Assessment of Long-Term Surface Water Quality in Mekong River Estuaries Using A Comprehensive Water Pollution Index

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ABSTRACT

Surface water quality (SWQ) has been degraded in the Mekong River Basin under increasing pressures of population growth, economic development, and global climate change. This study employed the comprehensive water pollution index (CWPI) to assess the spatio-temporal variation of SWQ in the downstream Mekong River estuaries. Eight water quality parameters were measured between 2005 and 2021 at 21 sampling sites downstream of the Mekong River. These parameters included total suspended solids (TSS), biological oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia ($N\text{-}NH_4^+$), nitrate ($N\text{-}NO_3^-$), phosphate ($P\text{-}PO_4^{3-}$), iron (Fe), and total coliform. Most of the monitoring locations in the estuaries of Ham Luong, Cua Dai, Ba Lai, and Co Chien exhibited slightly to moderately polluted conditions, as indicated by the CWPI values ranging from 0.67-2.91, 0.41-2.20, 0.27-3.02, and 0.37-2.95, respectively. TSS and Fe concentrations consistently exceeded the allowable limits, while the majority of values for $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$, and coliform remained within acceptable thresholds. Additionally, parameters indicative of organic pollution, namely BOD_5 and COD, displayed a noticeable upward trend between 2005 and 2021. SWQ exhibited significant spatial and temporal variations with TSS, organic matter, nutrients, and iron being the main areas of concern. These findings can provide guidance to policymakers involved in the assessment and enhancement of water quality in the presence of pollutant compounds that lead to a decline in water quality.

1. INTRODUCTION

Water resources are essential for living organisms, and their availability plays a crucial role in economic and economic growth activities (Le et al., 2023). In fact, water is a vital life-supporting factor, making up 70-90% of all living cells (Khan and Ansari, 2005). In addition, various economic sectors such as agriculture, industry, domestic usage, hydropower generation, fisheries, and other creative endeavors significantly depend on water resources (Effendi, 2016).

Numerous sources of pollution, including population growth, economic development, global climate change, and anthropogenic activities, have contributed to the degradation of surface water quality (SWQ) (Bojarczuk et al., 2018; Okello et al., 2015; Soares et al., 2020). Surface water pollution risks associated with socioeconomic development, such as nutrients, heavy metals, plastics, antibiotics, pesticides, and seawater intrusion, often exceed the environmental self-purification (Kroeze et al., 2016; Le et al., 2023; Liang and Yang, 2019). In turn, the deterioration of SWQ due to these pollution sources can cause adverse human health effects and diseases in humans (Kazi et al., 2009).

Regular monitoring and conservation programs are crucial on a global scale to prevent and control water pollution. Rapid techniques for assessing water quality

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can provide prompt information on the severity of water bodies pollution reliant on their physicochemical and biological parameters (Hossain and Patra, 2020). The Water Quality Index (WQI) is a popular approach used to describe SWQ due to its simple structure and user-friendly interface (Uddin et al., 2021). WQI, ranging from 0 to 100, is obtained by combining physical, chemical, and biological factors, which involves four processes: selection of parameters, transformation of raw data into a common scale, weighting, and aggregation of sub-index values (Chidiac et al., 2023). However, weight-based indices can suffer from imbalanced sensitivity if certain parameters are strongly or weakly weighted. Additionally, any changes in weight assignments can significantly impact the overall interpretation of water quality. For example, the lower concentration parameters can be influenced by higher assigned weights, which can result in false interpretations of the water quality (Juwana et al., 2012). In looking for solutions to the problem, the comprehensive water pollution index (CWPI) is proposed, which have integrated various water quality parameters into a single index (Mishra et al., 2016; Hossain and Patra, 2020). CWPI also utilizes unequal weights of environmental parameters to evaluate water quality. Furthermore, CWPI can be employed to evaluate the physical, chemical, and biological characteristics of water sources based on the available water quality standards for a given designated use (Hossain and Patra, 2020).

The Vietnam Mekong Delta (VMD) is a vulnerable region enduring a range of environmental challenges, such as rising sea levels, modifications in water flow, and nutrients from the upstream catchment. Several methodologies and techniques have been employed to gain a comprehensive understanding of this matter. Simulations from the Integrated Catchment Model predicted increased mean and flood flows, an earlier onset of monsoonal flows, and more dry spells until 2050, with nutrient fluxes potentially rising by 5% over the Greater Mekong Basin (Whitehead et al., 2019). The Self-Organizing Map classified 117 monitoring locations and pollution hot zones in the Lower Mekong Basin (LMB) based on water quality indicators monitored from 1985 to 2010, identifying eutrophication, salinity, and human interference as factors affecting water quality, particularly in the VMD (Chea et al., 2016). Water quality in the LMB was assessed using biotic and abiotic evaluation factors from 2000 to 2017, with the findings indicating degradation in the 2010s due to several factors such as flow modification, erosion, sediment accumulation, and wastewater, resulting from the rapid development of hydropower, extensive deforestation, intensive farming practices, plastic pollution, and the expansion of urban areas (Sor et al., 2021).

The risk of pollution is heightened by the extensive use of surface water in the VMD for domestic services, irrigation, and drinking water, which poses a potential threat to human, animal, and ecosystem health (Wilbers et al., 2014). Current research on water quality in the area has revealed the presence of organic pollutants, microorganisms, salts, total suspended solids, and metals. For example, the SWQ in An Giang Province, the region upstream of VMD, was assessed using water quality indicators and multivariate statistical techniques (Hong and Giao, 2022). In the Bassac river, canal pollution levels and seasonal variations in SWQ were examined using principal component analysis, water quality attributes (Wilbers et al., 2014), and the entropy-weighted water quality index (EWQI), as well as multivariate methods (Nguyen et al., 2022). In the Mekong River, the variation in the SWQ was analyzed in Ben Tre (Nguyen et al., 2018) and Tien Giang (Hong et al., 2022) Provinces using WQI and multivariate statistics, respectively. In general, existing studies mostly employ multivariate statistical approaches and water quality measures to examine short-term variations in the SWQ and identify their causes and drivers.

The objective of this study is to analyze the spatial and temporal distribution of SWQ downstream of the Mekong River in Vietnam from 2005 to 2021. Water quality data were collected at 21 locations along Cua Dai, Ba Lai, Ham Luong, and Co Chien estuaries and analyzed for eight parameters (i.e., total suspended solids (TSS), biological oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia ($N\text{-}NH_4^+$), nitrate ($N\text{-}NO_3^-$), phosphate ($P\text{-}PO_4^{3-}$), iron (Fe), and total coliform). Subsequently, box and whisker plots were employed to illustrate the changes in water quality parameters over time and across different locations. Finally, CWPI was calculated to assess the overall SWQ. The study outcomes are expected to provide pivotal information, primarily regarding the quality of surface water systems, and to assist in managing the coastal regions of the VMD.

2. METHODOLOGY

2.1 Study site

The Mekong Delta region is identified as the commencing at the intersection of the Mekong River and Tonle Sap River at Phnom Penh, Cambodia, and further divides into six principal channels of the Mekong River and three channels of the Bassac River before flowing into the East Sea. The Mekong River stretches for 150 km with a width ranging from 450 to 2,250 meters and a maximum depth of 10 m. The region experiences a monsoonal humid and tropical climate with an average temperature ranging between 27-30°C. Approximately 80% of the annual rainfall occurs during the rainy season, which lasts from May to October. Consequently, the Mekong River experiences a minimum discharge of around 200 m³/s in April-May and a maximum discharge of approximately 7,000 m³/s in September-October (Strady et al., 2017).

2.2 Data collection and processing

A total of 21 sampling sites were chosen to represent the SWQ downstream of the Mekong River from 2005 to 2021. Among these sites, three were located on the Cua Dai estuary (CD1-CD3), eight on the Ba Lai estuary (BL1-BL8), five on the Ham Luong estuary (HL1-HL5), and five on the Co Chien estuary (CC1-CC5) (Figure 1). The collection of surface water samples was carried out biannually between 2005 and 2016, in May (at the onset of the rainy season) and November (at the onset of the dry season). However, the sampling frequency was increased to four times a year between 2017 and 2021, with samples being taken in February (between dry seasons), May (at the onset of the rainy season), August (between rainy seasons), and November (at the onset of the dry season). The water samples were collected from a depth of 0.3-0.5 m below the water's surface. To assess water quality, eight water quality parameters, namely TSS, BOD_5, COD, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$, Fe, and total coliform, were measured. These water quality parameters were preserved and analyzed at the laboratory of the Center for Natural Resources and Environment Monitoring of Ben Tre Province using standard methods as described in Table 1.

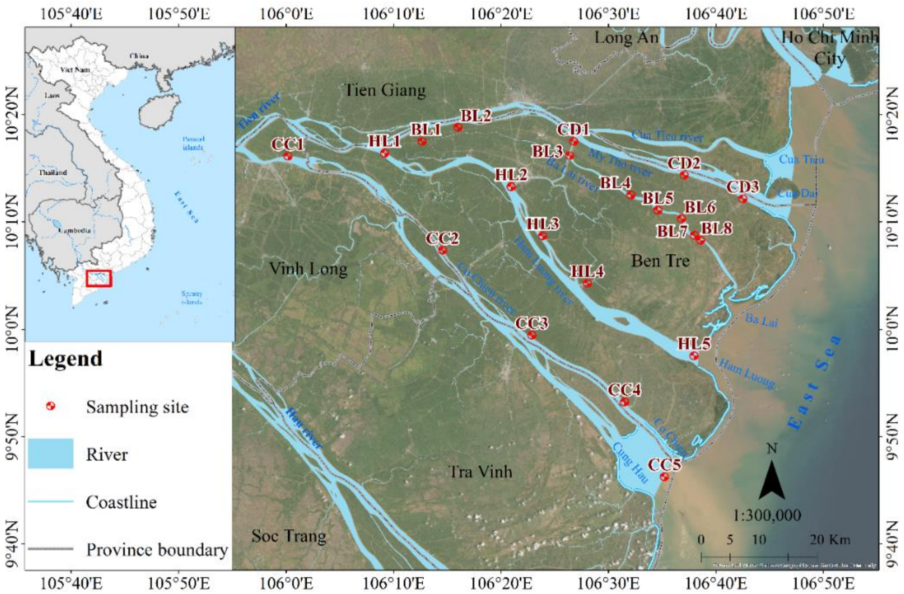

Figure 1. Map of the study area and sampling sites in the downstream of Mekong River

Table 1. Analysis methods and allowable limits of the parameters

Parameters	Units	Measurement methods	VN-Standards A2*
TSS	mg/L	SMEWW 2540D:2017	30
BOD_5	mg/L	SMEWW 5210B:2017	6
COD	mg/L	SMEWW 5220C:2017	15
$N\text{-}NH_4^+$	mg/L	SMEWW 4500-NH_3^+.B&F:2017	0.3
$N\text{-}NO_3^-$	mg/L	SMEWW 4500-NO_3^-.E:2017	5
$P\text{-}PO_4^{3-}$	mg/L	SMEWW 4500-PO_4^{3-}.E:2017	0.2
Fe	mg/L	SMEWW 3111B:2017	1
Coliform	MPN/100 mL	TCVN 6187-2:1996	5,000

2.3 Comprehensive water pollution index

Box and whisker plots were employed to illustrate temporal and spatial variations in water quality parameters. To assess the overall water quality, the comprehensive water pollution index (CWPI) was calculated for each sampling site using the formula (Mishra et al., 2016):

$$\mathrm{CWPI} = \frac{1}{n}\sum_{i=1}^{n}\frac{C_i}{C_{oi}}$$

Where; n is the number of water quality parameters, C_i is the measured concentration of water quality parameter i and C_{oi} is the standard permissible concentration of water quality parameter i.

In this study, the permissible concentrations of each parameter were determined according to Vietnamese water quality standards, QCVN 08-MT:2015/BTNMT, where the A2 standard was selected as a reference value for residential use with appropriate treatment, preservation of aquatic plants, or other purposes (Ministry of Natural Resources and Environment, 2015). The surface water quality was classified using the CWPI, where a value of ≤0.20 was considered clean, 0.21-0.40 was categorized as sub-clean, 0.41-1.00 was considered slightly polluted, 1.01-2.00 was considered moderately polluted, and ≥2.01 was classified as severely polluted (Mishra et al., 2016).

3. RESULTS AND DISCUSSION

3.1 Physical and biochemical water quality parameters

Values of physical and biochemical parameters of SWQ downstream of the Mekong River are depicted in Figure 2. The average concentration of TSS in the sampling sites was 85.68±55.84 mg/L, exceeding the allowable limit by 2.86 times and higher than that of recent findings in the VMD (Table 2). TSS consists of particles suspended in water, originating from both natural and anthropogenic activities such as construction, agricultural production, the release of artificial and organic chemicals from industrial sewage, and municipal and domestic wastewater (Nguyen et al., 2020). Aquaculture practices, particularly those related to *Pangasius* catfish farms, also contribute to the contamination of surface water with high levels of TSS due to the presence of food remnants, fish excrement, and metabolic waste (Dauda et al., 2019). The substantial levels of TSS in the downstream Mekong River indicate a significant degree of riverbank erosion, given its coastal location heavily impacted by estuaries and mudflats (Giao, 2020). Therefore, specific sources of TSS have yet to be identified and may require further investigation. A high TSS concentration can lead to a drop in dissolved oxygen levels, causing hypoxic stress and adversely affecting fish species' survival, diversity, and abundance (Mueller et al., 2017). The presence of TSS in water can also result in the accumulation of heavy metals and nutrients, causing elevated pollutant levels. When TSS settles at the bottom, it can disrupt the benthic environment and harm organisms (Mueller et al., 2017). Consequently, the presence of a high TSS concentration increases the likelihood of people being exposed to environmental pollutants and water treatment costs.

BOD_5 and COD are widely used parameters for assessing the organic pollution level in water. In the study area, the BOD_5 concentration ranged from 3 to 19.3 mg/L, with a mean of 6.23±3.01 mg/L, exceeding the permissible limit by 1.03 times. In contrast, COD concentration was relatively low, ranging from 3 to 30.93 mg/L, with a mean of 11.15±5.44 mg/L, which fell within the limits of Standard A2. BOD_5 can originate from various sources such as farming waste, livestock waste, landfill waste, and untreated waste directly discharged into the environment from domestic activities and services (Giao and Nhien, 2020). To prevent saltwater intrusion, many sluices and dams have been built along the Mekong River. However, keeping these structures closed for extended periods can increase environmental pollution, particularly organic pollution (Nguyen et al., 2022; Ngo et al., 2022; Tran et al., 2022).

Nitrogen and phosphorus compounds are primary pollutants with the potential to form secondary pollutants and cause eutrophication, which adversely affects aquatic organisms (Abdel-Raouf et al., 2012). Study results also found that the average concentrations of $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, and $P\text{-}PO_4^{3-}$ were within the limits of Standard A2, but many values exceeded national technical regulations for surface water. The levels of $N\text{-}NO_3^-$ were suitable for daily activities but toxic to aquatic life, especially in alkaline environments (Martin et al., 2008). The presence of nutrient compounds in surface water may result from the discharge of domestic wastewater containing detergents, industrial waste, and runoff from fertilizers. Excess nutrients discharged from *Pangasius* catfish feed could also contribute to elevated nutrient levels. Additionally, the reduction in sediment flow into agricultural areas has led to soil degradation (Le et al., 2023), resulting in the overuse of fertilizers and pesticides (Chapman et al., 2016), which can lead to a high level of nutrient compounds. Therefore, it can be inferred that water quality in the water bodies downstream of the Mekong River has been contaminated with nutrients, particularly N-NH_4^+ and P-PO_4^{3-}, suggesting the potential for eutrophication to occur in the water bodies within the study area.

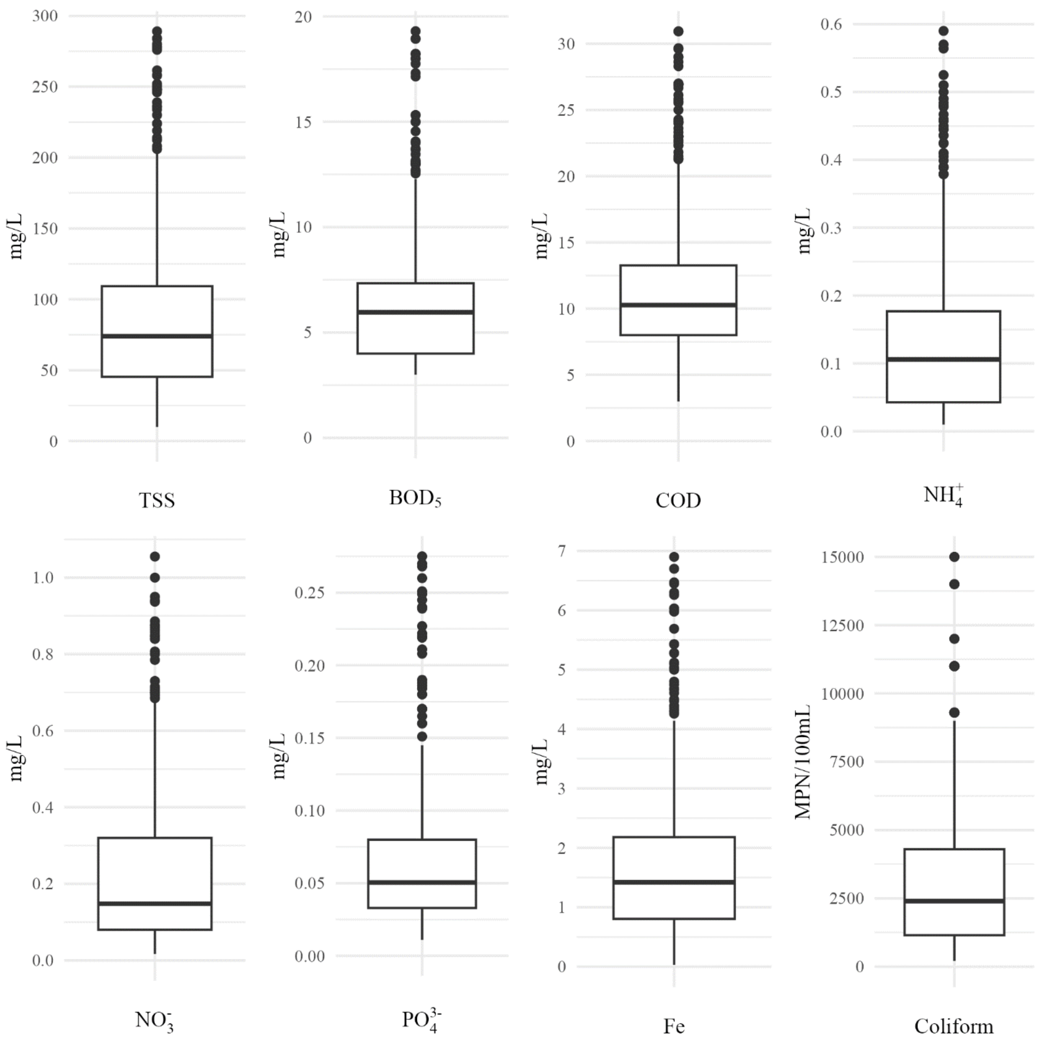

Figure 2. Surface water quality parameters downstream of Mekong River

The average Fe concentration in surface water ranged from 0.03 to 6.9 mg/L, with a mean value of 1.66±1.20 mg/L, which exceeded the limit by 1.66 times. The Mekong River was found to have a higher average iron concentration than the Bassac River. The presence of iron in surface water can be attributed to both natural factors, such as the presence of acid sulfate soil properties, and anthropogenic activities, such as washing acidic soil and intensive agricultural production (Giao, 2020). To assess water quality in the surface water monitoring program, various heavy metals such as iron (Fe), aluminum (Al), manganese (Mn), chromium (Cr), and cadmium (Cd) are measured. The selection of parameters to monitor and the monitoring locations for SWQ depends on the characteristics of pollution sources and available budget. The Center for Natural Resources and Environment Monitoring in Ben Tre Province currently uses iron to evaluate the SWQ in the downstream of the Mekong River through its monitoring program. However, there may be a need for additional updates because many studies have warned that arsenic poisoning poses the most significant health risk for both human and aquatic organisms in VMD (Strady et al., 2017).

Microbial contamination has become a significant concern in various water bodies located in the VMD, including Hau Giang, An Giang, Dong Thap, and Tra Vinh Provinces (Table 2). In contrast, the Mekong River exhibited coliform levels within the allowable limits, with a mean of 3,190±2,767 MPN/100 mL. The high presence of coliform, exceeding the national technical regulations for surface water, can be attributed to the discharge of significant amounts of organic waste into the river. The primary sources of this waste are aquaculture farms, rice fields, fish processing industries, and other industrial activities. The consumption of water with high coliform levels can lead to several health issues, such as gastrointestinal illness, fever, diarrhea, and dehydration (Divya and Solomon, 2016).

Overall, surface water in different water bodies downstream of Mekong River, VMD was contaminated with TSS, organic matter, and iron. On the contrary, microbiological pollution may not be the primary issue of water pollution in the Mekong River.

Table 2. Information regarding various surface water quality parameters in different regions of the VMD

	TSS (mg/L)	BOD_5 (mg/L)	COD (mg/L)	$N\text{-}NH_4^+$ (mg/L)	$N\text{-}NO_3^-$ (mg/L)	$P\text{-}PO_4^{3-}$ (mg/L)	Fe (mg/L)	Coliform (MPN/100 mL)
MKR	85.68 (10-289)	6.23 (3-19.3)	11.15 (3-30.93)	0.13 (0.01-0.59)	0.23 (0.01-1.05)	0.07 (0.01-0.28)	1.66 (0.03-6.9)	3,190 (210-15,000)
BR	34.8-50.8	7.3-8.3	12-12.8	0-0.1	0.34-0.38	0.1-0.23	0.3-0.47	1,156-1,657
HGP	32.8-101	6.3-14	14-25	0-0.92	0.23-0.54	0.1-0.36	0.5-2.26	3,225-15,275
AGP	53.33-59.59	13.65-24.19	21.14-37.22	0.36-2.19	-	-	-	11,067-31,363
DTP	34.60	15.03	22.34	0.29-0.45	0.99-2.70	0.1-0.59	-	1,708-25,300
TVP	57.39	7.03	24.81	-	-	0.09	-	153,229
CTC	24.7-57.9	3.3-4.7	-	-	0.2-0.3	0.2-0.3	-	19,140-28,600
TGP	78.9-121.8	8.0-8.9	14.4-17.3	0.3-0.5	0.1-0.4	0.1	-	972.9-2,261.2

MKR (Mekong River, this study), BR (Bassac River (Giao, 2020)), HGP (Hau Giang Province (Giao, 2020)), AGP (An Giang Province (Hong and Giao, 2022)), DTP (Dong Thap Province (Giao et al., 2021)), TVP (Tra Vinh Province (Le et al., 2023)), CTC (Can Tho City (Mutea et al., 2021)), TGP (Tien Giang Province (Giao et al., 2021))

3.2 Temporal changes in surface water quality

Figure 3 presents the variation in surface water quality downstream of the Mekong River over a 17-year period (2005-2021). Results from the Kruskal-Wallis test showed significant statistical differences ($p<0.001$) in all physical and biochemical parameters. TSS and Fe concentrations were mostly higher than the permissible limit. In contrast, most values of $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$, and coliform remained within the allowable limit. Parameters such as BOD_5 and COD, which serve as indicators of organic pollution, tended to increase from 2005 to 2021. However, BOD_5 and COD concentrations started to exceed the permissible standard in 2016 and 2019, respectively. The increasing tendency of BOD_5 and COD could be explained by seawater intrusion. The primary reason for the rise in BOD_5 and COD levels during the period from 2016 to 2020 might be seawater intrusion in many coastal areas in VMD, where seawater intruded up to 45-50 km from the estuary. The intrusion of seawater has been recognized as one of the most significant sources of pollution responsible for declining surface water quality (Le et al., 2023).

3.3 Spatial variation in water quality

The results of the CWPI analysis at the Mekong estuaries are shown in Figure 4. The CWPI values for the Co Chien, Ham Luong, Ba Lai, and Cua Dai estuaries ranged from 0.67-2.91, 0.41-2.20, 0.27-3.02, and 0.37-2.95, respectively. Overall, most of the observation stations indicated slightly to moderately polluted conditions. In particular, the observed values at HL1 in 2005 were categorized as being in clean or sub-clean conditions with a CWPI value of 0.27.

The SWQ at the river mouth location (CD3) in the Cua Dai estuary was severely polluted in 2010, 2015, 2016, and 2019, with CWPI values of 2.20, 2.91, 2.03, and 2.73, respectively. A similar trend was observed in the Ba Lai estuary, where the SWQ at the river mouth location (BL8) was severely polluted in 2015 and 2019, with CWPI scores of 2.14 and 2.08, respectively. Furthermore, the SWQ at BL4 was severely polluted in 2010, with a CWPI of 2.20. In the Ham Luong estuary, the SWQ at the river mouth (HL5) was severely polluted in 2010, 2015, and 2019, with CWPI scores of 3.02, 2.55, and 2.99, respectively. At the Co Chien estuary, the CC5 station had severely polluted water conditions in 2009, 2010, 2015, and 2019, with CWPI scores of 2.25, 2.00, 2.96, and 2.16, respectively. Additionally, the CC4 location had severely polluted water quality in 2010, with a CWPI of 2.12.

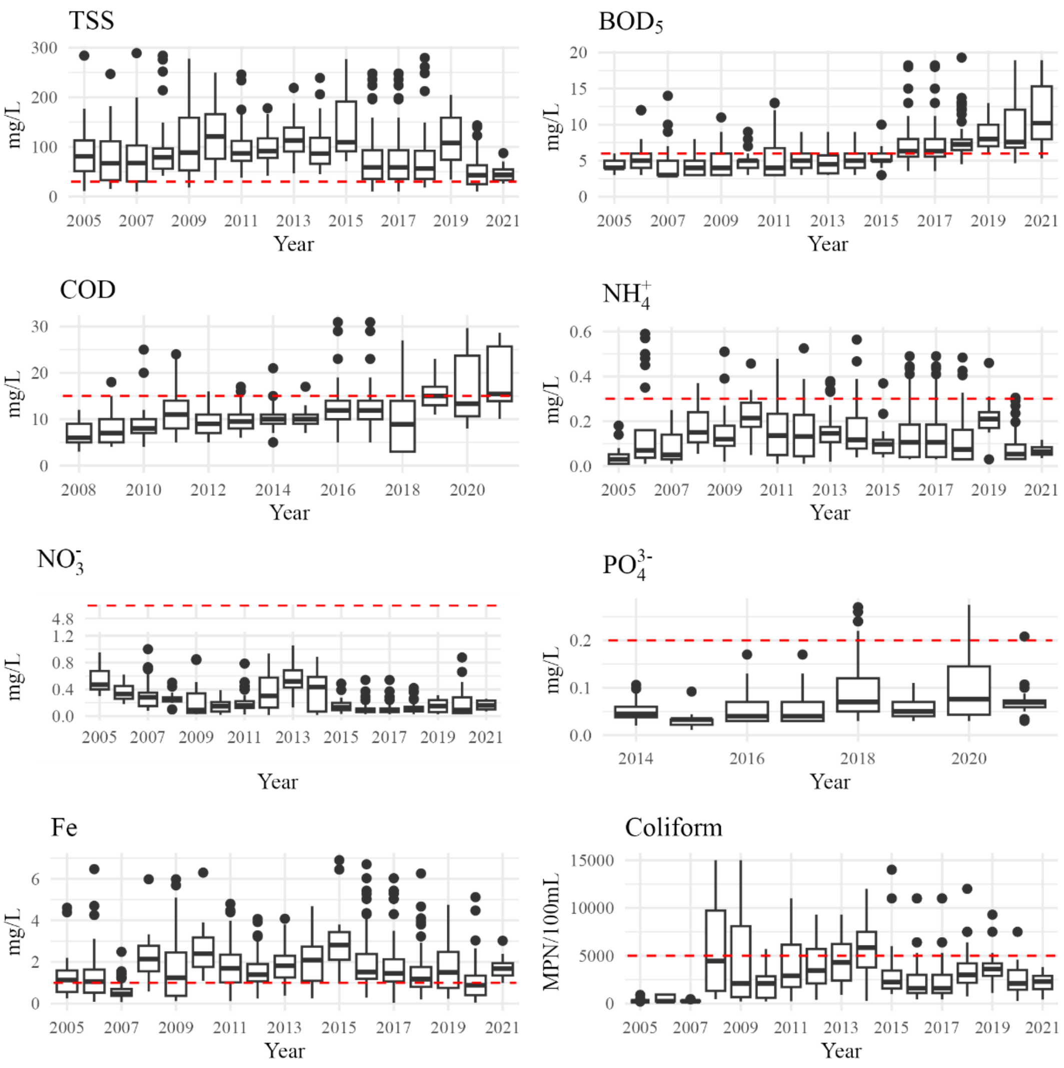

Figure 3. Box plots of surface water quality parameters downstream of Mekong River from 2005 to 2021. Dashed lines denote the Vietnamese technical regulation on surface water quality (Standard A2).

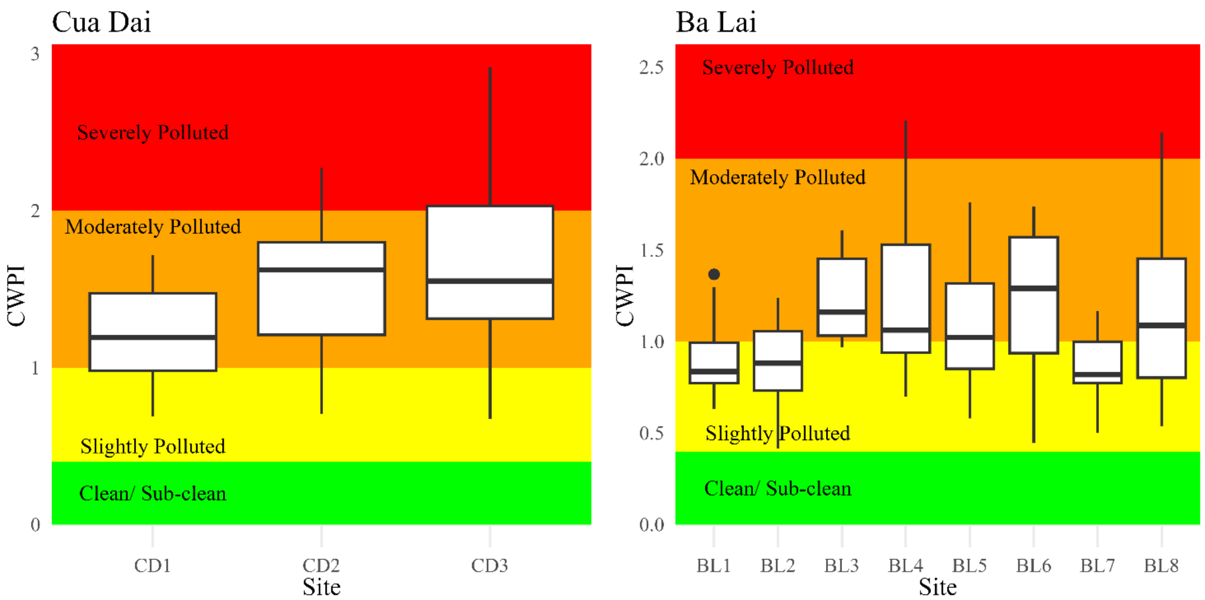

Figure 4. CWPI and the surface water quality in Cua Dai, Ba Lai, Ham Luong, Co Chien Estuaries

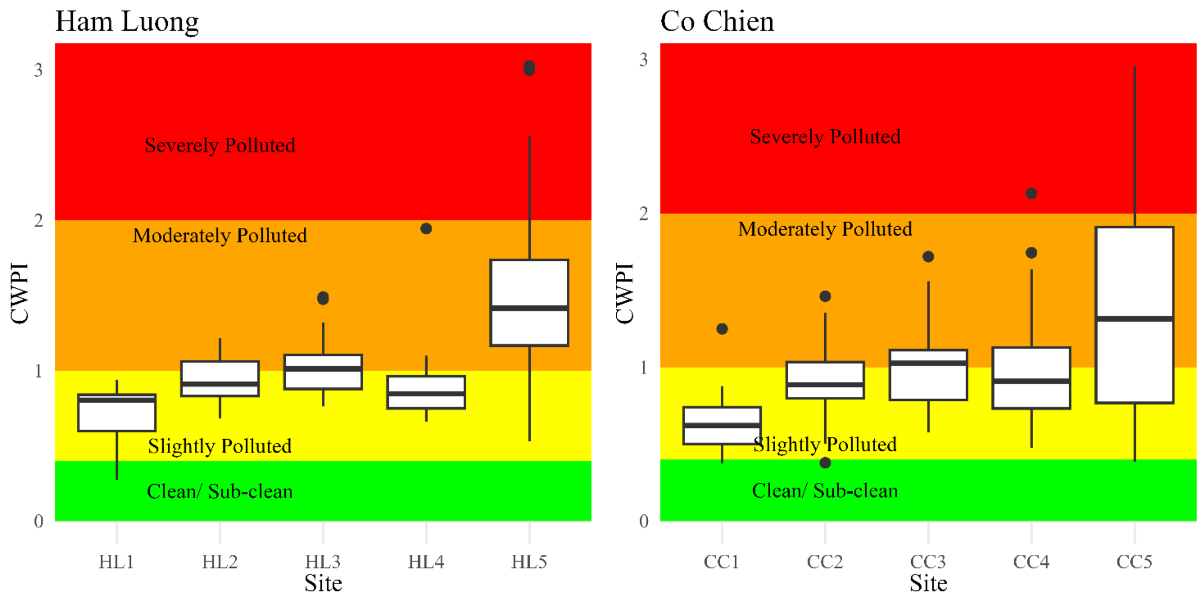

Figure 4. CWPI and the surface water quality in Cua Dai, Ba Lai, Ham Luong, Co Chien Estuaries (cont.)

The observed degradation in water quality in the years 2010, 2015, and 2019 could be attributed to significant saltwater intrusion experienced by the VMD during these years. The SWQ in the Ba Lai estuary exhibited a progressive deterioration from the upper (BL1) to the An Hoa area (BL3) due to the complex hydrological regime at this location, resulting from the confluence of three rivers, namely Ben Tre, Ba Lai, and An Hoa. The An Hoa area is frequently affected by erosion, leading to significant environmental disturbances (Tran et al., 2021). However, the SWQ from An Hoa to the Ba Lai dam (BL7) indicated an upward trend.

This study provides additional evidence that SWQ exhibits greater turbulence in the vicinity of river mouths, compared to those located further upstream. Additionally, the SWQ tends to degrade gradually as it approaches the estuary, consistent with previous research (Le et al., 2023). On the other hand, the Mekong River estuaries are being impacted by significant sediment accumulation, which has resulted in a decline in overall environmental quality (Tran et al., 2018).

The Mekong Delta region hosts relatively few large industrial zones; hence, organic pollution in its rivers predominantly stems from domestic activities and agriculture (Wehrheim et al., 2023). Effective water quality management in the Mekong River estuaries necessitates the control of external contaminants. Nonetheless, when selecting appropriate technologies, it is imperative to consider the following pivotal attributes of the Mekong Delta area: (i) limited cost recovery capacity, contingent upon personal income and prevailing economic conditions; (ii) absence of centralized wastewater treatment facilities; (iii) a predominantly flat topography characterized by intricate and interconnected river and channel systems, governed by geological and hydrological factors; and (iv) the unique culture and lifestyle of the local populace in the Mekong Delta (Huyen and Lai, 2019). To treat domestic wastewater in rural areas, septic tank coverage in the Mekong Delta region is nearly universal, except for homes located along rivers. Nevertheless, septic tanks achieve only a 45% and 25% removal of TSS and BOD, respectively (Huyen and Lai, 2019). To enhance processing efficiency, low-energy technologies such as an advanced-treatment septic system combined with constructed wetlands can be employed. In general, it is essential to establish and execute viable strategies and regulations for managing, controlling, and treating the primary sources of pollution to ensure sustainable development and a healthier environment for the Mekong River.

4. CONCLUSION

In the present study, the Comprehensive Water Pollution Index (CWPI) was assessed for 21 sampling locations downstream of the Mekong River using water quality parameters from 2005 to 2021. The CWPI clearly indicates that the majority of observation stations exhibited slight to moderate pollution conditions, with the quality of surface water deteriorating as it approaches the estuary. The accumulation of sediment has contributed to a decline in the overall environmental quality of the Mekong River estuaries. Surface water quality in the downstream Mekong River exhibited notable spatial and temporal variations, with TSS, organic matter, and iron emerging as primary areas of concern. This study clearly underscores the utility of CWPI as a valuable tool for assessing pollutants in human-impacted water bodies and for classifying river water quality. Furthermore, it is recommended that conservation plans be implemented proactively to maintain acceptable levels of TSS, organic matter, and iron in the Mekong River estuaries.

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