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Heavy metals contamination in coastal waters of South Vietnam

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The study was conducted to estimate the spatial and temporal variations, pollution levels, and potential sources of some heavy metals in the south coastal areas of Vietnam, using data obtained from the national monitoring stations from 2015 to 2021. The concentrations of As, Cr, Cu, Fe, Mn, Pb, and Zn in surface and bottom water samples at seven monitoring sites were analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for heavy metal pollution indexing. Results indicated that concentrations of almost all the heavy metals (As, Cr, Cu, Pb, Mn, and Zn) were lower than the threshold limits. In exception, Fe concentrations were 1.0 – 12.8 fold higher than the standard level of seawater quality in Vietnam. The highest concentrations of Fe, Cu, Mn, Pb, and Zn were observed in Dinh An and Rach Gia sites, which may be due to the influence of strong discharges from local rivers. The Contamination Factor (CF) and Contamination Degree (CD) values were far below 1, indicating that the seawater in these sites is at a low contamination level. The principal component analysis indicated that heavy metal concentrations in Ganh Rai, Dinh An, Rach Gia, and Ha Tien sites might be affected by natural factors; while it might also be caused by anthropogenic activities in Nha Trang, Phan Thiet, and Song Doc sites.

[**Keywords**: Coastal waters, Contamination degrees, Environmental monitoring, Heavy metals, Sources, Vietnam]

Introduction

In recent years, tourism, industrial, and aquaculture activities have been increasing rapidly in Vietnam, especially in the southern coastal areas. Despite economic benefits, these activities may cause negative effects on water quality and ecosystems due to the pollution of nutrients and heavy metals[1]. Among these pollutants, heavy metals are known to be dispensed into the coastal environment from both natural and anthropogenic sources[2,3]. The natural origins of heavy metals in the environment are mainly consequences of weathering and soil erosion[4]. Anthropogenic sources of heavy metals comprise sewage, industrial effluents, agricultural fertilizers, and coastal construction[4-6].

Nha Trang, Phan Thiet, Rach Gia, Ha Tien, and Song Doc sites are affected by coastal urbanization, port, and tourism activities, while the Ganh Rai area is mainly influenced by industrialization[7]. In addition, the Dinh An area is also known to be influenced by the Mekong Riverine flow. Some investigations on heavy metal pollution in the Vietnamese coastal area were conducted in the past[5,8-14]; however, these studies only focused on heavy metal pollution on a local/small scale and the data is collected for a short period. In the present investigation, the concentrations of As, Cr, Cu, Fe, Mn, Pb, and Zn have been studied, to assess pollution levels and potential sources of heavy metals on the Southern coast of Vietnam.

Materials and Methods

The studied area and sampling

The sampling area consists of seven monitoring sites on the South coast of Vietnam, including Nha Trang, Phan Thiet, Ganh Rai, Dinh An, Rach Gia, Song Doc, and Ha Tien (Fig. 1, Table 1) which were monitored for seven years, *i.e.* from 2015 to 2021. A total of 175 surface and bottom water samples were collected twice a year (dry and rainy season) in low tide using a 5L-Niskin water sampler (KC-Denmark). Water samples were collected and stored according to the American Public Health Association Manual[15].

Analytical methods

The concentrations of seven heavy metals, *viz.* arsenic (As), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and zinc (Zn) were determined by an Inductively Coupled Plasma Mass Spectrometer (ICP-MS, Agilent 7500) (after the samples were concentrated and digested). At the same

Table 1 — Characteristic features of monitoring sites along the South Vietnam coast

Monitoring sites	Regions covered and local rivers	Economic activities	Coordinates	Sampling depths (m)
Nha Trang	Nha Trang Bay, central south of Viet Nam. Cai river and Tac river	Transportation and port activities	109°13'12" E; 12°12'45" N	19.5
Phan Thiet	Phan Thiet Bay, central south of Viet Nam. Cai river	Transportation and port activities	108°06'37" E; 10°54'10" N	8
Ganh Rai	Ganh Rai Bay, South Vietnam. Sai Gon river, Dong Nai river, Thi Vai river	Industrial and navigation and port activities	107°01'05" E; 10°23'27" N	9.5
Dinh An	Dinh An Estuary, South Vietnam. Hau river	Agricultural and aquaculture activities	106°20'54" E; 09°31'51" N	8.6
Rach Gia	Rach Gia bay, South Vietnam. Cai Lon river	Urban activities	105°04'07'' E; 09°58'24'' N	2
Song Doc	Ong Doc estuary, South Vietnam. Ong Doc river	Aquaculture, urban and port activities	104°47'45" E; 09°02'05" N	5
Ha Tien	To Chau estuary, South Vietnam. To Chau river	Urban activities	104°28'13" E; 10°21'47" N	5

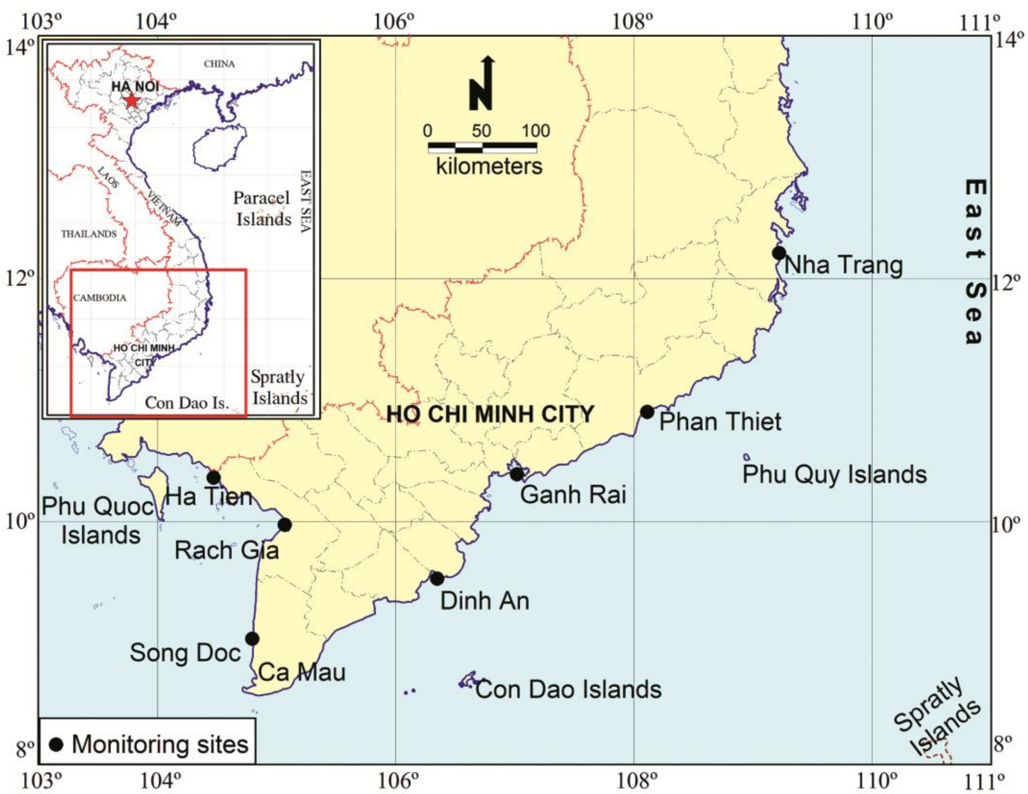

Fig. 1 — Location of monitoring sites on the south coast of Vietnam

time, temperature, salinity, pH, and Dissolved Oxygen (DO) were recorded in the field using a multi-parameter sensor (Handylab 680). Seawater samples were filtered immediately with a cellulose ester Millipore filter (0.45 µm pore size) for Suspended Particulate Matter (SPM) analysis. The Dissolved Inorganic Nitrogen - DIN (the total of NO_2^-, NO_3^-, NH_4^+) and PO_4 were measured using a spectrophotometer (Hitachi U2900).

Assessment of the degree of heavy metal pollution

The Contamination Factor (CF) is used to assess the pollution level of an observed metal in the water environment. The CF is calculated according to the equation:

$$CF = C_{sample} / C_{background}$$

Where, C_{Sample} is the mean content of heavy metal in seawater, and $C_{background}$ is the reference level for the metal[16]. The following criteria are used to describe the values of contamination factor[17], which are CF < 1: low contamination; 1 ≤ CF < 3: moderate contamination; 3 ≤ CF < 6: considerable contamination, and CF ≥ 6: very high contamination.

The Contamination Degree (CD), which represents the pollution level in the environment, is calculated according to the formula:

$$CD = \sum_{i=1}^{n} CFi$$

Where, *n* - represents number of analyzed elements, *i* - i[th] element (or pollutant), and *CF* - contamination factor. The following criteria are used to describe the value of the contamination degree: CD < 6, low contamination; 6 ≤ CD < 12, moderate contamination; 12 ≤ CD < 24, considerable contamination; and CD ≥ 24, very high contamination.

Statistical analysis

The analysis of variance (ANOVA one way) and Student *T*-test 2 tails were used to examine the difference (*p*-values < 0.05) of metal concentrations spatially and seasonally. Pearson correlation analysis was used to observe the correlations among metals and among metals and physico-chemical parameters. The principal component analysis was applied to estimate the potential sources of heavy metals for each station. Statistical analyses were carried out with Minitab 18.

Results and Discussion

The physico-chemical parameters of seawater

The physico-chemical parameters of water samples are illustrated in Figure 2. Values of pH, salinity, temperature, DO, SPM, PO_4, and DIN varied from 6.94 – 8.26, 2.5 – 34.6 ‰, 26.7 – 31.7 °C, 3.75 – 6.60 mgO_2/L, 1.9 – 252.4 mg/L, 4.7 – 63.5 µgP/L, and 30.8 – 718.4 µgN/L, respectively. The spatial differences of physico-chemical parameters in water samples were observed obviously ($p < 0.05$). The highest and lowest pH values were recorded in Nha Trang and Ha Tien, respectively (Fig. 2a). The water temperature showed an opposite pattern (Fig. 2c) to pH values. SPM clearly varied among the sampling sites, with the highest and lowest values in Dinh An and Nha Trang, respectively (Fig. 2e). Salinity and DO were maximum in Nha Trang and minimum in Rach Gia (Fig. 2b, d). In contrast, DIN and PO_4 concentrations had the highest values in Rach Gia and the lowest values in Nha Trang (Fig. 2f, g). The lowest salinity values in Rach Gia might be related to the strong discharges from local rivers (Cai River of Hau River system). Additionally, the high DIN and PO_4 concentrations might be explained by the low tidal currents and shallow depths of Rach Gia Bay, which might reduce the dilution of the substances.

The concentration of heavy metals in water

The concentration of seven heavy metals in water samples followed the order: Fe > Mn > Zn > Cr > Cu > As > Pb, which were 1134.1±1010.8, 14.1±8.1, 9.1±1.8, 5.6±1.0, 3.4±0.6, 2.9±0.7, and 2.7±0.4 µg/L, respectively (Fig. 3). Among these, concentration of Fe, Mn and Zn showed the significant spatial variations ($p < 0.05$). The minimal and maximal concentration of Fe occurred at Nha Trang (82.9 µg/L) and Dinh An (4,127.5 µg/L) (Fig. 3d). Concentration of Zn were in the range of 6.93 µg/L (Phan Thiet) to 12.48 µg/L (Dinh An) (Fig. 3g). Mn concentration varied from 3.35 µg/L (in Nha Trang) to 33.75 µg/L (in Rach Gia) (Fig. 3e). The concentration of other heavy metals were in the range of 1.86 – 5.05 µg/L for As, 2.95 – 7.75 µg/L for Cr, 2.60 – 5.75 µg/L for Cu, and 1.50 – 3.65 µg/L for Pb (Fig. 3a – c, f); however, no spatial differences were observed in these metals. In general, the highest average concentrations of Fe, Cu, Mn, Pb, and Zn were reported at Dinh An and Rach Gia. In Dinh An, Fe, Pb, and Zn were determined to be in maximal concentrations, while the maximal average concentrations of Cu and Mn were observed in Rach Gia. This may be explained by the strong discharges from local rivers. Dinh An is mainly a sub-distributary of the Hau River, while Rach Gia Bay has been influenced by the urban activities of Rach Gia City, through discharges of the Cai Lon River. Significant seasonal variation of heavy metal concentrations was observed, but only in the coastal bay waters, particularly at Rach Gia Bay.

In Rach Gia Bay, concentration of Fe, Cr, Cu, Pb, and Zn in wet seasons were higher than those in dry seasons; while in Nha Trang and Phan Thiet Bay, only Zn and Mn concentration showed this seasonal pattern. During the rainy season, runoff discharges increase due to high precipitation. The physical characteristics of Rach Gia Bay, such as shallow depths (< 2 m) and low tidal amplitude, might also obstruct the ability of water exchange. The Rach Gia area has an irregular diurnal regime with a tidal magnitude of about 1.0 m, and the current is also not great, *i.e.* from 10 to 20 cm/s.

Table 2 summarizes concentration of targeted elements in the waters of some other regions. Cu and Zn concentrations in this study were lower than

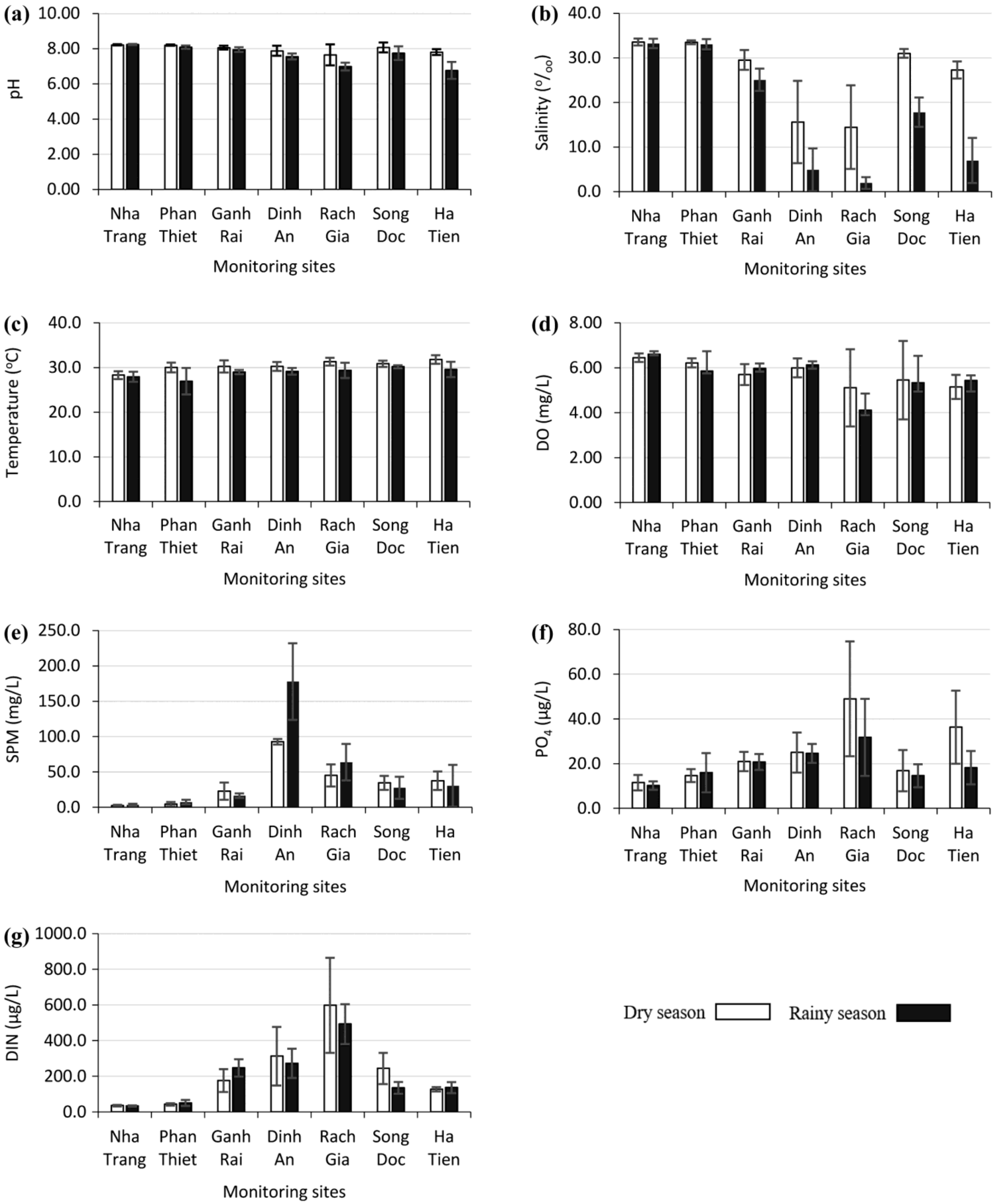

Fig. 2 — Variations in physico-chemical parameters (average) of coastal waters at seven monitoring sites: a) pH, b) Salinity, c) Temperature, d) Dissolved Oxygen (DO), e) SPM, f) PO_4, and g) DIN

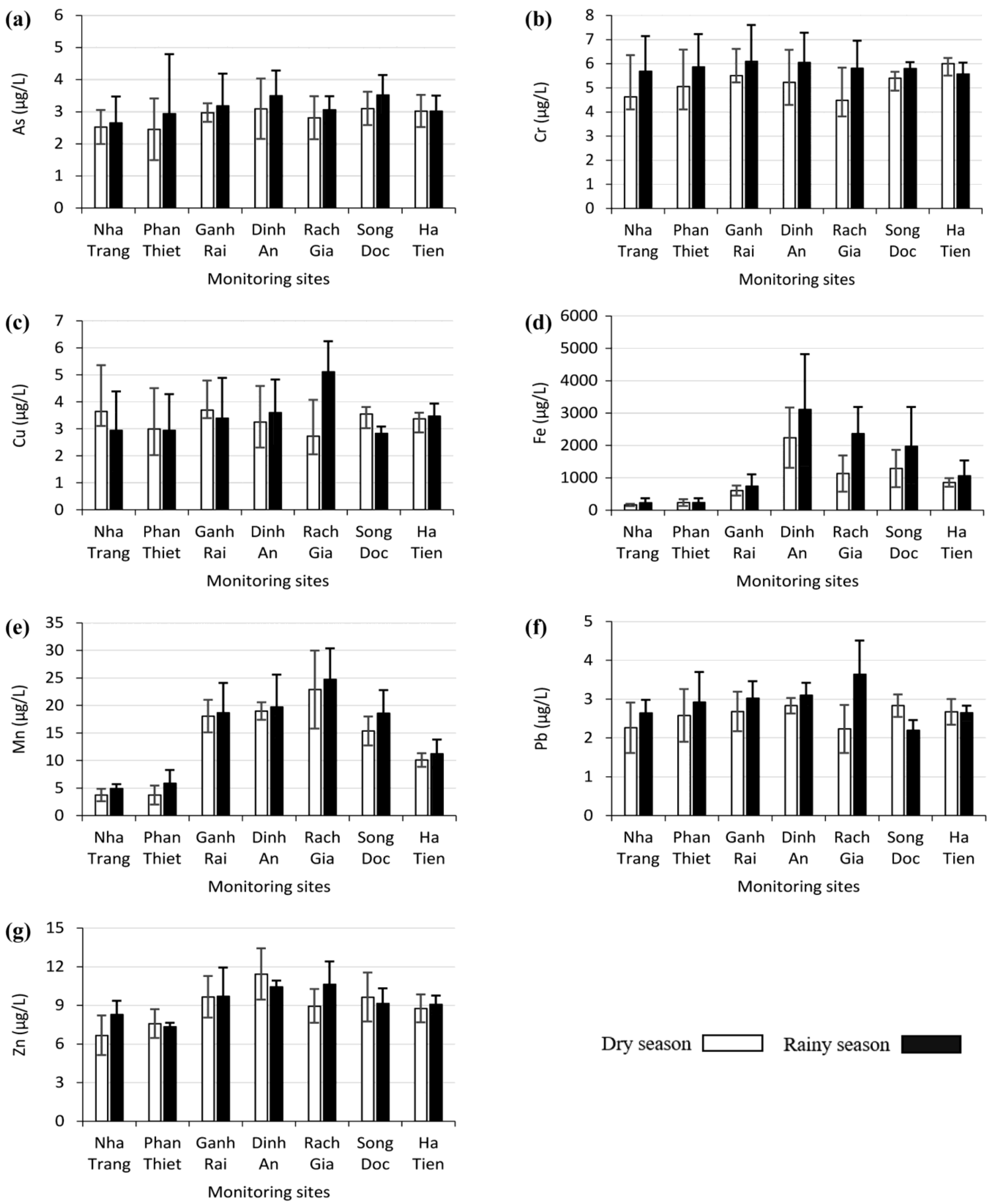

Fig. 3 — Variations in heavy metals (average) of coastal waters at seven monitoring sites: a) As, b) Cr, c) Cu, d) Fe, e) Mn, f) Pb, and g) Zn

Table 2 — Metal concentrations (µg/L) in seawater in the period of 2015 – 2020 for the studied sites, other reported regions (from literature), and the legal limits in QCVN 10-MT: 2015

Regions	As	Cr	Cu	Fe	Mn	Pb	Zn	References
Tonkin Gulf, Viet Nam	2.7 (2.2-3.1)	-	13.4 (8.0-17.5)	-	-	0.3 (0.1-0.6)	13.6 (7.1-65.3)	Le *et al*., 2021(ref. 18)
Downstream of Thi Vai Estuary, Viet Nam	-	10 (< 5-30)	-	900 (100-2.100)	-	-	10 (3-20)	Costa-Böddeker *et al*., 2017(ref. 21)
Yellow River Estuary, China	0.9 (0.4-1.4)	-	2.7 (0.1-4.5)	-	-	0.5 (0.2-1.3)	37.7 (12.0-81.8)	Tang *et al*., 2010(ref. 20)
Yangtze River Estuary, China	-	-	3.3 (2.9-3.7)	-	-	2.4 (2.3-2.4)	-	An *et al*., 2010(ref. 19)
Xiangshan Bay, China	2.6	-	4.5	-	-	2.2	16.8	Zhao *et al*., 2018(ref. 22)
The Bhairab River, Bangladesh	3.27-4.09	26.98-36.49	-	-	-	20.39 - 27.24	-	Ali *et al*., 2022(ref. 23)
The Mara River, Tanzania	90-470	460-680	-	-	-	400 - 760	-	Nkinda *et al*., 2021(ref. 24)
This study	3.0 (1.4-6.7)	5.5 (2.3-7.8)	3.4 (1.8-9.4)	1137 (67-6422)	14.1 (1.5-36.8)	2.8 (1.2-4.7)	5.9 (1.2-14)	This paper
Estuary areas	3.2	5.7	3.4	1986.1	16.6	2.8	10.0	This paper
Coastal bays	2.8	5.4	3.4	712.4	12.8	2.7	8.6	This paper
% values exceeded threshold limits	0%	0%	0%	64%	0%	0%	0%	
QCVN 10-MT:2015/BTNMT	20	100	200	500	500	50	500	

values from Tonkin Gulf[18], but Pb levels were higher[18] (Table 2). However, the As concentrations of both regions were similar. As, Cu, Pb, and Fe concentrations in estuary sites in this study were higher than in other estuaries, while Zn and Cr concentrations were lower[19-21]. Moreover, Zn and Cu concentrations in the bays of this study were less than those in Xiangshan Bay, but the As and Pb levels were comparable with those of Xiangshan Bay[22]. In general, As and Pb concentrations at monitoring sites of the studied areas were relatively higher than those in the other regions of China (Xiangshan Bay and Yellow River estuary). These areas receive pollutants from shipbuilding, power, and mining enterprises[20,22]. In contrast, the average concentrations of the observed metals in the entire study area were lower than those of the Bhairab River from Bangladesh[23], and the Mara River from Tanzania[24]. These water bodies were influenced by urban and mining activities, resulting in elevated As, Cr, and Pb levels. This shows that the influence of anthropogenic activities has not yet affected the aquatic environment of studied regions in terms of heavy metal pollution.

Assessment of heavy metal contamination

Contamination levels of studied heavy metals were assessed by comparison with the legal limits issued by QCVN 10-MT: 2015. The results showed that most of the heavy metal concentrations in the seawater of South Vietnam were lower than the legal limits. In exception, the concentration of Fe in Dinh An, Ganh Rai, Rach Gia, Song Doc, and Ha Tien were measured at higher values than 500 µg/L, by 2.9 – 12.8, 1.1 – 2.3, 1.6 – 6.9, 1.6 – 6.4, and 1.0 – 2.8 times, respectively. Iron is a dominant element in the earth's crust; therefore, the high concentrations of this heavy metal in these stations might have originated from natural erosion. The highest value was observed in Dinh An, which is a sub-distributary channel of the distributary Hau River, Mekong Delta. The fluvial water discharge and the suspended materials of Hau River were mainly transported through Dinh An channel[25]. This can be explained by the high SPM and Fe concentrations reported in the Dinh An site.

All CF values were far below 1, suggesting the influence of anthropogenic sources was not remarkable. CF values of As, Cr, Cu, Pb, and Zn ranged from 0.12 – 0.17, 0.05 – 0.06, 0.01 – 0.02, 0.05 – 0.06, and 0.01 – 0.02, respectively. Among them, As showed the highest CF value. The CF values of observed elements followed the order: As > Cr > Pb > Cu ≈ Zn. CD values ranged from 0.26 to 0.32, indicating that the seawater of the monitoring sites exhibited low contamination levels (Fig. 4).

Estimation of the potential sources of heavy metal

The relationships of parameters may explain the element sources and pathways. In this study, the strong positive correlation between pH-salinity and the negative correlations between salinity-SPM contents, salinity-DIN, and salinity-PO_4 concentrations were observed (Table 3). The SPM, DIN, and PO_4 concentrations in the monitoring sites might be affected by the terrestrial runoffs. The positive correlations between SPM and concentrations of Fe and Zn were also displayed. As these substances, indeed the same sources and may be derived from the natural erosion, through the adsorption of heavy metals in the suspended particles. In addition, the positive correlation among heavy metal concentrations, such as Mn-As, Mn-Cu, Mn-Pb, Pb-Cr, and Pb-Cu, indicated that they were of the same origin. The correlation of As, Cr, Pb, and SPM concentrations was not significant. Hence, these elements might be influenced by local anthropogenic activities more than natural erosion. Moreover, As and other heavy metals concentration in water might also be affected by the contents of the sediments and the movement of heavy metals to the overlying waters, especially in shallow waters.

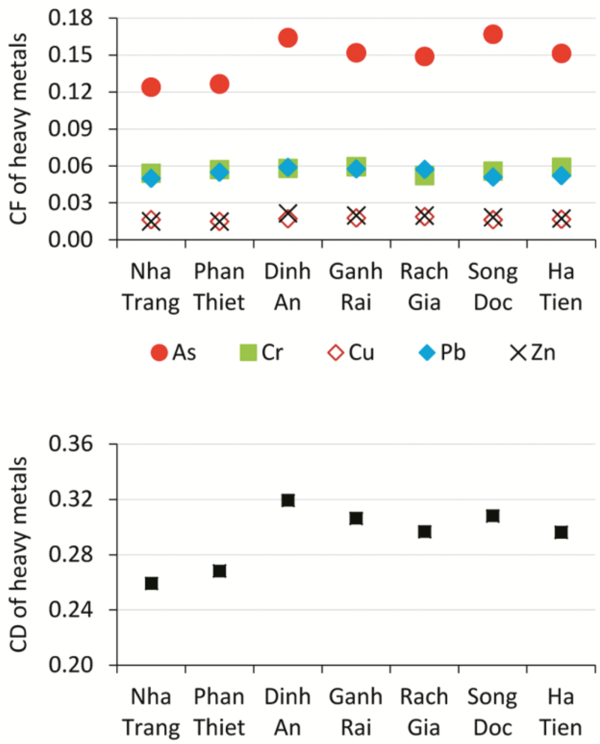

Fig. 4 — CF and CD values of heavy metals in seawater

The Principal Component Analysis (PCA) was applied to identify potential sources of trace elements in individual sampling sites. Two components explained from ~50 % to ~70 % of total variance (Table 4). In Nha Trang, the first component, PC1 (explaining 47.2 % of total variance), had positive loadings for Cr, Mn, Pb, and Zn. These parameters were not grouped with Fe, indicating that they might be influenced by local anthropogenic sources, *i.e.* transportation and port activities. The second component, PC2 (explaining 20.1 % of total variance), was positively comprised of Fe (natural erosion processes) and was negatively contributed to by Zn and PO_4 (domestic sewage). Therefore, PC2 reveals the influence of natural processes over the domestic sewage factor. Based on these results, trace element concentrations in Nha Trang were controlled mainly by anthropogenic inputs. The previous study

Table 3 — Matrix of correlation coefficients of trace elements in water of studied areas

	pH	Salinity	DO	SPM	DIN	PO_4	As	Cr	Cu	Fe	Mn	Pb	Zn
pH	1												
Salinity	**0.850****	1											
DO	**0.661****	**0.488****	1										
SPM	**-0.387****	**-0.610****	-0.242	1									
DIN	**-0.489****	**-0.625****	**-0.481****	**0.363****	1								
PO_4	**-0.285***	**-0.296***	**-0.320***	**0.322****	**0.585****	1							
As	-0.221	**-0.373****	-0.092	0.176	**0.304***	0.150	1						
Cr	0.203	0.047	**0.373****	-0.040	-0.091	-0.113	-0.130	1					
Cu	-0.286	**-0.370****	-0.218	0.237	**0.391****	0.033	0.130	0.191	1				
Fe	**-0.353****	**-0.665****	-0.160	**0.808****	**0.416****	0.158	**0.428****	0.098	**0.343***	1			
Mn	**-0.428****	**-0.673****	**-0.365****	**0.597****	**0.712****	**0.433****	**0.482****	0.142	**0.391****	**0.721****	1		
Pb	-0.169	-0.211	-0.178	0.239	**0.311***	0.052	-0.043	**0.400****	**0.612****	**0.299***	**0.377****	1	
Zn	**-0.375****	**-0.510****	-0.253	**0.489****	**0.555****	**0.462****	**0.390****	0.157	**0.479****	**0.404****	**0.675****	**0.357****	1

Bold type: The significant correlation. **: $p < 0.01$, *: $p < 0.05$.

Table 4 — PCA factor loadings of observed parameters at seven monitoring sites

Metals	Nha Trang		Phan Thiet		Ganh Rai		Dinh An		Rach Gia		Song Doc		Ha Tien	
	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2
As	-0.228	-0.382	0.437	-0.052	-0.397	0.085	0.085	0.427	0.034	0.553	-0.351	-0.237	0.219	-0.447
Cr	0.444	0.015	-0.288	0.464	0.427	0.136	0.456	0.022	0.438	0.297	-0.280	-0.399	-0.356	0.214
Cu	-0.355	-0.127	-0.283	0.108	0.239	0.333	0.353	0.397	0.467	-0.114	0.303	-0.429	0.463	0.033
Fe	0.179	0.488	-0.113	0.276	0.431	-0.237	0.457	-0.199	0.328	-0.006	-0.296	0.313	0.418	-0.276
Mn	0.425	-0.182	0.364	0.419	0.395	-0.336	0.418	-0.353	0.214	-0.497	-0.231	0.546	-0.047	-0.182
Pb	0.401	-0.339	-0.237	0.528	0.413	-0.030	0.453	0.107	0.511	-0.008	0.397	-0.219	0.345	0.388
Zn	0.331	-0.432	-0.211	-0.454	0.250	0.627	-0.222	0.374	0.333	0.185	0.325	0.192	0.425	0.292
DIN	-0.228	-0.512	0.444	0.180	-0.035		-0.098	-0.334	-0.168	0.512	0.383	0.313	0.011	0.638
PO_4	-0.300	-0.044	0.450	0.033	-0.165	-0.036	-0.112	0.482	0.187	0.221	0.393	0.149	-0.365	0.004
Total variance (%)	47.2	20.0	45.2	18.6	44.3	18.7	32.0	26.4	39.0	23.7	53.5	26.4	45.2	23.3

also proposed that the port, road construction, and river dredging activities caused the dramatic increase of trace element concentration in the seawater of Nha Trang Bay[5]. In Phan Thiet, DIN, PO_4, As, and Mn contributed positive loadings to PC1 (explaining the 45.2 % of the total variance). The origin of DIN and PO_4 might be derived from the municipal sewage[26]. Hence, the concentrations of As and Mn may be related to anthropogenic inputs. PC2 (explaining 18.6 % of the total variance) had high positive loadings of Cr, Mn, and Pb and moderate positive loadings of Fe. The occurrences of iron and manganese in coastal waters are mostly due to the riverine effluence[27]; therefore, this component might be the consequence of natural factors. In Dinh An, PC1 (accounting for 32.0 % of total variance) positively consisted of Cr, Cu, Fe, Mn, and Pb, presenting the riverine erosion processes with high loadings of Fe. PC2 (accounting for 26.4 % of total variance) had strong positive loadings of As, Cu, Zn, and DIN. The sources of DIN, As, Cu, and Zn might be related to agricultural activities (due to fertilizers, manure, and feed additives)[28-30]. In Ganh Rai, PC1 (explaining 44.3 % of the total variance) was positively loaded by Cr, Fe, Mn, and Pb, expressing a terrestrial erosion. Cu, Zn, and PO_4 contributed positive loadings to PC2 (which explained 18.7 % of the total variance). Ganh Rai Bay is fed by the adjacent waters of Dong Nai-Sai Gon downstream and the Thi Vai River, which are affected by areas of dense population, industrial zones, and the harbor activities of Ho Chi Minh City and Ba Ria-Vung Tau Province. The previous study reported that the harbors of Sai Gon and Thi Vai rivers caused serious eutrophication pollution, with high nutrient concentrations in the water[7]. Therefore, PC2 might be considered influenced by the anthropogenic factors, *i.e.* domestic sewage and harbor activities. In Rach Gia, PC1 (explaining 39.0 % of total variance) had high positive loadings of Cr, Cu, and Pb and moderate positive loadings of Fe and Zn. This component may be correlated to natural factors. PC2 (explaining 23.7 % of the total variance) was positively participated by As and PO_4. Phosphorus pollution in the water may originate from agricultural and industrial activities[31]. For this reason, this component distinguishes the importance of anthropogenic inputs. In Song Doc, PC1 (accounting for 53.5 % of the total variance) was positively impacted by Cu, Pb, Zn, PO_4 and DIN. The PO_4 and DIN may be related to agricultural activities, industrial pollution and riverside municipal sewage[32-33]; hence, Cu, Pb, and Zn might originate from the anthropogenic factors. PC2 (accounting for 26.4 % of the total variance) was positively impacted by Fe, Mn, and PO_4. This might be due to the impact of agricultural soil leaching along the region (Song Doc). Song Doc station is located in the Ca Mau Peninsula, which consists of acid sulfate soils (63 % of the total area) and alluvial saline soils (37 % of the total area)[34]. Hence, Fe and Mn might be released from the leaching of acid sulfate soils[35], while the source of PO_4 may be correlated to the use of phosphate fertilizers[36]. Therefore, this component displayed a natural causal factor. In Ha Tien, PC1 (explained 45.2 % of total variance) was positively influenced by Cu, Fe, and Zn and negatively impacted by DIN. This component was characterized by the natural inputs more than anthropogenic inputs. PC2 (explained by 23.3 % of total variance) was positively participated by PO_4, Pb, and Zn indicating dominance by anthropogenic factors, *i.e*. domestic sewage. In general, heavy metal concentrations in the studied stations of South Vietnam were controlled by natural sources, except for Song Doc. However, these concentrations in stations of Central Vietnam (Nha Trang, Phan Thiet) were influenced by anthropogenic factors rather than natural inputs.

Conclusion and recommendations

This study presents a comprehensive evaluation of heavy metal contamination in the coastal waters of South Vietnam. The concentrations of most heavy metals in water were lower than the threshold limits in the National Technical Regulation on Environmental Quality, except for Fe. The spatial distribution of observed metals was not clear, except for Fe, Mn, and Zn. Besides, the significant temporal variation was only found in the coastal bay waters. Contamination indices (CF and CD) indicated a low contamination of the studied regions with not much harm to the aquatic environment.

The Pearson correlation and the PCA suggested that the heavy metal concentrations in Nha Trang, Phan Thiet, and Song Doc regions might be contributed mainly by anthropogenic inputs; whereas, these concentrations in Ganh Rai, Dinh An, Rach Gia, and Ha Tien sites may be controlled by natural factors. Further studies should be implemented to have a clear understanding of the metal pollution sources.

Acknowledgments

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Conflict of Interest

The authors declare no competing or conflict of interest.

Ethical statement

This is to certify that the reported work in the paper entitled "Heavy metals contamination in coastal waters of South Vietnam" submitted for publication is an original one and has not been submitted for publication elsewhere. We further certify that proper citations to the previously reported work have been given, and no data/table/figure has been quoted verbatim from other publications without giving due acknowledgment and without the permission of the authors. The consent of all the authors of this paper has been obtained for submitting the paper to the Indian Journal of Geo-Marine Sciences.

Author Contributions

HPL: Conceptualization, methodology, data curation, writing- original draft preparation; VTH: Conceptualization, methodology, data curation, writing- original draft preparation, reviewing and editing; TDL: Conceptualization, investigation, methodology, data curation; HTN, HNP & TLVT: Investigation, methodology; DHNT: Investigation, formal analysis; TAV: Funding acquisition, project administration; PUVN: Investigation, data curation; VHD: Writing- reviewing and editing.

References

1 Giuliani S, Bellucci L G & Nhon D H, The coast of Vietnam: Present status and future challenges for sustainable development, In: *World Seas: An Environmental Evaluation, Vol II: The Indian Ocean to the Pacific*, 2nd edn, edited by Sheppard C, (Elsevier Ltd, Amsterdam, The Netherlands), 2018, pp. 415–435. https://doi.org/10.1016/B978-0-08-100853-9.00027-0

2 Harrison R M, Laxen D P & Wilson S J, Chemical association of lead, cadmium, copper and zinc in street dust and roadside soil, *Environ Sci Technol*, 15 (11) (1981) 1378–1383. https://doi.org/10.1021/es00093a013

3 Nour H E, Assessment of heavy metals contamination in surface sediments of Sabratha, Northwest Libya, *Arab J Geosci*, 12 (6) (2019) 177–186. https://doi.org/10.1007/s12517-019-4343-y

4 Haynes D & Johnson J E, Organochlorine, heavy metal and polyaromatic hydrocarbon pollutant concentrations in the Great Barrier Reef (Australia) environment: A review, *Mar Pollut Bull*, 41 (7–12) (2000) 267–278. https://doi.org/10.1016/S0025-326X(00)00134-X

5 Nguyen A D, Zhao J X, Feng Y X, Hu W P, Yu K F, *et al.*, Impact of recent coastal development and human activities on Nha Trang Bay, Vietnam: Evidence from a *Porites lutea* geochemical record, *Coral Reefs*, 32 (1) (2013) 181–193. https://doi.org/10.1007/s00338-012-0962-4

6 Naser H A, Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: A review, *Mar Pollut Bull*, 72 (1) (2013) 6–13. https://doi.org/10.1016/j.marpolbul.2013.04.030

7 Nguyen H N, The environment in Ho Chi Minh City Harbours, In: *The Environment in Asia Pacific Harbours*, edited by Wolanski E, (Springer, Dordrecht), 2006, pp. 261–291. https://doi.org/10.1007/1-4020-3655-8_17
8 Tham T T, Lap B Q, Mai N T, Trung N T, Thao P P, *et al.*, Ecological Risk Assessment of Heavy Metals in Sediments of Duyen Hai Seaport Area in Tra Vinh Province, Vietnam, *Water Air Soil Pollut*, 232 (49) (2021) 1–11. https://doi.org/10.1007/s11270-021-05014-5
9 Le T D, Nguyen H T, Le H P, Pham H N & Dao V H, Distribution of heavy metals and organic in the clam culture areas at Binh Dai, Ba Tri, Thach Phu in Ben Tre province, *Vietnam J Mar Sci Technol*, 19 (4A) (2019) 151–158. https://doi.org/10.15625/1859-3097/19/4a/14598
10 Nguyen T T H, Zhang W, Li Z, Li J, Ge C, *et al.*, Assessment of heavy metal pollution in Red River surface sediments, Vietnam, *Mar Pollut Bull*, 113 (1–2) (2016) 513–519. https://doi.org/10.1016/j.marpolbul.2016.08.030
11 Ho H H, Swennen R & Van Damme A, Distribution and contamination status of heavy metals in estuarine sediments near Cua Ong Harbor, Ha Long Bay Vietnam, *Geol Belg*, 13 (1–2) (2010) 37–47.
12 Le T V, La V B, Duong T K, Nguyen H T, Pham H T, *et al.*, Nutrients and heavy metals in seawaters at Phan Ri - Phu Qui transect, *Collect Mar Res Work*, 16 (2009) 78–88.
13 Ngo D N, Lunestad B T, Trang S T, Nguyen T S & Maage A, Heavy metals in the farming environment and in some selected aquaculture species in the Van Phong Bay and Nha Trang Bay of the Khanh Hoa Province in Vietnam, *Bull Environ Contam Toxicol*, 82 (1) (2009) 75–79. https://doi.org/10.1007/s00128-008-9561-z
14 Le T V, Pham V T, Nguyen H T, Duong T K & Pham H T, Heavy metal concentration in suspended solid and sediments of Binh Cang - Nha Trang Bays, *Collect Mar Res Work*, 9 (1999) 95–105.
15 Rice E W, Baird R B & Eaton A D (eds), *Standard Methods for the Examination of Water and Wastewater*, 23rd edn, (American Public Health Association, American Water Works Association, Water Environment Federation, Washington, D.C), 2017, pp. 40. ISBN: 9780875532875
16 Ministry of Natural Resources and Environment, The Socialist Republic of Vietnam, National Technical Regulation (QCVN 10-MT: 2015/BTNMT), National Technical Regulation on Marine Water Quality, Vietnam, 2015.
17 Hakanson L, An ecological risk index for aquatic pollution control - A sedimentological approach, *Water Res*, 14 (8) (1980) 975–1001. https://doi.org/10.1016/0043-1354(80)90143-8
18 Le V N, Tran D T, Nguyen V T, Dang H N, Le X S, *et al.*, The first step of application of water quality index (WQI) to assessment of sea water quality in the Gulf of Tonkin in 2018, *Vietnam J Mar Sci Technol*, 20 (4B) (2020) 171–181. https://doi.org/10.15625/1859-3097/15831
19 An Q, Wu Y, Wang J & Li Z, Assessment of dissolved heavy metal in the Yangtze River estuary and its adjacent sea, China, *Environ Monit Assess*, 164 (1–4) (2010) 173–187. https://doi.org/10.1007/s10661-009-0883-z
20 Tang A, Liu R, Ling M, Xu L & Wang J, Distribution characteristics and controlling factors of soluble heavy metals in the Yellow River estuary and adjacent sea, *Procedia Environ Sci*, 2 (2010) 1193–1198. https://doi.org/10.1016/j.proenv.2010.10.129
21 Böddeker S C, Hoelzmann P, Thuyen L X, Huy H D, Nguyen H A, *et al.*, Ecological risk assessment of a coastal zone in Southern Vietnam: Spatial distribution and content of heavy metals in water and surface sediments of the Thi Vai Estuary and Can Gio Mangrove Forest, *Mar Pollut Bull*, 114 (2) (2017) 1141–1151. https://doi.org/10.1016/j.marpolbul.2016.10.046
22 Zhao B, Wang X, Jin H, Feng H, Shen G, *et al.*, Spatiotemporal variation and potential risks of seven heavy metals in seawater, sediment, and seafood in Xiangshan Bay, China (2011-2016), *Chemosphere*, 212 (2018) 1163–1171. https://doi.org/10.1016/j.chemosphere.2018.09.020
23 Ali M M, Rahman S, Islam M S, Rakib M R J, Hossen S, *et al.*, Distribution of heavy metals in water and sediment of an urban river in a developing country: A probabilistic risk assessment, *Int J Sediment Res*, 37 (2) (2022) 173-187. https://doi.org/10.1016/j.ijsrc.2021.09.002
24 Nkinda M S, Rwiza M J, Ijumba J N & Njau K N, Heavy metals risk assessment of water and sediments collected from selected river tributaries of the Mara River in Tanzania, *Discov Water*, 1 (3) (2021) 1–20. https://doi.org/10.1007/s43832-021-00003-5
25 Xing F, Meselhe E A, Allison M A & Weathers H D, Analysis and numerical modeling of the flow and sand dynamics in the lower Song Hau channel, Mekong Delta, *Cont Shelf Res*, 147 (2017) 62–77. https://doi.org/10.1016/j.csr.2017.08.003
26 Le T V, Duong T K, Nguyen H T, Pham H T, Pham H N, *et al.*, Environmental quality of coastal waters of Phan Thiet bay, *Collect Mar Res Work*, 17 (2010) 43–52.
27 Landing W M & Bruland K W, The contrasting biogeochemistry of iron and manganese in the Pacific Ocean, *Geochim Cosmochim Acta*, 51 (1) (1987) 29–43. https://doi.org/10.1016/0016-7037(87)90004-4
28 Dumont E, Harrison J A, Kroeze C, Bakker E J & Seitzinger S P, Global distribution and sources of dissolved inorganic nitrogen export to the coastal zone: Results from a spatially explicit, global model, *Global Biogeochem Cycles*, 19 (4) (2005) 1–14. https://doi.org/10.1029/2005GB002488
29 Martinez J & Peu P, Nutrient fluxes from a soil treatment process for Pig Slurry, *Soil Use Manag*, 16 (2) (2000) 100–107. https://doi.org/10.1111/j.1475-2743.2000.tb00183.x
30 Mondal M K, Das T K, Biswas P, Samanta C C & Bairagi B, Influence of dietary inorganic and organic copper salt and level of soybean oil on plasma lipids, metabolites and mineral balance of broiler chickens, *Anim Feed Sci Technol*, 139 (3–4) (2007) 212–233. https://doi.org/10.1016/j.anifeedsci.2007.01.014
31 Cao X, Wang Y, He J, Luo X & Zheng Z, Phosphorus mobility among sediments, water and cyanobacteria enhanced by cyanobacteria blooms in eutrophic Lake Dianchi, *Environ Pollut*, 219 (2016) 580–587. https://doi.org/10.1016/j.envpol.2016.06.017
32 Colborne S F, Maguire T J, Mayer B, Nightingale M, Enns G E, *et al.*, Water and sediment as sources of phosphate in aquatic ecosystems: The Detroit River and its role in the Laurentian Great Lakes, *Sci Total Environ*, 647 (2019) 1594–1603. https://doi.org/10.1016/j.scitotenv.2018.08.029
33 Wang Y, Xie Z, Liu S, Wang L, Li R, *et al.*, Effects of Anthropogenic Disturbances and Climate Change on Riverine Dissolved Inorganic Nitrogen Transport, *J Adv*

Model Earth Syst, 12 (10) (2020) 1–17. https://doi.org/10.1029/2020MS002234

34 Phong N D, Tuong T P, Phu N D, Nang N D & Hoanh C T, Quantifying source and dynamics of acidic pollution in a coastal acid sulphate soil area, *Water Air Soil Pollut*, 224 (1765) (2013) 0–18. https://doi.org/10.1007/s11270-013-1765-0

35 Nguyen T V H, Takizawa S, Oguma K & Nguyen V P, Sources and leaching of manganese and iron in the Saigon River Basin, Vietnam, *Water Sci Technol*, 63 (10) (2011) 2231–2237. https://doi.org/10.2166/wst.2011.460

36 Vo T G & Nguyen M H, Aquaculture and Agricultural Production in the Mekong Delta and its Effects on Nutrient Pollution of Soil and Water, In: *The Mekong Delta System*, *Springer Environmental Science and Engineering*, edited by Renaud F & Kuenzer C, (Springer, Dordrecht), 2012, pp. 363–393. https://doi.org/10.1007/978-94-007-3962-8_14