complications in humans [15–18]. This phenomenon directly impacts human health and underscores the importance of addressing heavy metal pollution in aquatic environments.

In estuaries, heavy metal concentrations often exhibit different fluctuation patterns in water and sediment environments. The tendency for heavy metals to accumulate in sediments, because of adsorption and precipitation processes, leads to higher levels of these metals in sediments compared to the overlying water [19, 20]. Thus, sediments are widely recognized as a major sink for heavy metals in the aquatic environment [20], and they serve as effective indicators of metal pollution in rivers, estuaries, and other aquatic environments. Therefore, assessing the spatiotemporal variation of heavy metal contamination and conducting risk assessments are crucial steps in evolving effective pollution control and management strategies. Additionally, evaluating heavy metal levels in water and sediments can help identify pollution sources and guide targeted remediation efforts. Their ability to integrate, retain, and record heavy metals makes them effective indicators for monitoring and managing metal contamination, ultimately contributing to protecting aquatic ecosystems and human health.

The estuaries in Ba Ria-Vung Tau Province, located on the coast of the Southeast region of Vietnam, including Dinh, Cha Va, and Mo Nhat Estuaries, have many favorable conditions for developing an urban integrated marine economy, including port economy, tourism, industry, and aquaculture, and preserving marine life. The province has a tropical monsoon climate with two distinct seasons: a rainy season from May to October and a dry season from November to April. The average annual temperature is 27^{o}C, ranging from an average monthly temperature of 24.8^{o}C to 28.6^{o}C. The environmental quality of these estuaries is influenced by the activities of three large urban areas (Vung Tau, Ba Ria, and Phu My Cities), about 40 seafood processing factories, 46 ports (https://baria-vungtau.gov.vn/), and several industrial zones. The discharge of seafood production wastewater, domestic waste, pesticides from agriculture, aquaculture waste, and boat oils directly into rivers is a significant environmental concern that can lead to the pollution of estuaries and aquatic resources. Each of the pollution sources mentioned can indeed contribute to the introduction of heavy metals into aquatic environments, further exacerbating the deterioration of water quality and the potential harm to ecosystems.

This paper aims to evaluate the spatiotemporal distribution of six heavy metals (arsenic - As, cadmium - Cd, mercury - Hg, lead - Pb, zinc - Zn, and iron - Fe) in water and sediment environment and assess the pollution status of the heavy metals based on individual metals and overall metal contamination levels as well as a multiple metals index for the monitoring and sustainable management of estuarine environment of Ba Ria-Vung Tau Province.

MATERIALS AND METHODS

Collecting, preparing, and storing samples

The paper conducted two surveys for collecting water and sediment samples at 12 stations in the rainy season (in June and July 2022) and dry season (Dec 2022–Jan 2023) in Dinh River (station code: SD#), Cha Va River (CV#), Mo Nhat River (MN#) and reference station TV1 in the Ganh Rai Bay. These regions supply irrigation, navigation, aquaculture, and industrial activities (Fig. 1, Table 1). However, there are various activities and their impacts on specific regions, especially regarding heavy metal contamination in water bodies, such as industrial effluents, solid waste, domestic wastewater, and port activities.

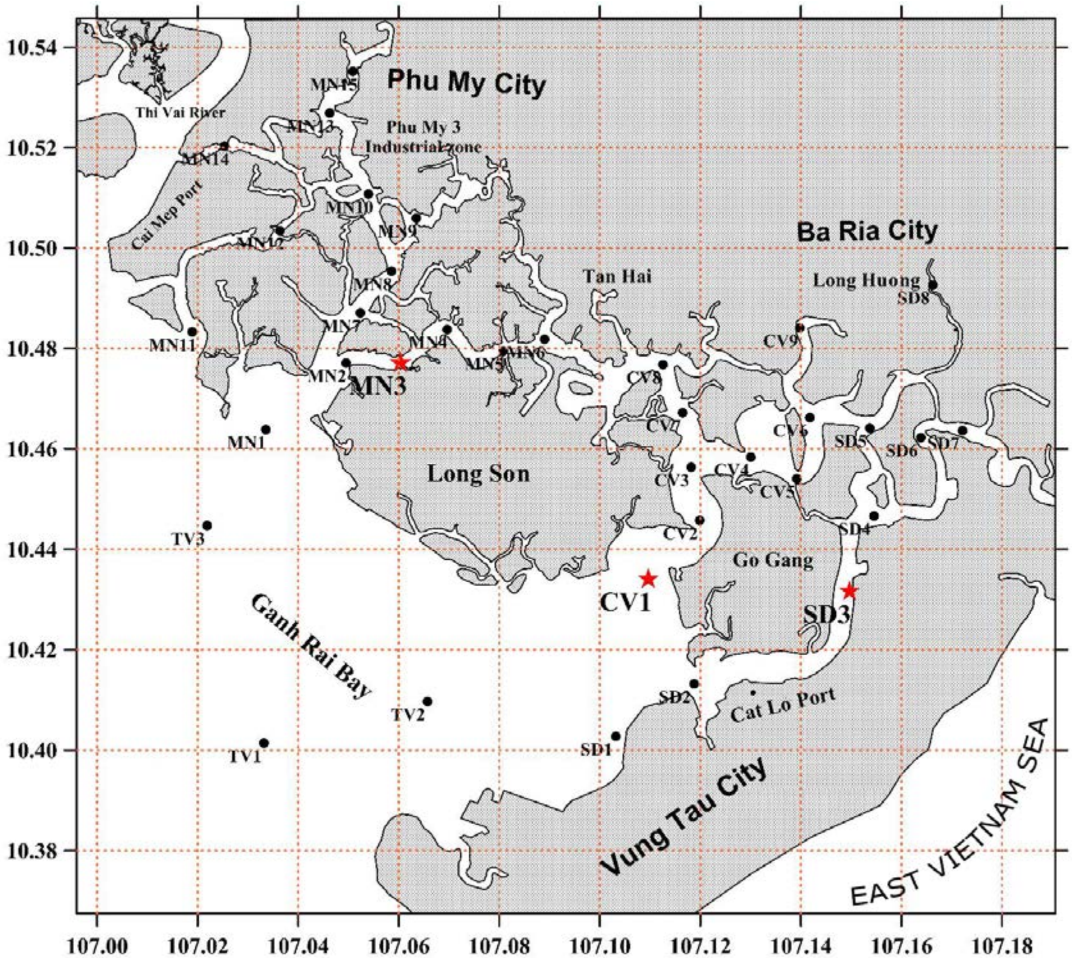

Figure 1. Sampling stations in estuaries of Ba Ria-Vung Tau Province

Table 1. Sampling location

Rivers	Cha Va	Dinh River	Mo Nhat
Station	CV2, CV4, CV8, CV9	SD2, SD4, SD7	MN2, MN4, MN8, MN15
Location	Ba Ria and Vung Tau Cities	Vung Tau City	Phu My District
Dominating activities	Aquaculture	Navigation Aquaculture	Industrial areas, port activities Aquaculture

Water samples were collected using the Niskin Water Sampler 6 L at the surface of the 1 m layer. The water samples were contained in polyethylene plastic bottles, acidified to pH = 2 with HNO_3 (65% supra pure, Merck), and kept at 4°C until analysis. Surface sediment samples were collected with steel stainless grab, sealed in polythene bags, and kept at 4°C until analysis.

Sample treatment and analysis

In the lab, water samples were digested by heating with HNO_3. The digested water samples were filtered and adjusted to a final volume of 10 mL. The sediment samples were dried using an oven at 105°C for 12 h and homogenized. After that, the samples, consisting of 2 grams each, underwent digestion in a Teflon beaker. This process involved the addition of 5 mL of 65% HNO_3 and 2 mL of 35% HCl. The temperature was raised to 170°C for 15 minutes using a microwave MARSXpress and then maintained at this temperature for 30 minutes. The treated samples were cooled at room temperature overnight, filtered, and diluted to 50 mL with 2% HNO_3. Heavy metal concentrations in samples were determined using SMEWW 3125B methodology [21] by Inductively Coupled Plasma Mass Spectrometer (ICP-MS Shimadzu 2030, Japan). The standard recovery rates for quality control ranged from 80–110%. The calibration curves were established with the variation of correlation coefficients from 93–99%.

Assessment of potential ecological risk

Table 2. The assessment indices used in this study for the evaluation of metal contamination

Quality indices	Formula	Parameters	Assessment criteria
Water			
Metal pollution index - *MPI* [22]	$MPI = \sqrt{\frac{\left(\frac{C}{L}\right)_M^2 + \left(\frac{C}{L}\right)_R^2}{2}}$	*C*: Observed concentration of metal in water; *L*: Standard permissible value of the metal; $(C/L)_M$: Maximum value of (*C*/*L*); $(C/L)_R$: Average value of (*C*/*L*)	0 ~ 1: Good quality; 1 ~ 5: Lightly polluted; 5 ~ 10: Moderately polluted; > 10: Heavily polluted
Metal quality index - *MI* [23]	$MI = \sum_{i-1}^{n} \frac{C_i}{(MAC)_i}$	*C*: Measured concentration of metal in water; *MAC*: Maximum allowed concentration for the metal in water	< 0.3: Very pure; 0.3 ~ 1.0: Pure; 1.0 ~ 2.0: Slightly affected; 2.0 ~ 4.0: Moderately affected; 4.0 ~ 6.0: Strongly affected; > 6.0: Seriously affected
Sediment quality			
Contamination factor (C_f) [24] Degree of contamination (C_d) [24]	$C_f = \frac{M_x}{M_b}$ $C_d = \sum_i^n C_f^i$	M_x: Mean measured concentration of a target metal in all sub-sediment samples; M_b: Pre-industrial "baseline" sediments	< 1: Low contamination; 1 ~ 3: Moderate contamination; 3~6: Considerable contamination; 6 ~ 12: oderate; 12 ~ 24: considerable; > 24: Very high degree of contamination

Contamination factor (C_f), Contamination degree (C_d), and Metal pollution index (*MPI*) were applied to evaluate individual metals and overall metal contamination levels. In contrast, the Metal Quality Index (*MI*) assessed the combined effects of multiple metals. The calculations and contamination degrees are presented in Table 2.

RESULTS

Situation of heavy metal in aquatic environment in estuaries

The average concentration of observed metals in water followed the decreasing order Fe (492.9 µg/L) > Zn (4.71 µg/L) > As (2.01 µg/L) > Pb (1.63 µg/L) > Hg (0.03 µg/L) > Cd (0.02 µg/L) (Table 3). These results indicated that all observed heavy metal concentrations in surface water were within national standards, suggesting that the water quality meets the regulatory criteria set by QCVN 08:2015/BTNMT [25].

For the spatiotemporal term, observation of heavy metal concentrations in surface water during both dry and rainy seasons is illustrated in Figure 2. It notes that during the dry season, the spatial variation of most heavy metals was unclear except for As and Hg, which were highly concentrated downstream and near the sea. In contrast, during the rainy season, the spatial variation became more evident, likely due to increased water flow and dilution effects. The concentrations of As, Cd, and Zn in the upstream waters of Cha Va and Mo Nhat were higher than in downstream waters, likely due to sewage from industrial activities in those areas. Additionally, in the Dinh River, high Zn concentrations were observed in the downstream area (Stations SD2, SD4), potentially because of effluents from the nearby port area. Based on the distribution of Pb concentrations in the Dinh River, the concentrations decrease from upstream to downstream. It also notes that the distribution trend of Pb concentrations in the Cha Va and Mo Nhat Rivers needs to be clarified. Pb and Zn contamination in the Dinh River is attributed to activities in the nearby port area and daily boat and ship operations.

Table 3. The average values, and ranges of the observed metals in water (µg/L)

Region	Value	As	Cd	Hg	Pb	Zn	Fe
Dry season							
Cha Va (*n* = 4)	Mean	2.14	0.021	0.064	1.79	4.37	433
	Range	1.87–2.54	0.011–0.033	0.011–0.115	0.89–2.59	3.09–6.74	313–618
Dinh (*n* = 3)	Mean	1.16	0.033	0.019	2.19	3.38	283
	Range	1.05–1.31	0.025–0.038	0.006–0.044	0.69–3.47	3.23–3.59	144–360
Mo Nhat (*n* = 4)	Mean	1.74	0.022	0.017	1.36	3.95	427
	Range	1.40–2.13	0.017–0.031	0.008–0.031	1.13–1.71	3.32–4.59	186–513
Background		0.71	0.006	0.005	0.79	1.5	112
Rainy season							
Cha Va (*n* = 4)	Mean	2.59	0.022	0.023	1.68	6.99	522
	Range	1.99–3.57	0.014–0.039	0.005–0.041	0.22–4.69	3.33–10.34	363–618
Dinh (*n* = 3)	Mean	2.12	0.015	0.036	3.45	7.33	681
	Range	1.74–2.64	0.013–0.019	0.035–0.037	2.22–5.62	4.56–8.86	609–806
Mo Nhat (*n* = 4)	Mean	2.24	0.040	0.017	0.44	3.12	661
	Range	1.80–2.74	0.006–0.073	0.007–0.034	0.30–0.59	2.07–4.22	272–853
Background		2.78	0.016	0.009	0.44	5.6	656
QCVN 08-2015 (A1 column)		10	5	1	20	500	500

Additionally, the statement briefly mentions that higher Fe concentrations in water are related to erosion processes, which are more active during the rainy season. Whereas the spatial distribution of Fe concentrations in the studied water bodies was unclear in most cases, there was a noticeable pattern of decreasing Fe concentrations from the upstream to the downstream area in the Dinh River. Furthermore, the elevated metal concentrations observed in these water bodies, exceeding background levels, indicate that terrestrial activities, such as industrial, agricultural, or urban activities, are the main contributors to metal contamination in the water.

Most metals did not show significant temporal variations; Fe concentrations increased during the rainy season due to surface runoff. Additionally, during the rainy season, metal concentrations were more concentrated in the upstream areas of the studied estuaries, particularly in areas with industrial plants. Specific metals like As, Zn, Cd, and Hg exhibited increased concentrations in these upstream areas during the rainy season, indicating a potential link to industrial activities and surface runoff.

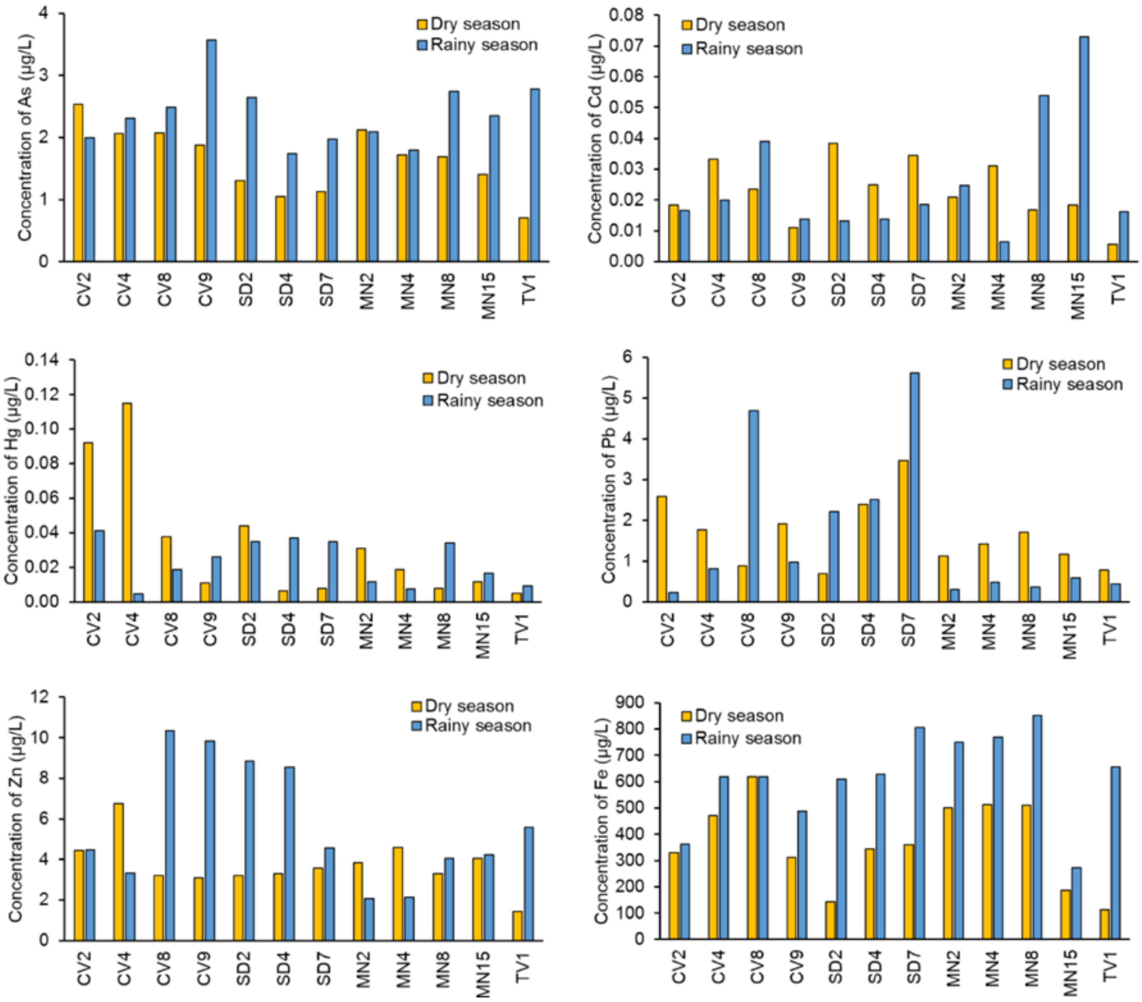

Figure 2. Heavy metal concentrations in estuarine water in Ba Ria - Vung Tau

Situation of heavy metal in the sediment environment of estuaries

The results provided information about the mean concentration of heavy metals in a sedimentary environment, specifically in studied estuaries (Table 4 and Figure 3). The mean concentration ranked in order of Fe (3,218 mg/kg) > Zn (42.32 mg/kg) > Pb (12.17 mg/kg) > As (6.91 mg/kg) > Cd (0.187 mg/kg) > Hg (0.064 mg/kg) indicated the relative abundance of these heavy metals in the sediment of the estuaries. Generally, all observed heavy metal concentrations in sediment samples were found to be within national standards of QCVN 43:2017 BTNMT [26] (Table 4). The concentrations of the observed heavy metals in the sediment samples were 1.02 to 7.87 times higher than the background levels, suggesting that the sediment in the estuaries was lightly polluted with these heavy metals.

Table 4. The average values, and ranges of the observed metals in sediment (mg/kg)

Region	Value	As	Cd	Hg	Pb	Zn	Fe
Dry season							
Cha Va (*n* = 4)	Mean	7.74	0.058	0.050	15.49	47.90	3,569
	Range	4.50–10.63	0.030–0.086	0.011–0.118	6.16–26.29	25.20–60.35	2,036–4,791
Dinh (*n* = 3)	Mean	6.04	0.125	0.037	10.60	31.91	2,188
	Range	4.74–8.36	0.030–0.200	0.013–0.062	6.64–15.05	21.70–50.56	1,666–2,792
Mo Nhat (*n* = 4)	Mean	7.70	0.363	0.045	10.42	50.82	3,757
	Range	5.26–10.68	0.146–0.921	0.014–0.082	7.25-16.04	38.76–60.85	2,009–4,660
Background		4.39	0.051	0.031	7.06	25.38	2,026
Rainy season							
Cha Va (*n* = 4)	Mean	6.14	0.077	0.105	11.18	42.42	3,517
	Range	3.92–8.68	0.054–0.095	0.047–0.201	6.23–16.42	15.72–61.05	2,445–5,208
Dinh (*n* = 3)	Mean	3.96	0.127	0.056	8.44	23.69	1,711
	Range	3.26–4.44	0.065–0.208	0.027–0.092	4.90-11.78	15.13–32.90	1,557–1,977
Mo Nhat (*n* = 4)	Mean	8.92	0.342	0.081	15.54	49.92	3,931
	Range	5.53–10.72	0.089–0.972	0.020–0.145	12.22-19.15	29.09–88.32	1,935–5,379
Background		4.52	0.039	0.009	8.11	50.06	1,799
QCVN 08-2015 (A1 column)		41.6	4.2	0.7	112	271	-

Similar to the aquatic environment, the heavy metal content in sediment also fluctuates significantly over space and time (Figure 3). In the case of the Dinh River, the heavy metal contents in its sediment were found to be lower when compared to the values observed in the Cha Va and Mo Nhat Rivers. While the overall heavy metal content was lower in the Dinh River, it is noted that the spatial distribution of Cd and Hg contents in the sediment was not apparent. In other words, there may be variations in the concentrations of cadmium and mercury within the river system. The highest values of Cd were found in the upstream areas of the Mo Nhat River (MN15), and the highest values of Hg were found in the upstream areas of the Cha Va River (CV9). These specific locations may have unique factors contributing to the elevated levels of these heavy metals. The decreasing trend in the concentrations of heavy metals such as As, Pb, Zn, and Fe from the upstream areas to the downstream areas of the Cha Va and Mo Nhat Rivers is an interesting observation. The highest concentrations of heavy metals were recorded at station CV9 (Pb, Zn), MN8 (Fe), and MN15 (As). It might be explained by the influence of local management, including urban release of sewage and industrial effluents, along with the contribution of increased heavy metal concentrations in upstream water as the primary source for elevated heavy metal concentrations in sediment upstream, is accurate and aligns with typical patterns observed in river systems affected by pollution.

The temporal distribution of heavy metals in these estuaries was influenced by seasonal factors, with dilution and sedimentation playing critical roles in the observed variations between the rainy and dry seasons. In the Cha Va and Dinh Estuaries, the average contents of heavy metals such as As, Pb, Zn, and Fe were lower during the rainy season compared to the dry season. In contrast, in the Mo Nhat estuary, there was no significant difference in heavy metal levels between the rainy and dry seasons. In the rainy season, increased precipitation leads to a dilution effect, which may result in lower concentrations of heavy metals in the rivers. The result could be because the heavy metals become more dispersed in the larger volume of water. In the dry season, decreased river flow can promote the sedimentation of heavy metals, meaning that the heavy metals settle and accumulate in the river sediment during periods of lower flow.

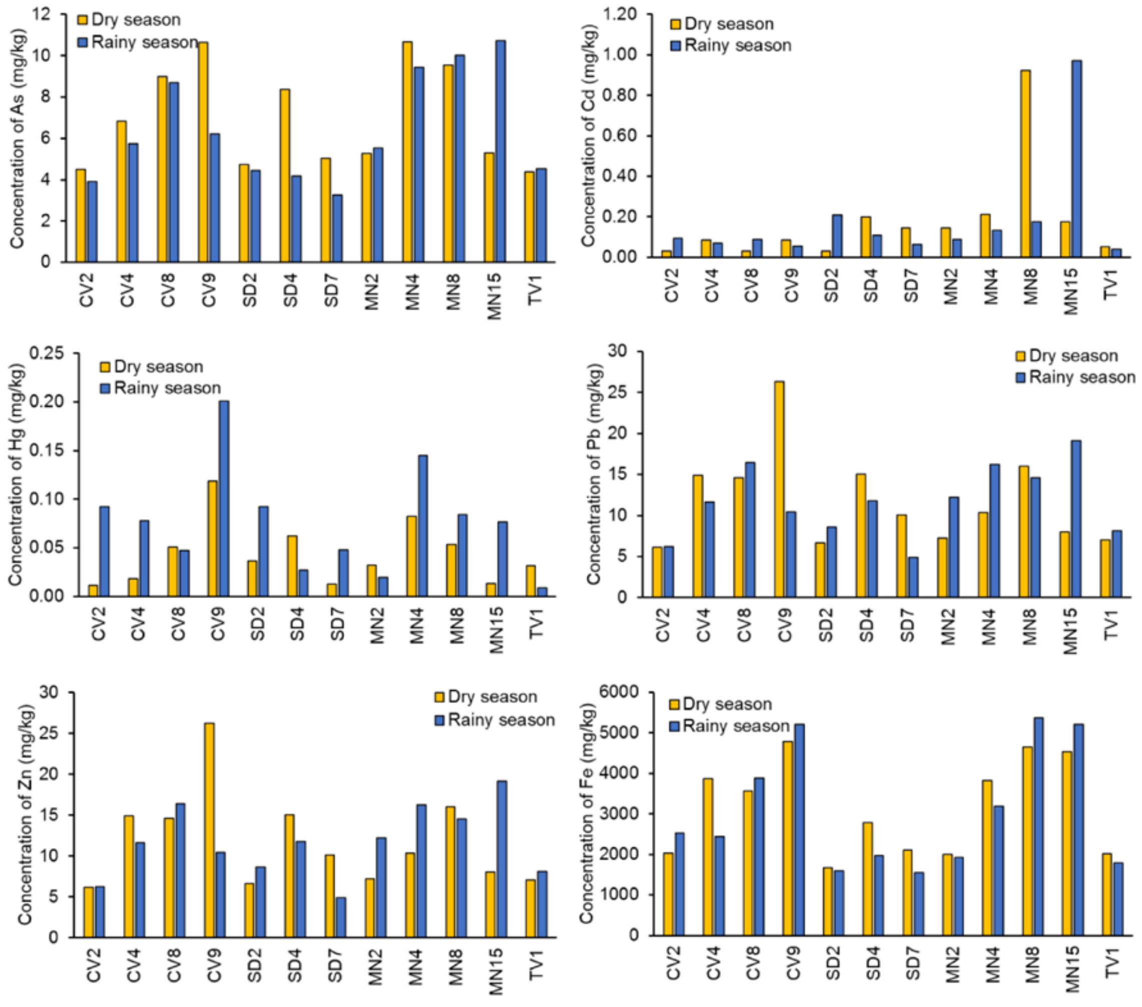

Figure 3. Heavy metal concentrations in sediment

DISCUSSIONS

Assessment of water quality

The metal pollution index (*MPI*) is an effective water pollution assessment tool. It describes the contamination status of the individual metal in water and is used to assess the metal pollution level in water bodies, specifically to protect aquatic life. The study calculated the *MPI* for six metals during both the dry season and the rainy season (Table 5). During the dry season, the calculated *MPI* values ranged from 0.005 to 1.081 for the six metals, whereas during the rainy season, the *MPI* values ranged from 0.003 to 1.559 for the same metals. Based on *MPI* standards for aquatic life protection. The results indicated that Fe was considered lighter pollution, with an MPI value greater than 1, implying that Fe levels in the water may be of less concern for aquatic life during both the dry and rainy seasons. On the other hand, the other metals (As, Cd, Hg, Pb, and Zn) do not pose a significant threat to aquatic life with *MPI* values less than 1. However, the *MPI* values show increased metal pollution in the Mo Nhat and Dinh Rivers during the rainy season due to surface runoff, highlighting the importance of understanding seasonal variations in water quality and pollution.

Table 5. Overall assessment of metal contamination levels in water

Sampling sites	Multiple metals	Estuary	The individual metals - Metal pollution index (*MPI*)					
	Metal quality index (*MI*)		As	Cd	Hg	Pb	Zn	Fe
Dry season								
CV2	1.15	Cha Va	0.235	0.006	0.098	0.113	0.012	1.081
CV4	1.37							
CV8	1.54							
CV9	0.93							
SD2	0.51	Dinh	0.132	0.007	0.035	0.146	0.008	0.641
SD4	0.93							
SD7	1.03							
MN2	1.31	Mo Nhat	0.200	0.006	0.027	0.079	0.009	1.021
MN4	1.30							
MN8	1.29							
MN15	0.59							
Rainy season								
CV2	0.99	Cha Va	0.315	0.006	0.034	0.187	0.018	1.154
CV4	1.52							
CV8	1.77							
CV9	1.43							
SD2	1.75	Dinh	0.251	0.009	0.029	0.022	0.007	1.646
SD4	1.76							
SD7	2.05							
MN2	1.61	Mo Nhat	0.243	0.012	0.035	0.230	0.016	1.429
MN4	2.14							
MN8	0.85							
MN15	1.65							

The metal quality index (*MI*) was used as a spatial measurement to assess the quality of water in different sites within the Cha Va, Mo Nhat, and Dinh Estuaries based on the presence of multiple metals (Table 4). The mean MI values for the Cha Va, Mo Nhat, and Dinh Estuaries were 1.34, 1.36, and 1.31, respectively. Bakan et al., [27] proposed that *MI* values greater than 1 indicate low-quality river water for aquatic life protection purposes. This suggests that the water quality in all sampling sites of the Cha Va, Mo Nhat, and Dinh Estuaries was of low quality for the protection of aquatic life. There is a seasonal variation in *MI* values, with an increase during the rainy season, primarily attributed to higher iron concentrations ($p < 0.05$). The main source of metal pollution in these rivers appears to be terrestrial leaching processes, emphasizing the importance of understanding and mitigating land-based sources of pollution for aquatic ecosystems.

Assessment of sediment quality

The contamination factor (C_f) is a practical approach used to assess the contamination status of individual metals in sediments (Hakanson, 1980). The assessing results indicated the concentration factors (C_f) of various metals in sediments during both the dry season and the rainy season, as well as the overall contamination degree (C_d) of the sediments. The sediments had relatively low levels of contamination for the observed metals. In the dry season, the order of C_f values for the metals from highest to lowest is As (0.47), Zn (0.25), Cd (0.18), Hg (0.17), and Pb (0.17). In the rainy season, the order is As (0.45), Zn and Hg (both 0.24), Cd (0.18), and Pb (0.17) (Table 6). Overall, the average C_f values were highest for As and lowest for Pb, suggesting that during both seasons, the sediments have higher concentrations of As than other metals, and Pb has the lowest concentration. *The contamination degree (C_d)* is the sum of the C_f values and is used to assess the overall contamination level of the sediments. The C_d values of the six heavy metals for the sediments ranged from 0.61 to 2.35. All C_d values were below 6, which is considered low, further confirming the relatively low contamination of these sediments.

Table 6. Overall assessment of metal contamination levels in sediment

Rivers	Sampling sites	The individual metals					Multiple metals
		Contamination factor (C_f)					Contamination degree (C_d)
		As	Cd	Hg	Pb	Zn	
Dry season							
Cha Va	CV2	0.29	0.05	0.12	0.10	0.15	0.71
	CV4	0.35	0.15	0.13	0.10	0.22	0.95
	CV8	0.71	0.21	0.33	0.15	0.31	1.71
	CV9	0.64	0.92	0.21	0.23	0.35	2.35
Dinh	SD2	0.71	0.08	0.47	0.38	0.34	1.99
	SD4	0.32	0.03	0.15	0.09	0.13	0.72
	SD7	0.56	0.20	0.25	0.21	0.29	1.51
Mo Nhat	MN2	0.30	0.03	0.05	0.09	0.14	0.61
	MN4	0.46	0.09	0.07	0.21	0.29	1.12
	MN8	0.60	0.03	0.20	0.21	0.32	1.36
	MN15	0.35	0.17	0.05	0.11	0.28	0.98
Rainy season							
Cha Va	CV2	0.28	0.06	0.21	0.09	0.12	0.76
	CV4	0.42	0.08	0.19	0.19	0.28	1.16
	CV8	0.59	0.06	0.20	0.22	0.33	1.40
	CV9	0.56	0.07	0.64	0.26	0.31	1.84
Dinh	SD2	0.31	0.12	0.26	0.11	0.16	0.95
	SD4	0.42	0.15	0.18	0.19	0.21	1.15
	SD7	0.28	0.10	0.12	0.11	0.11	0.71
Mo Nhat	MN2	0.36	0.12	0.10	0.14	0.19	0.91
	MN4	0.67	0.17	0.46	0.19	0.28	1.77
	MN8	0.65	0.55	0.28	0.22	0.28	1.98
	MN15	0.53	0.57	0.18	0.19	0.39	1.87

Heavy metal for sustainable management in estuaries of Ba Ria-Vung Tau

Assessing heavy metal contamination in water and sediment environments is a crucial indicator for evaluating environmental quality, both for ecosystems and human health. The individual assessments of specific metals, as well as overall contamination levels using metrics like C_f (concentration factor), C_d (contamination degree), and *MPI* (metal pollution index) in Dinh, Cha Va, and Mo Nhat Estuaries, may suggest low levels of contamination. However, it also emphasizes that the combined effects of multiple metals, as indicated by the Metal Quality Index (*MI*), may surpass a critical threshold (*MI* > 1), indicating a potential risk to aquatic life in estuaries, meaning that even if individual metals are present at relatively low levels, their combined impact can still pose a significant threat to the ecosystem, underscoring the importance of considering the synergistic effects of multiple contaminants when assessing environmental quality and potential risks to aquatic life and, by extension, human health.

In terms of the aquatic environment, the individual concentrations of heavy metals (specifically As, Cd, Hg, Pb, and Zn) of the Dinh, Cha Va, and Mo Nhat Estuaries were relatively low compared to the levels found in some estuaries that discharged into East Vietnam Sea (Table 7). These heavy metals in the aquatic environment were contributed by navigation, aquaculture, food processing, and other industrial activities. High concentrations of these metals were reported in the water from the Red River delta in northern Vietnam, which experienced significant pollution due to industrial discharges, agricultural wastewater, fertilizers, and pesticides in the delta, which likely contributed to the elevated metal levels [28]. The high values of As and Zn in water bodies were attributed to discharges from various industrial sources [29, 30], including mechanical engineering factories, textile factories, leather goods factories, rubber goods factories, tobacco factories, paper factories, and plastics factories. Strady et al., [29] mentioned that the rapid demographic and industrial growth of the economic hub, possibly Ho Chi Minh City in Vietnam is a significant challenge in managing environmental quality and controlling waste discharge into open waters.

Likely to the aquatic environment, the concentrations of heavy metals in sediment from various regions were generally reviewed in Table 7. Their concentrations (including As, Cd, Hg, Pb, and Zn) in sediment from these estuaries in Ba Ria-Vung Tau Estuaries were lower than the background (in station TV1, Table 4) as well as lower than those observed in some other regions, indicating that, in general, the estuaries had relatively lower levels of heavy metal pollution. Nevertheless, the concentration of these metals within sediment appears to be closely linked to economic activities in the area and its surroundings. In the Mekong River region, particularly along the Tien River, where agriculture and aquaculture were the primary economic drivers, the accumulation of heavy metals in sediment was notably lower compared to other estuarine regions in Asia [30]. On the other hand, at Duyen Hai Port, heavy metal levels in sediment have risen due to the influence of numerous submerged activities [35]. A similar pattern emerged in the Saigon River, which experienced increased lead levels owing to the impact of urban and industrial runoff, as well as port operations [29]. Likewise, in the Pearl River region, the substantial influx of wastewater resulting from urbanization, industrialization, and economic growth activities in the Pearl River Delta had led to a significant accumulation of heavy metals in sediment [32]. In all these instances, the broader context suggested a strong correlation between environmental pollution and its potential sources in these regions.

In general, the variation of heavy metal concentration in aquatic and sediment environment in Ba Ria-Vung Tau Estuaries suggests that industrial sources alone may not be the primary cause of heavy metal pollution in these water bodies and proposes that other factors, such as natural processes and variations in metal distribution, may be influencing the observed low levels of heavy metal concentrations. Recognizing multiple factors contributing to water quality issues in the estuaries suggests the need for a holistic and multidisciplinary approach to estuary management. Sustainable management strategies should consider not only industrial activities but also the broader environmental context, including natural processes and upstream inputs. Therefore, the monitoring management strategies could include tracking changes in heavy metal concentrations over time, identifying potential sources, and understanding the role of natural processes. These strategies also engage with various stakeholders, including industries, local communities, and government agencies, for sustainable estuary management. Recognizing the role of both industrial and natural factors in water quality allows for more effective and informed management strategies that protect the environment while promoting sustainable development.

Table 7. Heavy metal concentrations of some estuaries discharged to East Vietnam Sea

Location	As	Cd	Hg	Pb	Zn	Fe	References
Water (µg/L)							
Dinh Estuary	1.05–2.64	0.013–0.038	0.006–0.044	0.69–5.62	3.23–8.86	144–806	This study
Cha Va Estuary	1.87–3.57	0.011–0.039	0.005–0.115	0.22–4.69	3.09–6.74	313–618	This study
Mo Nhat Estuary	1.40–2.74	0.006–0.073	0.007–0.034	0.30–1.71	2.07–4.59	186–853	This study
Cai River, Khanh Hoa, Vietnam	-	-	-	2.60	8.49	329	[31] mean only
Tac River, Khanh Hoa, Vietnam	5.14	-	-	4.21	4.51	-	[31] mean only
Saigon River, Vietnam	0.32–1.66	n.d.–0.163		D.L.–1.00	4.2–107		[29]
Red River, Vietnam	0.38	0.700	0.100	16	47.5	815	[28] mean only
Mekong River, Vietnam	0.8–2.6	0.10–0.24	-	0.01–0.80	4.0–72.0	-	[30]
Pear River, China	0.16–8.18	0.0015–0.30	-	0.19–4.58	3.74–36.10	-	[32]
Sediment (mg/kg)							
Dinh Estuary	3.26–8.36	0.030–0.208	0.013–0.092	4.90–15.05	15.13–50.56	1,557–2,792	This study
Cha Va Estuary	3.92–10.63	0.030–0.095	0.011–0.201	6.16–26.29	15.72–61.05	2,036–5,208	This study
Mo Nhat Estuary	5.26–10.72	0.089–0.972	0.014–0.145	7.25–19.15	29.09–88.32	1,935–5,379	This study
Saigon River	-	0.05	-	1.27	33.7	58.2	[33] mean only
Saigon River, Vietnam	3.6–26.0	n.d.–0.710	-	15–68	175–602		[29]
Red River, Vietnam	-	0.35	-	66	127	-	[34] mean only
Duyen Hai Seaport, Vietnam	18.5	1.67	0.127	72.6	149	-	[35]
Mekong River, Vietnam	8.4–21	0.08–0.31	-	16–39	-	-	[30]
Pear River, China	10.22–22.81	0.04–0.84	-	21.43–63.83	51.88–186.49		[32]

CONCLUSIONS

This paper offers a comprehensive overview of the heavy metal pollution in water and sediment in the water bodies of Dinh, Cha Va, and Mo Nhat Estuaries, including information on compliance with environmental regulations, spatial distribution, temporal variation, background values, and contamination indices. The concentration of heavy metal pollution in water and sediment was found in the National Technical Regulation on Environmental Quality. The average concentrations of heavy metals in both water and sediment were mentioned to exceed background values. These concentrations in both water and sediment were high in the upstream areas, which were affected by industrial activities. During the rainy season, heavy metal concentrations in water increased, possibly due to increased runoff carrying pollutants into the water. In contrast, heavy metal concentrations in sediment decreased during the rainy season, which could be attributed to sediment transport and deposition processes influenced by increased water flow.

Contamination indices such as the Contamination factor (C_f), Contamination degree (C_d), and Metal pollution index (*MPI*) of the measured metals indicated low contamination. Heavy metals might be present above background levels, but they were not at levels that would be considered environmentally harmful or dangerous. Whereas heavy metal concentrations in water and sediment in the studied estuaries were elevated compared to background values, they remained within acceptable limits according to contamination indices. The observation implies that the overall quality of the aquatic environment is not severely compromised by heavy metal pollution despite the influence of anthropogenic activities, particularly industrial sources in the upstream areas. Monitoring and continued assessment of these parameters are essential for ongoing environmental management and protection.

Acknowledgments: The paper was funded by the provincial project "Study on environmental carrying capacity for build up the master plan of sustainable development of aquaculture in Ba Ria-Vung Tau Province" (2021–2023). We also would like to thank MARE project (Grant No. 2019-2079/001-001) for supporting the idea to promote sustainable development in coastal regions.

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